Bird Collections: Development and Use of a Scientific Resource

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Commentary

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Bird Collections: Development and Use of a Scientific Resource.—Bird collections were founded and built during the heyday of global exploration. The mission of these collections through most of their history has been to document avian diversity and its distribution and to serve as a resource for research and education. As bird collections became established and grew, ornithology itself became a scientific discipline and broadly expanded its purview. Today, there are more professional ornithologists than at any time in history, and collections-related research represents only a small portion of the discipline. This is healthy. Collections are but one means through which we study birds. But we cannot be lulled into a view that the day of the collection is past—a decided risk when fewer ornithologists have direct experience either with collections or with the multidimensional strengths that a collections-based approach brings to science.

Too little attention has been paid to the role of bird collections in science. This role is changing. Because we understand avian diversity better than that of most other classes of organisms, the central goal for establishing bird collections would seem to be largely accomplished. As anyone studying avian diversity knows, however, much remains to be done: systematics, patterns and processes of differentiation, and geographic variation in birds remain vigorous areas of new learning. But while those of us close to collections remain connected to these important questions, to others what we do is increasingly arcane. After all (tongue in cheek), isn't there already a field guide? To an undiscriminating public, much of this work would seem to be done once a field guide appears. And, indeed, explorations at that level in most regions are largely complete. But in other respects the scientific strengths of collections-based research are blossoming—with no end in sight to the fruits that can be borne.

Bird collections are probably the strongest and most dependable shared resource in ornithology. Biological collections in general represent the original "big science" expenditures in the life sciences, antedating by centuries large contemporary endeavors such as genome projects. Long-term investments in the development and maintenance of collections have produced a resource equivalent in many respects to the mega-science facilities found in other disciplines (e.g. large telescopes or super-colliders). A key difference is that this resource has a useful lifespan that greatly exceeds that of mechanical facilities. Bird collections need to be viewed as a highly versatile and indispensable resource integral to the continued successful (and economical) pursuit of a wide range of subjects. Importantly, these subjects are no longer restricted to ornithology.

Unlike other, contemporary "big science" projects, biological collections establish an object legacy—continuing sources of data that are repeatedly tapped to provide answers to questions about birds and environmental conditions. Many of these questions were not even imagined by those who have built these collections. Indeed, as the ways in which museum specimens are used multiplies with conceptual, technological, and environmental changes, it is clear that we need to refocus on how best to continue developing this resource.

Specimens and Science through Time

Mismatches in temporal relevance.—The classic analogy that natural history collections are like libraries invites direct comparisons between specimens and books. There is some material similarity to these objects; old books and bird skins are products of animal skin and plant materials. With care, books can easily last for many centuries, and a useful lifespan of more than a millennium is likely. Effective preservation of bird skins has been practiced for only about two centuries, but the skins will clearly last far longer. Beyond simple object comparisons, consider use: it is routine in collections-based work to use specimens 100 years old or older, and historical specimens are increasingly used to conduct retrospective studies—research asking questions about changes in birds and the environments they live(d) in. As time passes, preserved specimens increase in scientific value. By contrast, the value of journal articles and books we produce today will be relatively short-lived (see ISI Journal Citation Reports; www.isinet.com); after only a few decades most of our papers will no longer directly contribute to science. Thus, in terms of utility and relevance, these two products a researcher can leave behind—specimens and publications—have strikingly different trajectories. Publications are important. But the long-term scientific value of specimens is widely underappreciated, and we probably place too much emphasis on producing publications, the more ephemeral of the two products that we might leave as our scientific legacy.

"Biological filter paper."—Just as historical anthropogenic objects like books reflect changes in human history, so too can preserved specimens enable us to appreciate and measure changes. One of the most important developments in collections-based science is the retrospective study, a very powerful approach for assessing changes in populations and environments. Specimens document life in three dimensions: geographic space (locality), biodiversity space (taxonomy), and time (date). The last dimension is becoming increasingly important, because historical samples enable us to enlist this strong analytic approach to measure and understand change. Probably the broadest reward this science brings to society as a whole is through the increasing use of specimens as "biological filter paper," documenting "experiments" in the environments in which these animals lived. In many studies, a species or genus is chosen because it represents an important trophic level at which to measure bioaccumulation or magnification of contaminants. These measurements have profound implications for humans and the natural resources we manage, and these studies repeatedly demonstrate that historical samples are crucial. Birds are excellent bioindicators of environmental conditions, and bird specimens should continue to be at the forefront of this field. Continued acquisition of new specimens should be seen as a priority. The time dimension can be studied only with continued sampling of the avifauna.

"*Arrogance of the present*."—The scientific capabilities and accomplishments of today are truly impressive when compared with those of yesteryear. But this will be equally true in the future, when the accomplishments of today will be overshadowed by those of our successors. Thus, to better serve our science, we should consider how we might contribute to a future 50 or 100 years from now. What do we have that they will not? A key asset of the present is access to a biota that is still probably half intact. There is strong evidence that passing samples of this biota forward to future researchers is one of the most effective ways to contribute to the accomplishments of future science, and that archiving specimens will enhance the effectiveness of future wildlife management and conservation (e.g. through the growing importance of retrospective studies).

Going Forward

Collections are helping to answer widely important questions about birds and our shared environments, and meeting the needs of users is a central purpose of a collection. As the user community grows, so too should support and participation in continued collections development. And the strengths of collections must be considered broadly, separately from individual research programs.

With increasing frequency, specimen loan requests ask different questions of preserved material than the questions for which that material was originally preserved (e.g. feather plucking of skins for genetic, isotopic, or contaminant analyses, and disease screening of genetic samples). In fact, one cannot predict what question, specimen type, or taxon the next loan request will hit upon. This is a double-edged sword: it reassures us that collections are broadly useful, but it suggests that collections growth is becoming increasingly out of touch with collections-based science. As the array of possible uses has increased, our ability to foresee what the specimen needs of tomorrow will be has declined. There is little doubt that there will be need, however. Important questions about changes in populations and environments will expand the need for specimens, and adequate sample sizes from today will be required.

So it is clear that the resource itself must continue to be developed. Collections were built on general acquisition policies, and their broad usefulness today reflects this. Continued growth should follow this course (in a guided manner), and care must be taken to foster this growth without exclusive reliance on focused research programs. Individual research programs are important components of collections growth, but healthy growth requires a broader diet. Wider user needs are not likely to be met by a focus on the scientific questions of today, which, although important at present, tend to be either taxonomically narrow or broad but shallow in sample size. Even the best-focused research of today will not meet tomorrow's specimen needs—unless, in aggregate, we work to increase that likelihood. Thus, most collections-based biologists and curators advocate a general acquisitions policy for our shared collection resources. But it is important to note that we recognize costs and commitments and that we work to maximize the gains that each archived specimen represents. Most effort goes to fill gaps (taxonomic, geographic, and temporal) and to increase sample sizes to enhance statistical power. The challenge is that there are a lot of gaps, especially in temporal and numerical dimensions.

The preserved objects themselves, as continuing sources of new information, have primacy over associated data. Recognizing that diverse, long-term scientific gains are achievable, more components of individual birds are being preserved, such as skin, partial skeleton, tissues, and stomach samples. Given the surprises that technology and science have derived from bird specimens thus far, it is not too outlandish to suppose that interdisciplinary teams (e.g. ornithologists, entomologists, parasitologists, virologists, isotope ecologists, computational and systems biologists, and community geneticists) will one day delve into a treasure trove of preserved avian stomach and tissue samples to extract complex network analyses of environments, communities, and biospheres. The fact that modern bird specimens are preserving so many attributes of today's biota speaks to the strengths of whole-organism sampling and preservation. Ornithology has yet to develop a more economical or efficient method than whole-organism sampling to accomplish such important, multidimensional documentation. This must be more widely understood.

Fashion trends are trumping strong science.—The fashionable concept that the only good science is science that tests hypotheses has in some respects been detrimental to collections. Simple exploration, description, and comparison—the types of science upon which collections were established—are today "poor cousins" in terms of recognition, funding, and publication. This has occurred despite the obvious importance of collections in establishing the baselines of our understanding of biodiversity and its distribution in space and time. Specimens and collections can, with planning, continue to establish and provide the baselines from which hypotheses are developed and tested, in dimensions that are both traditional (e.g. biodiversity) and nontraditional (e.g. environments, contaminants, and diseases). Our science will be strongest when we recognize and support these multiple legitimate pathways and contributions to how knowledge is developed. Hypothesis testing is an important component of individual research programs. But hypothesis testing alone, except in the most general manner (e.g. "things will change"), is an inadequate basis for continued collections growth.

An altogether different phenomenon has emerged around humans killing birds for science. Fastidiousness in this regard wildly outstrips our responses to other, much greater sources of avian mortality, and collecting for science is singled out for astonishing levels of restriction and scrutiny. The contortions through which many permitting agencies are willing to go to squeeze scientific sampling (nearly out of existence in many cases) is truly amazing. Most of this regulation is not biologically defensible, and it is not conservation. Permitting is useful and necessary, but it often seems to be a political means of imposing belief systems on others, affecting government and wildlife management to the detriment of science and society. It is ironic that the very agencies that would benefit most from the knowledge that specimens would deliver to their management programs are so often hostile to this knowledge development. This is self-handicapping behavior.

Individual researchers also need to examine how their beliefs affect their work and their scientific commitment. The act of killing a bird for science is difficult for those who do it and seemingly a personal barrier for those who choose not to. Those not directly involved often have strong beliefs surrounding this act. Many have not sorted out their feelings and beliefs about scientific collecting, nor have they thought through the long-term consequences of their choices to either support or not support this activity. Two beliefs are often involved: belief in the sanctity of the life of an individual bird, and belief in an erroneous worldview of conservation in which every individual matters. I do not wish to demonize these beliefs, but it is wrong to impose them on others. Too often, permitting systems are being used to do so, which is detrimental to research and management. Equally problematic are choices by researchers that cause these belief systems to diminish the scientific effect of their own work. Too many workers go out of their way to avoid collecting birds, even if their studies would be better for it. Usually, science in general would be better served if they collected as part of their efforts. I long ago integrated collecting with banding, because I realized that I was releasing most of the data I was working so hard to obtain.

Except when noncollecting is necessary, owing to factors such as small, fragile populations or the requirements of a study to follow living birds, specimens should be an expected product of most field ornithology. By not delivering fully on the scientific promise of an effort, time and money are often inefficiently used and thus—in part—wasted. This can be viewed as misallocation of scarce resources. Some will argue that time does not allow them to both collect and accomplish their goals. If those goals are strong science, some change is warranted. Even banders should be preserving all accidental casualties. Researchers should understand that by choosing not to collect (or, if killing birds violates a personal belief, choosing not to preserve salvaged specimens), they are diminishing their own scientific legacy. One can retain a strong respect for life and conduct good science that includes preservation of specimens.

Everyone working with birds should consider the details of these issues. Conservation must focus on populations; every individual dies. In most populations, every individual does not matter. Study population biology. Do the math. Recognize that bird populations are a renewable resource, and that scientific collecting represents a practically insignificant (and non-additive) proportion of annual avian mortality. In turn, specimens provide multiple benefits to science, wildlife management, conservation, and society. The vast majority of bird populations can easily support the small amounts of collecting that will maximize scientific gain for the resources expended in avian research.

