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CourseSource

Lesson

Teaching Biodiversity with Museum Specimens in an Inquiry-Based Lab

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Abstract

In response to the growth of biology datasets and broad efforts to digitize data, an increasingly important skill for science students is the management and analysis of large datasets. We designed an inquiry-based lab module to introduce students to museum research by quantitatively evaluating ecogeographical patterns using a VertNet dataset. VertNet is a free, NSF-funded database of museum specimens from over 100 research museums with spatial, temporal, and morphological data for thousands of individual specimens. Patterns observed by natural historians provide a context for students to enter the world of museum research. These patterns, especially in mammals, are largely associated with latitudinal gradients. For example, Bergmann's Rule states that animals are larger in colder environments, an adaptation to conserve energy in harsh climates. Allen's Rule states that endotherms in colder environments will have shorter extremities. After learning these general patterns, students develop questions to pursue for a particular group of mammals. Students measure available museum specimens and supplement their data with a downloadable