Specimen salvage.—Many birds are killed inadvertently by humans (e.g. in collisions with towers, windows, or vehicles, or by pet cats) or die naturally. These are potential specimen "salvages," and this source is greatly underutilized. On average, however, salvaged specimens are of less value than specimens actively collected for science. Concentrations in geographic and taxonomic space limit the effectiveness of salvage, as does the often mutilated or rotting condition of salvaged birds. An active salvage program can rapidly fill local gaps and become saturated in the areas (geographic and taxonomic) represented in the salvage stream. Thus, museum interest in salvage usually comes below the interest in actively collected specimens, because the latter have been taken with science specifically in mind and are thus more useful and in better condition. But salvage has value, and in one respect this value is underexploited. The relative concentrations of salvaged birds in geographic and taxonomic space represent an opportunity to obtain birds from areas not usually collected (e.g. cities and parks), to archive rare species from captivity, and to develop large sample sizes of some species. These opportunities seem to be rarely exploited, perhaps because the questions these samples can be used to address tend not to be in the realm of traditional museum studies. However, their value for biomonitoring, for example, is high, and this is an area where agencies, governments, and individuals unwilling to kill birds should be actively developing partnerships with museums.

Monitoring and surveillance.—Birds play a prominent role in environmental monitoring, yet we often lack good baseline data against which to measure change. Too much avian monitoring and surveillance involves only counting animals. This is like taking health and disease statistics without addressing causation. Collecting, preparing, and archiving bird specimens through time is an economical way to enable implementation of retrospective studies when perceived changes occur, allowing detection of correlative changes that may have happened in such things as contaminants, food, and habitat use (e.g. through stable-isotope analyses), diseases, parasites, genetic diversity, sex and age structure, and traditional phenotypic parameters. This approach is effective for the monitoring and surveillance of populations, species, and environmental change. And the utility of these materials is not directly correlated with time. The other two dimensions that collections document (positions in biodiversity and geographic spaces) can produce important baseline information almost immediately. Specimens do not need to "ripen" for years to be useful. As a discipline, we have not effectively planned how best to do this job of using science for effective environmental stewardship. Nonlethal field work, counting, monitoring, and surveillance all remain important, but it is imperative to couple these approaches with a sample-based component if we are to maximize our success in bird conservation and management.

Leveraged research and partnerships.—Collecting and sending specimens or specimen loans, especially to people at other institutions and in other countries, indirectly leverages research support (i.e. time and money) for the species being collected. Thus, through specimens, a management agency, an institution, a state, or a country can often get work done that they themselves could not do or could not afford to do, providing increased knowledge about that resource. (And I emphasize the importance of basing such efforts on vouchered specimens.) Indeed, it is surprising that more resource management agencies and their permitting personnel do not recognize this important and effective means of inexpensively learning about the resources they manage. The most effective managers will be those with the best science to apply to their management plans; courting the appropriate researchers with specimens and samples is highly effective in developing such partnerships.

Two other important partnerships are those between institutions (e.g. museum and state or federal agencies) and those between researchers and a repository. Agencies responsible for resource management are increasingly dissociated from the sample-based perspective of museums, a situation that is harming us all. With our shared goals of understanding and successfully managing and conserving wildlife, we are natural partners, and we need to bridge this divide and begin working more effectively together to obtain and archive the specimen resources that will enable the very best science and scientific management. The best "bridge" is general and specimen-based: changes will occur in many dimensions (many of them unpredictable), and adequate numbers of specimens can be highly effective in documenting these changes, for both contemporary and retrospective studies.

Individual researchers also have much to gain by partnering with a repository. Properly archiving your specimens and samples for perpetuity has widely recognized scientific benefits. Such partnerships are best arranged before writing proposals for funding and permits (and certainly before initiating fieldwork). Proposals are strengthened by an archival component, and most funding agencies support the added costs that ensure proper preparation and preservation. Those costs are generally a small portion of the total, and writing them into proposals, with input from the repository, is now routine. Reviewers are increasingly (and properly) expecting to see this. In their turn, repositories need to grant researchers specific rights to research priority, with a sunset clause (e.g. rights of refusal on potentially competing user requests being guaranteed for five years or as long as the researcher is conducting active research on the material). These partnerships are among the easiest to generate, because the immediate gains are apparent to all. Moreover, this approach ensures that important research material and associated data are not lost to science because of a local freezer failure or a lab or office cleaning.

Supporting the resource.—Archiving specimens costs money and time, and museums cannot carry the burden alone. For example, just sending dead birds to a museum does not get the job done. Preparation capacities at museums are always saturated, and this is a bottleneck. Enhancing preparation capacity would have immediate benefits, and a broader distribution of preparation activities would work to the strengths of museums as repositories. This is a community resource, and it is time to develop community-wide solutions to collections development and maintenance. These solutions should be local, regional, and national, but a key basis is that those who are users or beneficiaries of specimens and related data need to become supporters and contributors.

Conclusions

Bird collections are a community research resource and provide broad benefits to our science, to the management and conservation of birds, and to society. In addition to strong contributions in traditional research, collections are making important, long-term contributions to issues that have little to do with the reasons for their establishment. These contributions are often more important to society than the original reason(s) for making the collections, and this needs to become part of the planning and reward processes for continued collections growth. Presently, most growth is focused on short-term gains; yet, as products of science, the specimens themselves have a much longer useful life than the publications generated from them. We recognize this, in part, simply by maintaining existing collections. The next step is to make new investments to enhance future gains. There is clear indication today of a need to collect, prepare, and archive specimens, and to do so in a way that increases the array of preserved components (i.e. animal parts), sample sizes, and dimensions (in biodiversity, geographic, and temporal spaces) available to present and future researchers. A lot of the world's biodiversity will ride the conservation coattails of successful avian management and conservation. As ornithologists, we have the opportunity and obligation to lead in this area. Specimens have been and should continue to be an integral part of the science behind monitoring, managing, and conserving our biological resources. Together we can direct collections growth to establish the baselines that we know will enhance our effectiveness in sound environmental stewardship.—KEVIN WINKER, *University of Alaska Museum, 907 Yukon Drive, Fairbanks, Alaska 99775, USA. E-mail: ffksw@uaf.edu*

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Old Bones in New Boxes: Osteology Collections in the New Millennium.—Skeletons and bones are the most durable specimens in avian collections. They are nearly maintenance-free in comparison with skins, spirit specimens, or tissues. They are data-rich and, to some, aesthetically striking—yet avian osteological specimens have always been a minor constituent of museum bird collections. Systematic ornithology of the previous centuries focused on plumage and external morphology, and birds collected in the field were perforce transformed into the compact, round skin specimen that forms the bulk of the world's museum collections. These traditional skin specimens were considered of paramount importance and, to the collectors and curators, represented "value—money value and scientific value" (Coues 1874).

The traditional preparation of skin specimens leaves only the cranium and the distal elements in the wings and feet, and early collectors usually discarded the remaining bones and the torso. Sometimes, however, partial osteological specimens comprising the axial skeleton, femur, and humerus or other combinations were prepared from the torso as an ancillary step in the scientific collection process, usually only if there were time available after the higher-priority skins were prepared. Often, single elements were preferred, and some collections specialized in synoptic collections of crania or sterna. Olson (2003) points out that because sterna were easy to obtain from skinned torsos, they were often the element of choice in anatomical collections, even in cabinets of curiosity (Fig. 1). The great French encyclopedist l'Herminier constructed a classification of birds based solely on sterna (l'Herminier 1827), and Coues and other 19th-century ornithologists distinguished several taxa (e.g. Pelecaniformes, Alcidae) on the presence or absence of a perforate nasal (Coues 1872).

Although exceptions exist, avian skeletons of the past were most often prepared as mounted displays and thus, as is often the case even today, data were secondary to the aesthetics of presentation. Consequently, osteological specimens collected before the mid-20th century are often incomplete or data-poor, or comprise mixed proveniences—particularly those used as reference collections for bone identification. Olson (2003) provides a succinct history of avian osteological collections and should be consulted for a more complete background on their development and the nature of early specimens. Here, we explore some possible

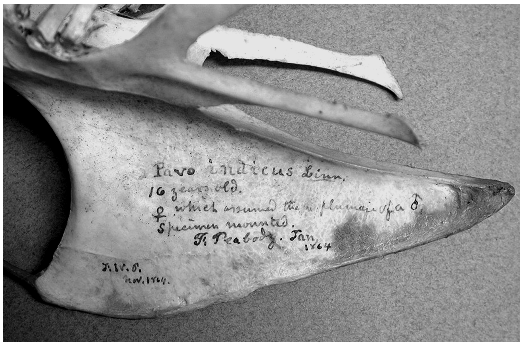

Fig. 1. Peafowl (*Pavo cristatus*) MCZ 342364. Sternum with collection information noted on specimen: "Pavo indicus Linn./16 years old./♀ which assumed the plumage of a ♂/Specimen mounted./F. Peabody. Jan, 1864".

reasons for the relative unpopularity of avian osteological specimens, examine the value and use of bony specimens in modern ornithological research, and suggest possible directions and solutions for the future.

CURRENT STATUS OF AVIAN OSTEOLOGICAL COLLECTIONS

Avian osteological specimens come in several different forms, from complete skeletons with all major bones to single isolated elements (Table 1). **Complete** skeletons are the foundation of most modern osteological research collections: in these, every major bone of the bird is preserved, including left and right elements. The disadvantage of these skeletal specimens is that their preparation precludes nearly any other type of specimen, with the exception of tissue specimens, because the skin and internal anatomy of the collected bird are usually destroyed in the process. **Partial** skeletons have elements missing; the most common partial skeleton prepared in modern treatments leaves only a left or right set of distal elements (e.g. ulna, radius, carpometacarpus, hallux) in the skin, the distal end of the maxilla, and other bones necessary for a durable skin specimen (Winker 2000). Partial skeletons encompass a broad range of included elements (sometimes only the torso elements, sometimes articulated sterna and clavicles, etc.). **Mounted skeletons** are nearly always **complete** (but not **entire**; see below) and usually were intended for display, but some of the earliest research specimens were mounted with the elements articulated for movement. Mounted specimens are difficult to use for research, because many of the character-rich locations on bones near their articulating surfaces are often obscured by wires or holes, and early preparators would often use bones from several specimens to "part out" missing or pathological elements.

Lots, or bulk collections of bones, are most commonly associated with subfossil or archeological settings. The Museum of Comparative Zoology (Harvard University) and the U.S. National Museum (Smithsonian Institution), for example, have numerous large boxes of many thousands of Great Auk (*Alca impennis*) bones gathered from slaughter sites on Grand Funk

Table 1. Classes and features of avian osteological material.

Class [a]	Entire [b]	Associated [c]	Articulated [d]	Vouchered [e]
Complete	Usually	Yes	?	Usually
Partial	No	Yes	?	Usually
Mount	Usually	?	Yes	?
Lots	No	No	No	?
Elements (Recent)	No	No	No	Often
Elements (Fossil)	No	No	No	No

[a] **Complete** specimens have all major bones (paired elements plus axial elements) usually kept for scientific study. **Partial** specimens lack some major elements, purposefully or through attrition. **Mounts** are assembled skeletons intended for display. **Lots** are bulk collections of bones, sometimes sorted by element type (e.g. humerus), some not. **Elements** are single bones of recent or fossil origin.

[b] **Entire** specimens have all bones, including minor elements such as phalanges and hyoids; thus, most complete specimens are entire, whereas not all mounts are entire.

[c] **Associated** specimens comprise bones from only one individual.

[d] **Articulated** specimens have adjacent elements joined, often by dried ligaments or skin and rarely by wire, string, etc.

[e] **Vouchered** osteological specimens were originally identified by reference to the intact bird when collected; thus, by definition, no fossil is vouchered.

Island, Canada. While nearly every major bone is represented, very few of these specimens are associated; that is, there is no way to determine which bones came from the same bird. **Single elements** are most commonly associated with fossil specimens or specialized reference collections for comparative studies. As mentioned above, early avian anatomists focused on sterna or crania, for example, to the exclusion of other bones.

Each of these forms of osteological specimens can be characterized by four primary features: whether they are entire, associated, articulated, or vouchered. **Entire** specimens have every bone preserved from the collected bird. Although most complete specimens are entire, there are many which, as a consequence of collection or preparation mishaps, lack a few very small or delicate bones, such as the hyoid, the cranial xiphoid of pelecaniform birds, the alula, and so on. Entire specimens offer the greatest research value, but are rarest in the early specimens. An **associated** skeleton originates from a single bird, and nearly every complete or partial specimen with data is associated; mounts may or may not be; and lots and single elements, by definition, are never associated. **Articulated** elements are what make a prepared mount, but elements can also be articulated by dried ligaments and skins, as in some early complete and partial specimens or in semi-prepared skeletons.

By far the most problematic issue with osteological specimens is vouchering. A **vouchered** specimen was identified by reference to the actual bird when it was collected or prepared. Partial skeletons often lack easily diagnosable elements, and mistakes in identification or other lapses during preparation can lead to errors very difficult to detect later (see below).

Survey of Major Collections

Overall, skeletal specimens constitute ~7% of the total specimens held in 10 of the largest ornithological collections (Table 2). There are some notable variations from this general pattern, attributable to the particular history of a museum collection. For example, the number of osteological specimens at Florida State Museum exceeds the number of skin specimens by ~30%, whereas those at the British Museum represent only ~1% of the total collections. The Florida collections were, in large part, formed by Pierce Brodkorb, a leading avian paleontologist of the 20th century. The British Museum's collection started out as,

Table 2. Relative proportion of skeletal specimens to traditional skin specimens at selected top avian collections, ranked by number of skeletal specimens. Data from various sources, including Wood et al. (1982), Mearns and Mearns (1998), and J. Hinshaw (pers. comm.).

Museum [a]	Skeletons	Skins	Skeletons/ skins (%) [b]	Skeletons/ total (%) [c]
USNM	51,931	513,000	10	9
FMNH	49,294	360,199	14	12
ROM	44,268	135,972	33	25
AMNH	25,000	850,000	3	3
FL	23,238	17,794	131	57
UMMZ	23,086	171,225	13	12
KU	21,463	53,401	40	29
LSU	21,000	142,000	15	13
MVZ	19,537	159,283	12	11
BM	~15,000	~1,000,000	~2	~1
MCZ	~6,000	~340,000	~2	~1
Total	300,000	3,782,874	8	7

[a] AMNH: American Museum of Natural History; BM: British Museum of Natural History; FL: Florida State Museum; FMNH: Field Museum of Natural History; LSU: Louisiana State University; KU: University of Kansas Museum of Natural History; MCZ: Harvard University Museum of Comparative Zoology; MVZ: University of California, Berkeley, Museum of Vertebrate Zoology; ROM: Royal Ontario Museum; UMMZ: University of Michigan Museum of Zoology; USNM: United States National Museum.

[b] Proportion of skeletal specimens to skin specimens.

[c] Proportion of skeletal specimens to total number of specimens.

and remains, the premier collection of bird skins; skeletons never had a chance there. Similarly, osteological collections represent a large part of the University of Kansas collections, because of the long history of skeletal preparations begun by Charles Bunker in the first decade of the 20th century (Hall 1951, Johnston 1995).

The number of osteological specimens in a collection does not necessarily correlate with the depth of taxonomic coverage. The U.S. National Museum has by far the greatest diversity of specimens, with 5,109 species represented (Table 3), more than half the known species of birds. The Field Museum of Natural History and the Royal Ontario Museum rank at the top of the list for mean number of specimens per species, an index that relates to the collecting effort for series of specimens rather than single examples. The British Museum collection, while ranking about seventh in number of species, has only ~5 specimens per series. These data reflect several interacting factors. First, the top-ranked institutions have dynamic collecting programs that continue to preserve osteological specimens. By contrast, osteological collections begun in the late 19th and early 20th centuries were usually intended for the study of comparative function and morphology. The modern emphasis on the study of geographic and population variation demands more specimens than the comparative approach. Second, space is always a factor, and some collections are unable to expand beyond their current size. But expansion is needed—more specimens are needed in avian museum collections.

Table 3. Depth of skeletal specimen holdings in ten top avian collections. Data from Wood et al. (1982).

Museum [a]	Species [b]	Mean specimens/ species	Rank [c]
USNM	5,109	10.16	3
FMNH	3,151	15.65	4
ROM	3,020	14.66	6
AMNH	4,000	6.25	2
FL	2,889	8.07	16
UMMZ	3,524	6.55	7
KU	2,769	7.75	14
LSU	3,175	6.64	11
MVZ	2,148	9.09	10
BM	3,000	5.00	1

[a] See abbreviations in Table 2. Collections are ranked by the number of species represented by osteological material.

[b] Number of species represented by skeletal specimens.

[c] Ranking in world based on total number of specimens (including skins, skeletons, spirit anatomicals, etc.).

More specimens are needed because many species of birds are still unrepresented by even a single skeletal specimen. For example, 30% of tinamou species have no osteological specimens, and 67% of the genera have unrepresented species (Table 4). In more speciose orders, the pattern is similarly bad. In Apodiformes, for example, 33% of species have no specimens, 46% of genera have species with no skeletal specimens, and 74% of species have ≤10 specimens. For Caprimulgiformes, 40% of species have no specimens, 50% of genera have species without any specimens, and overall, 84% of species have ≤10 specimens.

Clearly, osteological specimens are underrepresented in the top museum collections, but the global situation is likely much worse than this. Osteological specimens have migrated from smaller museums and natural history cabinets into the collections of major museums, thus skewing the skeleton:skin ratio higher in those few institutions. The frequency of skeletal collections among all scientific collections may be much lower than 8%. For example, several recent estimates of the total number of bird specimens existing in world collections range from 8 to 10 million (Banks et al. 1973, Goodman and Lanyon 1994, Mearns and Mearns 1998), whereas the total number of skeletons and other osteological specimens probably does not exceed 500,000 (Wood et al. 1982, Wood and Schnell 1986, Mearns and Mearns 1998). In other words, <5% of the world's ornithological collections are represented by osteological material of any kind—single elements to entire complete skeletons.

SHORTCOMINGS AND BENEFITS OF OSTEOLOGICAL MATERIAL

There may be many reasons for the discrepancy in specimen preferences, but one aspect unrelated to scientific use of osteological material is the relatively high labor cost and delay associated with preparation. Skilled preparators can make skin specimens very quickly in the field; thus, for example, Elliott Coues and Henry Henshaw, in the 1880s, competed for the quickest preparation on a friendly wager. The

Table 4. Taxonomic coverage by osteological specimens of selected avian orders. See text for explanation. Data from Wood et al. (1982).

Order	Species frequency (no specimens) [a]	Species frequency (1–10 specimens) [b]	Genus frequency (no specimens) [c]
Tinamiformes	0.30	0.24	0.67
Procellariformes	0.04	0.23	0.08
Sphenisciformes	0.00	0.06	0.00
Gaviiformes	0.00	0.00	0.00
Podicipidiformes	0.00	0.30	0.00
Pelecaniformes	0.02	0.15	0.17
Ciconiiformes	0.07	0.39	0.16
Falconiformes	0.19	0.45	0.19
Anseriformes	0.01	0.16	0.05
Galliformes	0.19	0.40	0.27
Gruiformes	0.22	0.50	0.30
Charadriiformes	0.05	0.28	0.12
Columbiformes	0.26	0.47	0.48
Psittaformes	0.15	0.42	0.30
Cuculiformes	0.29	0.39	0.35
Strigiformes	0.27	0.46	0.53
Caprimulgiformes	0.40	0.44	0.50
Apodiformes	0.33	0.42	0.46
Coraciiformes	0.20	0.44	0.32
Piciformes	0.18	0.53	0.48
Total	0.19	0.40	0.31

[a] Frequency of species with no osteological specimens.

[b] Frequency of species with 1–10 osteological specimens, including partial skeletons.

[c] Frequency of genera having species without osteological specimens.

winner (Henshaw) completed a study skin of a recently collected House Sparrow in one minute and thirty-five seconds; Coues took five seconds longer (Cutright and Brodhead 1981). Under normal conditions, Coues felt that four specimens an hour was an acceptable rate (Coues 1874); with today's more rigorous requirements, one specimen an hour is fairly typical (Winker 2000). By contrast, the fastest completion of an entire skeleton by D.C. took three-and-a-half days, including about three hours of dedicated technician time in preparation; the rest of the time was taken by beetles cleaning the bones of extraneous tissue. This additional burden of time and personnel costs dissuades most collectors and museums from casually adding osteological material to the collection mix.

The bottlenecks in osteological preparation are bone-cleaning and element-numbering. Most skeletal preparators now use dermestid beetles (*Dermestes maculatus*) to remove flesh and connective material from the skeleton, a technique first developed at the University of Kansas by Charles Bunker at the turn of the last century (Matthiesen 1989, Johnston 1995). A few specialized applications may require bacterial maceration, chemical treatment, or boiling for cleaning bones; but these techniques are rarely employed, because of undesirable effects on the bones. The consensus is that bone-cleaning with dermestid beetles (or other carnivorous invertebrates, like marine crustaceans) is more efficient (Matthiesen 1989, Winker 2000), but the process is generally held to be noisome and undesirable (Weed 2003).

After the bones are cleaned, the skeleton is usually disarticulated and then soaked in various solutions, depending on its condition—a weak ammonia solution to reduce odor, for example. Most importantly, each element is annotated with the specimen acquisition or register number. An experienced preparator can number (nearly) every element of a robin-sized bird in about an hour; smaller birds and larger birds can take longer, because of small bone size or additional preparation time associated with greasier bones. Numbering of elements is a critical step in the process, because if it is not done there is a great danger of mixing or losing elements in use. Given the more numerous steps in skeletal preparation as compared with skin preparation, there are many opportunities to lose elements, to exchange bones with other specimens of the same species, or to intermix different species under preparation at the same time. Despite this, and because of the high demands on personnel in numbering, many osteological specimens in the world's museums are unnumbered or only partially numbered (perhaps as high as 25% overall; D. Causey pers. obs.).

Nonetheless, osteological material has many positive aspects. In contrast to study skins, which offer few standard morphological measurements and are subject to wear, avian skeletons make possible many more quantitative measurements with a high degree of replication (see Olson 2003 for more details). Osteological specimens are low-maintenance, have high durability, and are much less susceptible to variations in storage regime, insect damage, or post-preparation degradation than other specimen types (Matthiesen 1989, Winker 2000, Olson 2003).

New Directions in Curation

Of the two main impediments in preparation of osteological specimens, element-numbering seems the most tractable for improvement. Several new technological developments offer promising alternatives to numbering each element by hand with pen and ink. Precision laser engraving can be quite quick, about 1 s per element, using numbers, letters, symbols, even barcodes (Fig. 2). One great limitation is that the engraving physically alters the surface of the bone by removing material through carbonization, which may be objectionable for many types of research application.

Fig. 2. Great Currasow (*Crax nigra*) MCZ 340401. Coracoid shaft marked by laser engraving. Note the traditional pen and ink numbering "401" that was applied over 100 years ago. The engraving "MCZ340401" is 8.5 mm long.

Precision microfibers (or microtaggants) as small as 5 µm in diameter carrying up to 10^7 different codes can be applied to the external surface of bony elements through a spray adhesive. The advantage is that an entire skeleton can be marked in a single spray; the grave disadvantage is that the microfibers must be read using a microscope and decoded. Loss of the codebook would make this type of system unintelligible—a shortcoming shared with barcoding and other symbolic marking.

Microprecision inkjet printers offer a close replicate of manual numbering, and as the resolution increases (in 2005, 1,200 dpi [dots per inch]), and with computerized control for printing on curved surfaces like bone shafts, become increasingly more useful for rapid numbering of elements.

All these technological alternatives to manual numbering, and others, have the potential to speed the preparation process of osteological material, but all suffer the same problem of high cost. Even a relatively cheap precision inkjet printer ($40,000 in 2005) is likely beyond the budgets of most museums, so technological solutions may have to await the creation of a centralized, entrepreneurial specimen-processing facility, similar to what has evolved in molecular biology for oligonucleotide synthesis and DNA sequencing. Many institutions now outsource that work, which used to be done in individual laboratories, to central facilities or for-profit enterprises.

Future Research in Osteological Collections

Osteological collections continue as a resource for current avian research (Fig. 3). Traditional uses are focused on the bony morphology, and examples of recent published research include comparative anatomy and morphology (Ponton et al. 2004, de Margerie et al. 2005), paleobiology (Holdaway et al. 2003, Causey et al. 2005), paleontology (Bourdon et al. 2005, Clarke et al. 2005), avian systematics (Mayr 2003, Zhou and Zhang 2003), and zooarcheology (Plug et al. 2003, Fiori et al. 2004).

Recently, avian osteological material has served as a resource for research far removed

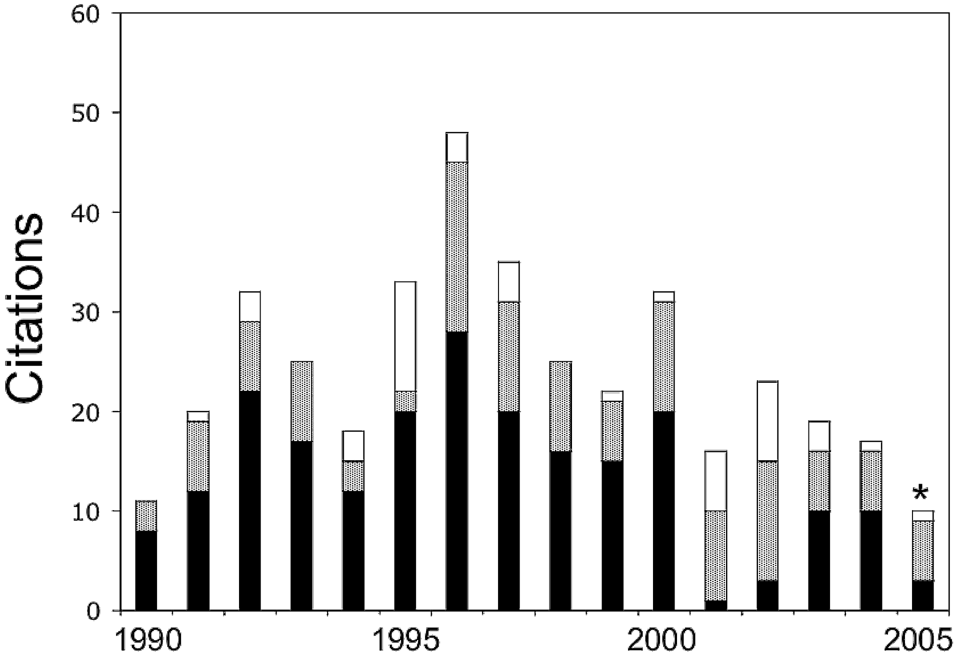

Fig. 3. Published research based primarily on osteological material since 1990. Solid bars: comparative ecological and evolutionary studies; shaded bars: paleontology; open bars: systematic studies. Data abstracted from citations listed in *The Zoological Record*. The histogram marked with an asterisk represents citations for only the first quarter of 2005.

from the purposes originally assigned to bony material. For example, modern material-analysis of avian bones, tendons, and other connective tissues has greatly facilitated medical and veterinary treatments, as well as provided new insights into vertebrate evolution (Naldo et al. 2000, Summers and Koob 2002, Tully 2002). Bone has proved to be an excellent source of DNA, and subfossil bone has been used to enable molecular study of extinct populations and species of birds (Terbutt and Simons 2002). It should be pointed out that studies focused on the ancient DNA contained in bone often use specimens collected before DNA was known to science (i.e. 1860). Osteological specimens collected today are just as likely to serve as a resource for presently unknown scientific technologies 150 years in the future.—Douglas Causey, *Department of Biological Sciences, University of Alaska, Anchorage, Alaska 99508, USA* (*e-mail: dcausey@uaa.alaska.edu*) and Jeremiah Trimble, *Museum of Comparative Zoology, Harvard University, Cambridge, Massachusetts 02138, USA.*

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Future of Avian Genetic Resources Collections: Archives of Evolutionary and Environmental History.—In the past 30 years, genetic resources collections (GRCs) have shifted position within ornithology, from a novel supplement to traditional voucher collections to a major core source of raw material fueling multiple subdisciplines. The demand for specimens from GRCs now greatly exceeds both the demand for traditional voucher specimens and, in many cases, the resources available to museums to maintain GRCs. The projection for the next decade is ever-increasing use. Here, we present a brief update on modern principles and challenges of collection, storage, organization, use, and dissemination of genetic resources and electronic information associated with such collections, drawing heavily on the experience of building, loaning, and curating the GRC of the Burke Museum at the University of Washington. The Burke Museum was established under the curatorship of Sievert Rohwer in 1986 and is now the second-largest such collection for birds in the United States, after that of Louisiana State University. In addition, we make a number of recommendations for ensuring the long-term sustainability and value of avian GRCs.

Unique challenges for avian genetic resources collections.—There are now several large (5,000–60,0000 individual specimens) avian GRCs in North America, Europe, and Australia, and many other museums and individuals have smaller GRCs. These collections typically consist of frozen tissues (heart, liver, muscle) of birds. In many cases, field and storage practices have changed little since their origin in ornithology in the 1970s and 1980s (Johnson et al. 1984). Because sampling from genetic resources is destructive and nonrenewable without further collecting, there are a number of issues regarding loan policies and reciprocation that are specific to these collections. The fate of GRCs is tied, even more intimately than the fate of voucher collections, to the future of field collecting; whereas traditional GRCs consisting of frozen tissues must eventually be renewed by continued fieldwork, current voucher collections will, in principle, remain intact and valuable without any further fieldwork. Particularly for small to midsize museums with little internal funding for the upkeep of GRCs (such as the Burke Museum), it remains a challenge to provide for the increasing demand on GRCs while at the same time recouping costs for field collecting, curation, and storage of tissues. These collections and others like them face a unique set of challenges: how to balance the activities that build, preserve, and promote use of their collections with an eye toward maintaining optimal use for future researchers.

Genetic resources collections demand little space, but take substantial staff time to organize and are expensive to maintain. Frozen collections need almost constant vigilance even with an alarm system installed (Dessauer et al. 1996). Because they are newer than traditional collections, they usually represent a small (≤35%) overall proportion of specimens, but are nonetheless heavily used. Loan activity can become a large investment for the host institution: for example, in 2003 the Burke Museum loaned subsamples of 5% (1,500 tissues) of its collection to researchers at other institutions, with a substantial outlay in both staff time and supplies. At the Burke, the upward trend in activity has been consistent over the past 10 years and shows no sign of diminishing. Because these loans are to individuals at institutions all over the world, they indicate a general increase in demand on tissue collections.

Field collecting and molecular protocols.—Since their inception, avian GRCs have been used primarily in the arena of systematics, including molecular phylogenetics and phylogeography. More recently, common uses have come to include conservation genetics and stable-isotope analysis, in which chemical signatures derived from tissues can help determine recent diet or habitat from which the tissue was collected (see Rocque and Winker 2005). In the past 25 years, the uses of avian GRCs have changed dramatically, from protein, DNA hybridization, and RFLP (restriction fragment length polymorphism) studies requiring relatively large amounts of blood or other tissues to polymerase chain reaction (PCR) based DNA sequence and fragment analyses requiring only picogram quantities of DNA (e.g. amplified fragment length polymorphism (AFLP) analysis; Wang et al. 2003). Ironically, because of their exquisite sensitivity even with degraded DNA templates, PCR methods have, in our view, contributed to the decline of meticulous field collection and archiving practices, because the threshold of quality for PCR methods is often lower than for other molecular biological approaches. Tissue culture methods have the advantage of providing an unlimited supply of genomic material but are labor-intensive to set up and, to our knowledge, have not been adopted by ornithologists as they have been by mammalogists (e.g. the Zoological Society of San Diego's Center for Reproduction of Endangered Species [CRES]).

We conducted an informal survey of five of the major avian GRCs in the United States to determine trends in loan activity and research use. Our findings suggest that 60–70% of current loans are for phylogenetic studies (i.e. involving one or a few exemplars of different species) and that the vast majority of remaining loans are to researchers studying population genetics (i.e. many individuals of a single species). Loans for other types of projects (e.g. stable-isotope analysis, studies in basic molecular evolution) are currently uncommon. Sadly, researchers using techniques such as BAC (bacteria artificial chromosome) library construction (which requires very high molecular weight DNA) or microarrays and expressed-sequence-tag (EST) surveys of gene expression (which require intact RNA transcripts) cannot make use of most avian GRCs because the DNA and RNA have not been stored appropriately. With this in mind, it is imperative that the method of preservation, both in the field and in the GRC itself, maximize the potential uses of the tissue, especially as specialized techniques in genomics become more taxonomically widespread (Couzin 2002, Edwards et al. 2005). Flash-freezing fresh tissue in liquid nitrogen, though logistically complicated, still represents the gold standard for preservation of avian tissues in the field (Engstrom et al. 1999). Storage of tissues in lysis buffer (Seutin et al. 1991) has the advantage of not requiring deep freezing and is very effective for isolating high-molecular-weight DNA, but lysing cells makes isolation of RNA or even of purified mitochondrial DNA a problem. Some protocols and storage buffers offer the ability to preserve RNA for PCR assays (Miller and Lambert 2003). However, even nitrogen storage will be inadequate for many molecular protocols if the tissues are left at ambient temperature for hours after the blood sample is obtained or the individual sacrificed. Thus, an appropriate goal for GRCs would be to gather a synoptic collection of one or several RNA-quality samples per species.

Genetic resources collections will undoubtedly play a large role in "DNA barcoding," an initiative whose goal is to genetically characterize many existing museum voucher specimens with a short DNA sequence(s) to facilitate future field identification and species discovery. DNA barcoding is controversial, not only because it is closely linked with the controversial idea that DNA sequences can form the sole basis for taxonomy (DNA taxonomy), but also because of the many well-known theoretical shortcomings of short, single-locus molecular characterizations of biodiversity for purposes of species assignment (Moritz and Cicero 2004). We suggest that curators and users of GRCs scrutinize carefully the claims of DNA barcoding and draw a distinction between the theoretical issues surrounding species designation by DNA and the potential practical benefits to the additional information provided by DNA sequences. By maintaining a utilitarian view of this controversy, genetic resources curators and collections stand to leverage substantial resources if DNA barcoding is conducted on the large scale outlined in some schemes (Stoeckle 2003), and few would deny that even a single DNA sequence attached to a voucher can only increase the information content of that voucher.

Organization and archiving of genetic resources collections.—Most avian GRCs store tissues in cryogenic conditions—either the vapor phase of liquid nitrogen or in electric freezers set at around –80°C (Prindini et al. 2002). The major advantage of liquid-nitrogen systems is that they increase the long-term stability of macromolecules and the breadth of uses to which the tissues can eventually be put. However, they often take up more floor space—an important consideration for collections with space limitations. Also, samples are sometimes more difficult to see and access in liquid-nitrogen freezers, and it is more difficult to accommodate samples in nonstandard containers, which may be a problem for collections with very active loan and acquisition programs. It is known that archiving in mechanical freezers maintains materials above the critical preservation temperature for many biomolecules (Franks 1985); this, in conjunction with a frequent lack of backup freezer space, puts many GRCs in jeopardy. Indeed, the past decade has seen the thawing and eventual loss of several large and vital avian GRCs. The storage system chosen for GRCs will vary depending on the use and resources available to the collections. For example, freezers are generally less expensive to operate; when the Burke Museum decided to increase its storage capacity for tissues in the late 1990s, we chose increased freezer space over nitrogen, primarily because it was cheaper to set up and maintain. By contrast, the American Museum of Natural History's Ambrose Monell Collection for Molecular and Microbial Research is housed in an endowed, state-of-the-art storage system based entirely on nitrogen—maintenance costs typically run ~$40,000 per year (R. Desalle pers. comm.). Hopefully, institutions wishing to switch to nitrogen storage can convince those who pay the utility bills for freezers that they can at least partly recoup electrical costs by investing in nitrogen. In either case, tissues are typically kept in uniform-sized (2 mL) cryovials and organized in boxes and racks for easy retrieval. We expect that, for tracking and mapping purposes, most large GRCs will complement traditional hand-written vial labels with computer-generated labels or bar codes, which are permanent, easier to standardize, and less susceptible to degradation.

Collections are usually organized taxonomically or numerically (by museum or collector number), and taxonomic organization has been recommended elsewhere (Dessauer et al. 1996). The Burke Museum GRC has adopted a numerical organization scheme because we felt it permitted rapid retrieval of tissues and valued that the scheme can be used efficiently by anyone, especially student helpers who may be unfamiliar with specific taxonomies. Organization systems become crucially important as collections grow in size, complexity, and loan activity, and even managers may find themselves caring for tissues from organisms outside their area of taxonomic expertise. Because Burke researchers frequently collect generally rather than for a specific research project, we found that adding new tissues at the end of a number series is substantially easier than threading these tissues one by one among those already installed in numerous boxes. Numerical organization also minimizes the difficulty of incorporating future taxonomic revisions and, because precise location of a given tube is always known, loan processing remains rapid. On the other hand, numerical organization can be a hindrance when sampling multiple samples from a single taxon, which may be distributed over several collectors and accessions throughout one or multiple freezers.

Traditional and digital vouchers for genetic resources collections.—Because of a growing acknowledgment of the importance of voucher specimens for molecular research (Winker et al. 1996, Ruedas et al. 2000), a primary goal for many collections is to have all or most of their samples vouchered with traditional specimens (Thomas 1994). However, for frozen-tissue repositories, this traditional definition of a voucher can become impractical and—for many collection endeavors involving endangered species or in countries where permits to conduct destructive sampling are difficult to obtain—hard to implement. Such nonvouchered samples are undeniably valuable, often have substantial associated data, and in most cases are identified correctly to species, yet museums are naturally reluctant to absorb large numbers because of space constraints and lack of vouchers.

In some cases, such samples are associated with field voice recordings or photographs, or both, to increase their reliability. The term "e-voucher," coined by Monk and Baker (2001), applies to such documentation: "An e-voucher is a digital representation of a specimen…[it] may be ancillary to a classical voucher specimen or it may be the only representative of the specimen in the collection." The goal of the collector should be to document the collection event with all means available. Collection events involving multiple levels of vouchering (e.g. morphological, molecular, digital) will inspire greater confidence and permit a broader array of scientific inquiry by enhancing their evidentiary value.

Digital access and a global genetic resources network.—Maximal use of biomaterials in contemporary research demands sophisticated coordination of collection records married to primary data (molecular biology-based data, digital images, etc.) via electronic and computer technology. Future methods in taxonomy need to be integrated by a transparent, "virtual" organizational schema that provides unity to taxonomy and molecular systematics (Godfray 2002). Currently, avian GRC databases are heterogeneous in structure and organization. However, many more museum collections will be coming online in the future, and networking them could be facilitated by harmonizing vocabularies and developing standards early on. Coordination of existing collections and information will enhance the value and accessibility of collections (Hoagland 1997, Cambon-Thomsen 2003, Peterson 2005), and awareness of the inventory of tissues available, or lack thereof, may help stimulate needed field collecting. Several preliminary efforts for a common digital framework for GRCs are in the works, such as an initiative from the AOU Committee on Bird Collections currently being organized by Carla Cicero (C. Cicero pers. comm.). Modern bioinformatics initiatives will ultimately link tissue-specimen collection records with bibliographic citations, competing taxonomic determinations, and geospatial referencing information; indeed, some GRCs, such as those at the Museum of Vertebrate Zoology, Berkeley, already have such capabilities in place. The ultimate goal is to develop a national infrastructure capable of supporting research involving genetic resources by promoting the linkage of biological resource collections' online specimen records with the publications and data derived from those specimens.

To achieve maximum value, tissue repositories need to be networked with one another and with collections containing voucher specimens (Dessauer et al. 1988). Such digital networks for voucher collections, such as ORNIS (Ornithological Research Network Information System), promise an exciting future for those collections. The International Society for Biological and Environmental Repositories (ISBER; see Acknowledgments) provides a forum for such collaboration and communication on advances in tissue collection and preservation protocols, along with current best practices associated with repository management. The Organization for Economic Cooperation and Development's (OECD) Working Party on Biotechnology is calling for a global network of biological resource collections to be established (Organization for Economic Cooperation and Development 2001). The Global Biodiversity Information Facility (GBIF) is similarly calling for the establishment of an international network of biodiversity collections with online databases to provide coordinated electronic access to their catalogues.

Conclusions.—Given the difficulty of procuring funds for collections-based research, the often greater difficulty of obtaining the necessary collecting permits, and, finally, the concomitant destruction of habitats for birds globally, it is not difficult to imagine that collections of organisms made today may well be the last opportunity the scientific community has to obtain archival material for many of the world's species. Continued efforts to secure GR samples from all species, both threatened and common, are justified insofar as each specimen represents a unique record of environmental and evolutionary history (Sheldon and Dittmann 1997, Sheldon 2001). Thankfully, a modern paradigm of preservation that maintains not only the collecting locality and morphological identity of specimens, but also the integrity of the biomolecules within them, is generally accepted. Hopefully, societal acknowledgment of the value of these biomolecules will translate into increased support for GRCs and the museums and other institutions that maintain them.—

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New Directions for Bioacoustics Collections.—Bioacoustics collections contain recordings of sounds produced by animals. The technology that made possible the capture of ephemeral sound events appeared more than 100 years ago (Koch 1955). However, for biologists who sought to record animal sounds in the field, technological innovations in truly portable sound equipment and reliable media emerged only after World War II. Nevertheless, before the introduction of the portable magnetic tape recorder, pioneers at Cornell University experimented with recording sound on motion picture film (Brand 1935). A recording field-trip required a truckload of equipment, and it took weeks to get the film developed. But there were successes with this cumbersome technology, including the only known recording of the Ivory-billed Woodpecker (*Campephilus principalis*), made in 1935 by the Cornell expedition to Louisiana (Kellogg 1962). Biologists who rediscovered the Ivory-billed Woodpecker in Arkansas in 2004 were trained to listen for the bird with this recording, and it is crucial to researchers in the Bioacoustics Research Program at Cornell in evaluating more than 17,000 hours of automated recordings made to detect calling individuals since December 2004.

A specimen in a bioacoustics collection is a recording of one target animal or group of animals and the associated metadata. The sounds produced by the animal(s) are usually recorded in one session for a variable length of time (seconds, more often minutes, or even days, as technological advances improved storage capacity). Specimens are obtained on master field recordings that may contain multiple specimens and multiple species from multiple locations. A "label" for an acoustic specimen, separating it from other specimens on a master tape (or other media), is the narration by the recordist (Kroodsma et al. 1996). In the era of reel-to-reel tape, specimens were cut out of the master tape. Thus, specimens in bioacoustics collections are termed "recordings" or "cuts." More recently, especially with the advent of analog cassettes, cuts were duplicated from the master field recordings, preserving the integrity of the master field tape.

A white leader tape was added to each specimen obtained from the master field tape. This leader served as a visible label onto which was written information about species, location, and date. The specimen was then spliced onto a tape reel containing cuts from the same species. This species reel organization simplified retrieval of specimens and until very recently was the way all major sound collections maintained their sound specimens. The three major collections, listed in alphabetical order, are (1) Borror Laboratory of Bioacoustics (BLB), The Ohio State University (blb.biosci.ohio-state.edu); (2) Macaulay Library (ML), Laboratory of Ornithology, Cornell University (birds.cornell.edu/lns); and (3) National Sound Archive (NSA), Wildlife Division, The British Library (www.bl.uk/nsa). Other important collections include (and see Kettle 1989): Bioacoustics Laboratory and Archive (BLA), Florida State Museum; Center for Sound Communication, Odense University, Denmark; Sound Library, The Australian National Wildlife Collection; and Library of Wildlife Sounds, Museum of Vertebrate Zoology, University of California.

Analog magnetic tape, depending on the formulation, has a life expectancy of 10–40 years and degrades with each use through magnetic particle loss. Thus, analog tape collections started in the late 1940s were recently faced with loss if not duplicated. Duplication to new analog tape stock has the same limitations, is labor-intensive, and is becoming costly as digital media erodes the market for analog media. Digital duplication to files on a computer hard drive or transfer to other digital storage media such as optical disk is also labor-intensive. However, digital storage possesses many advantages—including lack of degradation, rapid streaming to new media, and random access—that make it a superior archival solution.

Digital technology has initiated a new era in animal sound recording, rivaling in importance the introduction of magnetic tape recording and affecting everything from how sound is obtained to how it is stored, documented, and examined. Though digital sound recording has been available for more than two decades, the archive community moved cautiously until standards for digitizing were established.

Critical to the accurate digitizing of animal sounds was the availability of computer hardware capable of sample rate and amplitude resolution (bits) sufficient to accommodate the full spectral and dynamic ranges of most animal sounds. Archives also require reliable, affordable media that maintain integrity over time. Optical disk media that tested to archival requirements did not become available until the mid-1990s (technical reports addressing these and other issues can be found in Grotke [2004] and on the BLB website [see Acknowledgments]). Storage on optical disk reduces housing space and storage requirements, and life expectancy is on the order of 100+ years (judging from accelerated aging tests). Redundant backups are made (a working and an archival disk, at minimum), and the original analog tapes are compactly stored under optimal conditions offsite. The current digital revolution in sound archives should bring about (1) creation of a digital archive, (2) development of internet accessibility, and (3) improvement in acoustic analysis tools for research and conservation efforts.

In creating a digital archive, we must preserve the historical analog collection, strive to streamline the addition of new specimens, and improve access to specimens. In a digital archive, specimens are digitized from the analog species reels and new material from master field recordings of various analog or digital formats on various media. The time-consuming editing process cannot be avoided, but digital data stored to computer files are easily accessed for editing; unwanted segments are deleted and specimens are copied into their own files. The digital files are then written to optical media (CD-R at the BLB and NSL, DVD-R at the ML) in the order processed rather than parsing them to species reels, thus reducing labor.

A protocol of error-testing each optical disk when it is written and sampling the collection across its life must be established to measure media integrity. Because access on optical disk is random rather than sequential, specimen retrieval, once the optical disk is located, is far more rapid than with tape media. Processing of loan requests is thus simplified, but necessitates a system to track a specimen's location. Thus, a database—to which an optical disk number and other data are automatically added to each specimen's record and from which data retrieval is simple—is critical to the functioning of a digital archive (Nelson and Gaunt 1997, Nelson et al. 2001). A byproduct of this systematic transfer of all specimens from analog to digital format has been verification that all specimens exist, that they are playable, and that the metadata are correct and complete in the database.

The ability to make recordings accessible over the internet is a major benefit to storing sound recordings digitally. The first step—giving users access to the full catalogue data via searchable databases—has been or soon will be accomplished for the major collections.

The second phase of internet accessibility is online access to the sound specimens themselves. The BLB site currently has sample sounds wherever a sound spectrogram is displayed (click on the spectrogram), and all recordings of sparrows, tanagers, and New World warblers are available for audition (the full collection will follow shortly). Streaming sound capability allows users to place orders for auditioned recordings that meet their needs. Distribution of specimens through our websites for offline use is also available.

In the past, users had to depend on our staff to make these decisions. With auditioning and downloading of files available, whole new projects and user bases can be accommodated. Users come with diverse goals, from researchers wanting sounds for descriptive, mechanistic (learning, sound production and transmission), comparative, and evolutionary approaches, to educators looking for samples for lectures, demonstrations, and student projects. Increasingly, we supply material for exhibits by museums and government agencies. We continue to service the general public, as well as commercial producers of films and documentaries, CDs of animal sounds, devices to attract or repel animals, and so on. Easy access to the sounds will facilitate research, conservation, and educational efforts.

This era of major changes to our archives, supported by funding from the National Science Foundation and the Office of Naval Research (to ML), is clearly enhancing our ability to process accessions and access existing specimens. Sounds are but one component of animal behavior. The ML has developed a sister collection to the sound collection that includes video images of animal behavior (Dantzker 2004).

Too often, animal sound recording efforts, especially those from published research, fail to be deposited in public archives. The professional researcher should know that these recordings are as important as traditional specimens and treat them accordingly (Kroodsma et al. 1996). An archive's internet site may, in the future, facilitate the transfer of specimens from recordists to archives by allowing contributors to enter data for their sounds online, to be used as a database for their collection and to be transferred to the archive database as specimens are deposited, possibly also over the internet. Other benefits to research should follow. For example, ML and Totally Hip Technologies have developed a QUICKTIME browser component that will allow any internet client to preview waveforms and spectrograms of any digital sound called up by a search. They have also developed annotation software that will allow demarcation and retrieval of specific segments within archive recordings.

Public sound archives will continue to serve the public by producing synoptic series on animal sounds, an area in which the ML has excelled, as has the BLA with its ARA record series. These are invaluable as aids in training students, ecotourists, native people, and others in identification of animals by voice, especially in areas where visual contact is limited or impossible, as in conservation and biodiversity identification efforts in the tropics (Gaunt and McCallum 2004).—Sandra L. L. Gaunt (*e-mail: gaunt.2@osu.edu*) and Douglas A. Nelson, *Borror Laboratory of Bioacoustics, 1315 Kinnear Road, The Ohio State University, Columbus, Ohio 43212, USA*; and Marc S. Dantzker, Gregory F. Budney, and Jack W. Bradbury, *Macaulay Library, Cornell Laboratory of Ornithology, 159 Sapsucker Woods Road, Ithaca, New York 14850, USA.*

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Free and Open Access to Bird Specimen Data: Why?—Ornithology is in a unique position in systematics. Birds are the only major taxon for which more than 99% of species taxa at every point on the surface of the Earth are likely to be known to science (Mayr and Vuilleumier 1983, Peterson 1998). Scientific collections of birds document the distribution and diversity of more than 10,000 species worldwide. Although even these collections are in need of augmentation and improvement (Remsen 1995, Winker 1996, Peterson et al. 1998), data associated with existing specimens constitute a rich source of information about avian distribution and diversity. This resource could serve as the basis for many exciting analyses and insights into the natural history, ecology, systematics, and conservation of birds (Remsen 1995), and as a guide and motivation for further improvement of the specimen basis and information resources.

The need for more efficient access to ornithological data, however, is great. Systematic efforts to document and study avian diversity rely on the specimen record as a critical guide. Biodiversity conservation efforts depend heavily on avian information, as bird distributions can inform conservation planning and prioritization much more completely than other, less well-known taxa. Numerous other applications in natural history, biogeography, ecology, natural resources management, and even public health also draw insights from avian data (Rappole et al. 2000). This situation thus calls for an efficient system serving accurate ornithological information broadly, both to meet such varied needs and to demonstrate the critical importance of the resource that underlies them.

Presently, such a system does not exist. For example, recent efforts to assemble a list of all specimens of Red Junglefowl (*Gallus gallus*) in natural-history museums in North America and Europe took six and a half months of letter-writing and e-mailing to result in a list of 752 specimens (Peterson and Brisbin 1998). Similarly, efforts to assemble large-scale data sets on migratory bird breeding and wintering areas, necessary for modeling the future distribution of West Nile Virus in North America, were stymied by inefficient access to information and took many months of effort and unnecessary tricks of data manipulation (Peterson et al. 2003).

The technology for such a biodiversity information system nonetheless exists; it was, in fact, developed on the basis of avian data sets, with funding from the National Science Foundation. Subsequently, several efforts have begun assembling such systems across many taxa (see Appendix). Most exciting is that developers of these systems have collaborated to develop a next-generation technology that will meld all these regional efforts into a single, global biodiversity information system—the technology, termed "DiGIR" (distributed generic information retrieval), has won broad acceptance and has been incorporated into many efforts.

Ornithology, with its large quantities of high-quality information regarding an important indicator taxon, has the opportunity to lead this new world of biodiversity informatics. Several other taxonomic communities have already advanced in integrating their data resources via the internet (for examples, see Appendix), and several institutions have already ventured their ornithological data resources in a prototype internet-based distributed system (The Species Analyst, now superseded by ORNIS). Nevertheless, many computerized ornithological data sets remain either unavailable over the internet or available, but not integrated with data sets from other institutions.

Free and open access and data value.—Biodiversity information has traditionally been concentrated in Europe and North America, even though biodiversity is focused in tropical and subtropical regions. This contrast results from the complexities of the history of scientific exploration, economics, and educational and scientific opportunities. Like biodiversity itself, access to information about biodiversity is unbalanced.

Modern internet technologies make feasible a system in which information resources can be accessed by anyone, anywhere on Earth. The internet provides a medium of information flow that is limited only by internet access, a barrier that is rapidly disappearing over much of the planet. Hence, the regional imbalances that characterize the current situation can be largely alleviated.

The key point of most debates on the subject of free and open access has been the value of specimen data (Graves 2000). Museum curators know that the information associated with the specimens they curate is valuable, and for that reason they have often guarded such information carefully—the limited budgets at most collections, many of which are in serious financial situations (e.g. recent problems at the Academy of Natural Sciences, Philadelphia), demand that any resource be used wisely. Moreover, resources dedicated to computerization and broad data provision may occur at the expense of specimen care and building the collection itself. However, "valuable" data that are not used yield nothing to the owners or curators of those data.

By contrast, data that are used increase markedly in value. Biodiversity information is too often derived from secondary sources (range maps, field guides, etc.), which both reduces data quality and denies credit to those institutions that house the primary data (often natural-history museums). A system with free and open access to data, however, permits users to access the primary, vouchered information as close to its source as possible. Similar to the marketing strategies of Netscape and Adobe Acrobat, in which providing free and open access is instrumental in building a market share and making a product, such access is key to establishing natural-history museum collections as the premier source of information about biodiversity.

In this sense, the value of data does not decline, but rather increases, as a result of free and open access. That is, as primary ornithological data from specimens become the primary source of information on the distribution of birds, those data gain value. Furthermore, open access to specimen data results in feedback that leads to higher quality, again increasing the value. By contrast, data for which access is restricted do not benefit to the same extent from analysis, scrutiny, feedback, and interest.

Distributed, not centralized.—A key feature of the information systems under discussion is their distributed nature. Distributed databases may be scattered across regions and countries, but are integrated via the internet. This structure offers distinct advantages: (1) data remain at the owner institution and are usually not centralized; (2) data served can be updated as often as desired, keeping information up-to-the-minute; (3) data ownership is never in question; (4) owner institutions can restrict or limit access as desired (e.g. to limit precision of data regarding distributions of endangered species, to protect rights of investigators regarding publication of works in progress, etc.); and (5) the collaborative nature of the effort is emphasized. Hence, although it required several years of dedicated activity to develop and distribute, this "architecture"makes the idea of providing free and open access to information much more palatable in a number of ways.

Value added.—Serving ornithological information is not a one-way interaction, not just a service to the broader community. Rather, uniting data resources into a single pool allows for several ways of adding value to the primary data. First and foremost, georeferencing locality information becomes much more feasible—because of the redundant nature of localities (specimens from single localities scattered across multiple collections, efficiency of georeferencing work on more densely collected landscapes), such an effort on a collection-by-collection basis is very inefficient. The success of efforts for georeferencing mammal specimen data (Stein and Wieczorek 2004, Wieczorek et al. 2004) is an excellent example. Several additional possibilities—use of ecological niche modeling to detect identification errors, standardization of taxonomic information, and use of collector itineraries to detect date–locality errors—are being developed. All these improvements to data can be repatriated to the owner institutions to improve the base quality of their data sets and information content of the specimens.

Funding potential of community efforts.—A particular advantage of community collaborations is their excellent potential to leverage funding. The appeal of funding an effort in which all institutions in a community participate is much greater than that of funding an initiative that is based at a single institution. Clear evidence of this potential is the success that several taxonomic groups have had in getting funding for community efforts to integrate data: ichthyology, funded by the National Science Foundation and the Office of Naval Research; mammalogy, funded by the National Science Foundation; and herpetology, funded by the National Science Foundation—summing to more than $4.5 million in new funding for informatics efforts in scientific collections. These resources would likely not exist without their community basis.

ORNIS and the future.—A fully integrated ornithological information infrastructure has enormous potential, and has now been funded by the National Science Foundation. Approximately 4–5 × 10^6 bird specimens are held in North American museums, and ~80% of those specimens have been committed to participation in ORNIS. Perhaps yet another 4 × 10^6 bird specimens are held in European museums, and an unknown quantity are held in museums elsewhere in the world (2–3 × 10^6 more?). Hence, a rough estimate is that on the order of 10–12 × 10^6 bird specimens exist worldwide. If this resource were fully computerized and integrated into a distributed "world museum" of ornithology, the resource would be enormously useful in a broad diversity of applications. Integrating specimen-based data with observational data is enriching the specimen-based information still more: a recent addition to the ORNIS network included 15 × 10^6 observational records from several projects based at the Cornell Laboratory of Ornithology.

At present, much information about birds is drawn from secondary sources. Conservation organizations prepare secondary information resources (lists of endangered species, distributional summaries, etc.). Field guides synthesize information into range summaries and distribution maps. Other resources are assembled solely on the basis of observational information, which lacks vouchering and can be unreliable in some circumstances (Phillips 1986). These secondary resources are too often used as the basis for answering important questions about birds.

Why are specimen data—the ultimate "library of life" information resource for biodiversity—not already the primary information resource for birds? The answer lies in the difficult and inefficient access that has characterized this resource. Simply, the data are not used because they are hard to access. As ornithology provides better and more efficient access to specimen data resources—via ORNIS and related solutions, and their descendents—the user base will grow. Only in this way can avian collections get the key recognition and support they deserve and need.—A. Townsend Peterson, *Natural History Museum and Biodiversity Research Center, University of Kansas, Lawrence, Kansas 66045, USA* (*e-mail: town@ku.edu*) and Carla Cicero and John Wieczorek, *Museum of Vertebrate Zoology, University of California, Berkeley, California 94720, USA.*

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Appendix

The following are websites for efforts to assemble biodiversity information systems: MaNIS (elib.cs.berkeley.edu/manis); HerpNet (www.herpnet.org); Global Biodiversity Information Facility (www.gbif.net); Red Mundial para la Información de la Biodiversidad (www.conabio.gob.mx/remib/doctos/remib_esp.htm); Virtual Australian Herbarium (www.rbgsyd.gov.au/HISCOM/Virtualherb/virtualherbarium.html); SpeciesLink (www.cria.org.br/projetos); European Natural History Specimen Information Network (www.nhm.ac.uk/science/rco/enhsin/). For information on distributed generic information retrieval (DiGIR), go to digir.sourceforge.net/.

For examples of taxonomic data resources on the internet, see www.speciesanalyst.net/fishnet/ (ichthyology); elib.cs.berkeley.edu/manis/ (mammalogy); www.herpnet.org (herpetology). On efforts for georeferencing mammal specimen data, see elib.cs.berkeley.edu/manis/. The ORNIS website is at ornisnet.org.

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Use of Bird Collections in Contaminant and Stable-isotope Studies.—Preserved biological specimens are increasingly providing source material for research that is moving beyond traditional questions in collections-based studies. Technological advances are facilitating both traditional and nontraditional uses of these shared research resources. For example, advances in analytical chemistry have enabled researchers to obtain data on heavy-metal contaminants and diets from a single feather. Future technological advances will increase nontraditional use of specimens, and two areas of rapid growth at present are in contaminant and stable-isotope studies. We address these developments and their implications for bird collections.

Contaminants.—Retrospective contaminant studies of the 1960s and 1970s premiered a new and important use of specimens. One of the first studies to use bird specimens in contaminant research documented a 10- to 20-fold increase in feather mercury among seed-eaters and raptors after the introduction of alkyl-mercury seed dressings (fungicides) in Europe in the 1940s (Berg et al. 1966). That research led to the banning of those seed treatments, and subsequent retrospective analyses using specimens confirmed the effect of alkyl-mercury fungicides by documenting the decline of mercury concentrations in feathers after the ban (Westermark et al. 1975). Probably the best-known use of museum specimens in retrospective research documented eggshell thinning in raptors following the introduction of DDT in 1947 (Ratcliffe 1967, Hickey and Anderson 1968). These studies and others (see Kiff 2005) contributed to the eventual ban of DDT in many countries.

Researchers have documented high levels of contaminants in the biota of undeveloped regions, citing the global distribution of pollutants as the cause (Arctic Monitoring and Assessment Programme 1998). As global contaminant burdens increase, spatially and temporally distributed biological samples are needed to document changing contaminant levels. Archived avian specimens can document levels of heavy metals, because heavy metals bind to feather keratin at the time of growth (Crewther et al. 1965). Archived specimens were used to document increases in mercury pollution in several avian food webs (Appelquist et al. 1985; Thompson et al. 1992, 1993). Time series of archived seabirds were also used to document increases in feather mercury concentrations in two avian food webs over the past 100 years, which were correlated with anthropogenic inputs (Monteiro and Furness 1997, Thompson et al. 1998).

Although most specimen-based retrospective contaminant analyses have dealt with mercury, all heavy metals can be measured in feathers. Feathers are useful indicators of elemental body burdens at the time of growth, because feathers provide a route for elimination of contaminants (Goede and de Bruin 1984). Contour feathers seem to have the least variation among feather types, allowing comparison among studies (Furness et al. 1986). Despite a general lack of information on toxicity thresholds in feathers (e.g. what concentrations in feathers indicate negative organismal effects), feathers from museum specimens represent a powerful tool for comparing temporal and spatial distributions of heavy metals in the environment.

Birds are useful biomonitors of their environments, and they offer an opportunity to sample at different trophic levels. Contaminant studies generally use tissues and organs not normally preserved by museums. But, with planning, use of birds as biomonitors can be coupled with standard museum processing and preservation to simultaneously achieve very different scientific gains. Enhancing working relationships between museums and contaminants biologists benefits both groups, and this is an important direction of future growth for collections. Increasingly refined analytical abilities will continue to enhance the usefulness of museum specimens for contaminant studies as new techniques reduce the amount of sample required for analyses. Small amounts of muscle tissue now preserved for genetics, for example, may also prove valuable in future contaminants research.

Stable isotopes.—Stable isotopes are increasingly being used in ecology, population biology, and ecosystem monitoring. Isotopic ratios among many naturally occurring elements vary geographically and are incorporated into local food chains. Different tissues (e.g. feather, bone, liver, kidney, and muscle) have different isotopic turnover rates, and the tissues of archived specimens can be used to provide clues regarding seasonal ecological processes in, for example, migratory birds. Isotope ratios of carbon are often distinct among terrestrial, freshwater, and inshore and pelagic marine food webs, and nitrogen shows predictable trophic enrichment (e.g. Hobson 1999, Kelly 2000). Analyzed in concert, these widely studied isotopes have been used to delineate food webs, infer foraging locations, and document diet shifts. Stable-isotope ratios, like heavy metals, are incorporated into feathers at the time of growth and remain inert, providing a record fixed in time (Mizutani et al. 1990) that enables researchers to monitor long- and short-term changes in ecosystems using avian specimens.

Feather stable isotopes from archived Atlantic Northern Fulmars (*Fulmarus glacialis*) documented broad-scale diet shifts during the 20th century, probably attributable to the whaling industry (Thompson et al. 1995). The ability to detect ecosystem-scale shifts in food webs with stable isotopes is also proving useful in ecosystem monitoring. Studies using archived whale baleen suggested long-term changes in oceanic primary productivity in the Bering Sea, one of the world's most important fishing grounds (Schell 2000). This hypothesis is being tested using archived specimens of Bering Sea birds (G. J. Divoky pers. comm.). Similarly, specimen-based isotopic analyses suggest historical dietary changes in federally listed populations of the Marbled Murrelet (*Brachyramphus marmoratus*), providing insight into possible reasons for their decline (S. Beissinger pers. comm.). This type of research is increasing and highlights the value of historical specimens in documenting change.

Stable isotopes such as deuterium, oxygen, strontium, and sulfur also show regional variation. This variation can be enlisted to address classic questions of population biology (i.e. spatial and temporal distributions) in highly mobile organisms, such as migratory birds. In individuals and populations that move among isotopically distinct regions, multiple stable-isotope analyses have the potential to track organisms throughout their annual cycle, and this is another growing research area (Hobson 1999). Presently, these markers do not provide sufficient resolution to monitor regional movements among habitats or to assess population mixing, and more work is needed to understand links between abiotic and biotic isotopic signatures within the systems (geographic and taxonomic) being studied. However, research on the physiological processes governing stable-isotope ratios in consumer tissues (e.g. Gannes et al. 1997, Pearson et al. 2003), coupled with local environmental studies, will likely enhance our understanding of the relationship between biotic isotopic ratios and the environment and improve the ability to track organism movements.

The proliferation of stable-isotope research has significant implications for specimen use and is an important direction of growth for collections. These studies have shown that specimens are a valuable resource for understanding populations, diets, and changes over time in populations and their environments. This research requires destructive sampling of small pieces of specimens, and such use is certain to increase. This increase should be coupled with expanded participation in building the resource. As Winker (2005) noted, the multidimensional benefits gained through whole-organism sampling suggest that this is the most effective common ground on which to focus such expansion. With planning, this approach would also provide the widest possible array of tissue types for contaminant and stable-isotope studies.

Value of archived specimens.—Archived specimens provide important baselines for comparison with modern counterparts. This is especially true when attempting to document environmental contamination. Previous retrospective studies in birds highlight the need for, and general lack of, good temporal series. At present, museums generally do not have adequate time series to answer temporal questions with rigor. Unlike genetic samples, some isotopic ratios and contaminant concentrations from the same location can change rapidly and exhibit large variation within and among years. Documenting trends and historical changes at useful geographic scales with statistical power requires continued sampling and proper archiving.

Birds are often sacrificed in food habit, energetic, physiological, population, and pollution studies. Although these studies provide valuable information on avian biology, archiving the specimens can provide important long-term data. We strongly encourage researchers to deposit sacrificed birds into collections and to offset costs to repositories by providing funds for preservation of this resource (see Winker 2005). Archived bioindicators become biomonitors that can be used to establish baselines for future retrospective research.

As museums and new partners continue to build specimen series, it should be recognized that time- and space-saving techniques, such as preparing flat skins, can often be used without compromising the value of the preserved material. Nondestructive sampling (e.g. feather or blood collection) is sometimes used by researchers because it is seen as saving space, time, and money. However, it does not yield the long-term scientific strengths of preserved whole animals and therefore is not supported by most museums. Broad issues of quality control exist in samples that are small in quantity, destined largely for destruction, and unvouchered (Winker et al. 1996, Payne and Sorenson 2003, Smith et al. 2003). For example, using feathers plucked during banding for stable-isotope, contaminant, and genetic research (e.g. Smith et al. 2003) may increase sample sizes for some studies, but sample destruction makes replication problematic. Stable isotopes and contaminants can vary within a single feather and among feather types (Furness et al. 1986, Bearhop et al. 2002, Dauwe et al. 2003); without vouchers, analyses may not be verifiable or repeatable. In short, unvouchered subsamples of birds do not have the high scientific value of the modern museum specimen.

Preserving specimens for retrospective research is clearly important and requires a dynamic vision of how collections will be used in the future. Continued technological advances ensure that specimens will continue to produce answers to unanticipated questions (Suarez and Tsutsui 2004). Birds are important monitors of ecosystem health. New uses for specimens demonstrate an important and growing role for collections in population and ecosystem management. It is important that these "new uses" be documented and publicized to make the scientific community and public aware of the increasing user base and the dynamic role that museums play in conservation and environmental sciences. Public, political, and financial support is necessary if museums are to meet their obligation to anticipate "new uses" and ensure that collections archive material that will meet the needs of future research.—DEBORAH A. ROCQUE, *University of Alaska Museum and the Department of Biology and Wildlife, 907 Yukon Drive, Fairbanks, Alaska 99775, USA* (*Present address: U.S. Fish and Wildlife Service, 1011 East Tudor Road, Anchorage, Alaska 99503, USA; e-mail: Deborah_Rocque@fws.gov*) and KEVIN WINKER, *University of Alaska Museum and the Department of Biology and Wildlife, 907 Yukon Drive, Fairbanks, Alaska 99775, USA.*

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History, Present Status, and Future Prospects of Avian Eggshell Collections in North America.—Bird egg collecting was formerly a popular pastime in North America, having originated as a cultural import from England during the great Victorian era of natural history. Although Audubon took a few eggs in the 1830s and 1840s, widespread hobbyist egg collecting did not really take hold in North America until the 1860s, following the issuance by Stephen Fullerton Baird, Secretary of the Smithsonian Institution, of a "call to arms" (Baird 1861). His circular listed numerous as-yet-undescribed eggs needed by the Smithsonian and detailed instructions on how to preserve them. The study of eggs, or "oology," as its adherents termed it, was at its zenith on this continent from about 1885 through the 1920s. Owing to changes in social attitudes and regulation, hobbyist egg collecting had declined markedly by the start of World War II and had completely faded from the American scene by 1970. Thus, the "oological chapter" of North American natural history lasted about a century (Kiff 1989a).

The vast majority of collectors were adolescents who took only eggs of the common species in their neighborhoods, but I have compiled biographical data for 1,200 adult collectors (1,195 males; 5 females) active at some point during the period from 1850 to 1970. Egg collecting was justified on both scientific and recreational grounds (Grinnell 1906), and many of the great lights of American ornithology, including Elliott Coues, Robert Ridgway, and Grinnell himself, collected bird eggs in their early years. T. Gilbert Pearson, a co-founder of the National Audubon Society, Audubon biologist Alexander Sprunt, Jr., and even Guy Bradley, the Florida Audubon warden whose shooting death by an egret plumer in 1905 sparked the modern Audubon movement, were all egg collectors.

Serious oologists collected and stored eggs as entire clutches, or "sets," beginning in about the 1870s. The contents were removed through a single blowhole in the middle latitudes of the eggs. Thus, a museum "egg specimen" consists only of an empty eggshell with its associated eggshell membranes. Each specimen was inscribed in permanent black ink with a collector-specific "set mark," typically consisting of such essential information as species identity (indicated by AOU number), collecting year, and number of eggs in the set. Details on collecting locality, collecting date, location of the nest, and collector name were recorded on a "data slip," a card that often contained the printed name and address of the collector. Oological preparation and curatorial techniques are discussed more fully in Kiff (1989b) and Limbert (2003).

The findings, mostly anecdotal and descriptive, of oological studies were published in an astonishing array of small journals, many short-lived (Underwood 1954). The best of this lot in the late 19th century was the *Ornithologist and Oologist*, and later important oological journals included *The Warbler, The Nidiologist, The Osprey,* and *The Journal of the Museum of Comparative Oology*, all of which contain solid descriptive information still useful to contemporary ornithologists. *The Oologist* was the longest-lived journal of the genre, though it was not the best. It was published monthly from 1884 to 1941 and was discontinued only when the hobby ran out of enough practitioners to keep it going. Other than amassing their collections, the most lasting contribution of the oologists was the A.C. Bent life histories series, which relied heavily on their field observations. Indeed, the egg measurements from the Bent volumes still survive largely intact (albeit rounded off to whole millimeters) in the modern egg field guides by Harrison (1978) and Baicich and Harrison (1997).

Present extent of North American egg collections.—Unlike avian study skins, skeletons, and spirit specimens, egg collecting was always primarily an endeavor of amateurs, and even the largest institutional collections are amalgamations of multiple private collections. A process of consolidation of collections was begun in the late 19th century by several wealthy collectors, including John Lewis Childs (Floral Park, New York), J. Parker Norris, Sr. and Jr. (Philadelphia), and Edward Arnold (Battle Creek, Michigan), and was continued in the mid-20th century by Wilson Hanna (San Bernardino County Museum, California), Ed Harrison (founder of the Western Foundation of Vertebrate Zoology [WFVZ] in Los Angeles), and Nelson Hoy (Media, Pennsylvania). The WFVZ continued to focus on collections acquisition later than all other institutions; by 1994, its holdings included ~180,000 egg sets, representing the combined assets of more than 300 separate collections (Kiff 2000).

Surveys of North American institutions and the few living oologists confirmed the existence of ~463,000 specimens in 72 collections (Kiff 1979, Kiff and Hough 1985) by the early 1980s. In the intervening two decades, I have become aware of only a handful of additional collections, mostly of modest size. I estimate that there are presently around 80 egg collections of research importance in North America and that, in aggregate, they contain <500,000 egg sets. Judging from comparisons of collector field catalogues with existing collections, I have the impression that the majority of the scientifically useful egg specimens collected in North America survived the move from private closets to institutions.

Nearly all the largest egg collections in North America are located in the largest natural-history museums, as might be expected. By now, the trend toward consolidation of collections has slowed. The WFVZ has acquired a few minor collections in the past decade, as has the University of Kansas Museum of Natural History, but orphaned egg collections may now go unclaimed. A large, previously unreported collection was purportedly sold to a European collector by a private high school, to which it had been inappropriately donated, and it is probably now lost to the research community. Globally, there are probably no more than 300 major bird egg collections, including some in private obscurity, and they contain a disproportionate representation of taxa from western Europe, North America, southern Africa, and Australia.

Uses of collections.—Although most "oologists" were amateurs, they generally recorded useful and reliable data with their sets. Egg specimens and their associated data have probably been used in a greater variety of biological studies than any other type of avian specimens. At the WFVZ alone, the egg collection was used in more than 4,000 research projects from 1956 to 1994 (Kiff 2000), and many egg specimen uses were discussed by Green and Scharlemann (2003) and Limbert (2003). Thus, it is all the more curious that there never seems to have been a time when egg collecting was primarily a scientifically oriented activity, despite the pretenses of its main practitioners.

The most traditional lines of specimen-based egg studies involve their external morphology, including mass, length and breadth, shell thickness and texture, color, and shape. These characters have significance in studies of taxonomy (Zelenitsky and Modesto 2003), ecology (Svensson 1978), evolution (Moksnes and Røskaft 1995), physiology (Rahn et al. 1985), and genetics (Tryjanowski et al. 2001). Almost every issue of the major ornithological journals now contains at least one paper on one of these egg collection-related topics.

Many contemporary lines of research involve the use of eggshell fragments, often in connection with conventional whole eggshell collections. The study of eggshell ultrastructure by scanning electron microscopic techniques is a field of interest not only to poultry scientists, but also to taxonomists (e.g. Mikhailov 1997). Bird egg collections are valuable reference tools for archaeologists (Sidell 1993) who search through Indian middens and Grand Canyon caves. Additional uses of eggshell fragments include studies of x-ray diffraction (Gould 1972), pigmentation studies (Kennedy and Vevers 1976), and isotopic analyses (Hobson 1995). Studies of the effects of environmental acidification on passerines, especially in Europe (e.g. Graveland 1998), rely heavily on baseline information provided by egg collections. Using museum collections, Green (1998) and Scharlemann (2003) documented declines in eggshell thickness among

Turdus species that probably resulted from reduced calcium availability caused by environmental acidification.

Egg collections were critically valuable in documenting widespread eggshell thinning (Ratcliffe 1967, Hickey and Anderson 1968) caused by DDE, a breakdown metabolite of the pesticide DDT. By now, hundreds of eggshell-based studies of this contaminant have appeared in all major regions of the world, and the present ban on DDT use in all but a handful of countries is a direct result of this research. Specimen-based data documenting severe eggshell thinning among Brown Pelicans (*Pelecanus occidentalis*) and other seabird species and DDE-caused extirpations of Bald Eagles (*Haliaeetus leucocephalus*) and Peregrine Falcons (*Falco peregrinus*) on the California Channel Islands (Kiff 1980) provided critical evidence in the "Montrose Case," a U.S. Department of Justice suit against the last U.S. manufacturer of DDT. The case lasted for a decade and culminated in a natural-resource damages award of $140.2 million in 2001. Historically, that episode probably represents the most important use, from an economic standpoint, of any avian specimen type. Studies of the effects and extent of other contaminants, particularly heavy metals (Grandjean 1976), have also involved the use of eggshells and museum egg specimens. Becker (2003) recently summarized the many advantages of bird eggs and other avian specimens as biomonitoring tools.

The data associated with eggshell collections are almost as valuable as the specimens themselves, and they may prove to be particularly valuable in climate change studies. For example, Crick and Sparks (1999) recently showed that passerines in the United Kingdom are initiating egg-laying earlier in the year, probably in response to global-warming trends, and egg collection data could be used to detect such a trend in North America. The classic study by Väisänen (1969) showed how egg collections can be used to document changes in the historical distribution of a species paralleling changes in climatic conditions. Studies of this type are hampered by myopic regulatory attitudes, particularly in the United Kingdom, that have led to the virtual cessation of scientifically based egg collecting in recent decades, so only a partial record of broad environmental changes can now be reconstructed from egg collections.

Egg collection data have often been used to document the historical distribution of bird species for conservation management and other purposes (Kiff 1989c, Houston 2002). However, reconstructing entire historical ranges of bird species from egg specimen data (or any kind of specimen data) often requires the same sorts of extrapolations that plague paleontologists, owing to the patchy distribution of collectors. In North America, egg collectors tended to be concentrated in the most populous states and provinces, and large portions of the continent are unrepresented in existing collections. Of the 1,200 egg collectors for whom I have at least some data, 146 lived in California, almost all of them south of the San Francisco Bay area, and only 3 lived in neighboring Nevada.

Indeed, egg collections rarely, if ever, provide random samples at any level, and certain information from them should be used with caution. From my personal acquaintance with about 30 now-deceased egg collectors, I have concluded that the most obvious collector biases involved egg size and color selection (the odd ones were more desirable and are thus overrepresented in collections), collecting date (the start of the breeding season is better represented than the end for common species), clutch size (larger clutches were considered more desirable), and parasitized clutches (some collectors thought that sets with cowbird eggs were "ruined" and did not collect them or simply threw out parasite eggs). In addition, many (perhaps 5%) of the specimens in North American collections are misidentified or represent deliberate frauds. Perhaps techniques will be devised in the future that will allow us to confirm the identity of questionable specimens, but it is unlikely that they will involve DNA, a substance that only poorly prepared eggs contain.

Future prospects and recommendations.—Most of the following suggestions were discussed more fully in Kiff (1978) and are as relevant now as then:

(1) Preserve traditional oological knowledge. There has been almost a complete loss of oological expertise within the museum community, not only firsthand familiarity with proper preparation and curatorial techniques, but also a loss of knowledge about such factors as the reliability of individual collectors, collector biases, interpretation of set marks, and species whose eggs were often misidentified.

Few contemporary collection managers know how to blow an egg properly, or even have the tools to do so. As a consequence, almost no egg specimens are being preserved, owing to the loss of knowledge of proper preparation techniques, lack of institutional support, regulatory restrictions, and unfavorable funding trends. To my knowledge, there are no "working oologists," though the studies of many researchers involve egg- or nest-related questions. No North American egg collection is staffed by an individual with traditional oological interests or knowledge, and even the WFVZ collection, which contains nearly 40% of all egg specimens in North American institutions (Kiff and Hough 1985), has not had a trained biologist directly supervising it for the past decade. Thus, the body of traditional oological knowledge may vanish, except on the browned pages of extinct journals, and existing egg collections may gradually become objects of greater interest to historians than to biologists.

(2) Provide funding for egg collection conservation and growth. Funding prospects for the support of egg collections remain bleak. There are no longer "angels" from the private sector who will invest in egg collections, primarily because there are no longer any self-serving motives for doing so. Government agencies, particularly those at local and state levels, are financially stressed, and museums of all types have suffered as a consequence. Federal funding can be found for the computerization of egg specimen data, but not for their interpretation. With a few commendable exceptions, traditional university natural-history museums are also fading from the scene, and many of the collections now housed at the WFVZ were relinquished by institutions with an ever-waning interest in organismic biology.

(3) Consolidate egg collections. Fred Lohrer suggested to me that a Nature Conservancy-type organization devoted specifically to saving and housing natural-history collections might be formed. This could promote the consolidation of collections, perhaps in regional centers, and leverage funding opportunities. I think it is a good idea in theory, especially in regard to consolidation of collections. Most substantive research on eggs and other avian specimen preparations relies heavily on large sample sizes. Therefore, the smaller the collection, the more limited the possibilities for research use. The two main challenges to such a concept are finding the requisite funds and persuading institutions to contribute their collections to the cause. Perhaps the most effective funding strategies will emphasize the many applications of egg collections for conservation and biomonitoring purposes.

(4) Collect eggs and eggshell fragments for environmental monitoring purposes. Without continued, well-planned preservation of egg specimens, many useful opportunities for documenting environmental changes will be squandered. As discussed above, several exciting lines of research rely on eggshell fragments, and they do not necessarily involve the use of conventional museum specimens. In the future, egg collecting and egg collections will likely take a different form, and the exquisite preparation techniques of the Victorian era may give way increasingly to eggshell fragments stored in vials.

(5) Compile a global database of basic data on egg size, color, shape, eggshell thickness, and similar parameters. The most important major reference source for egg measurement and color data for birds of the world remains the monumental "Handbuch der Oologie," begun by Max Schönwetter and brought to fruition by Wilhelm Meise (Schönwetter 1960–1992). There is no equivalent work in the English language, and these types of data are widely dispersed in the literature and field notebooks. The creation of a comprehensive database of basic egg data would be a tremendous time-saver for researchers and, like all such compilations, be helpful in revealing the many gaps in our knowledge and in existing egg collections.—Lloyd F. Kiff, *9999 West Star Acres Drive, Star, Idaho 83669, USA. E-mail: lkiff@aol.com*

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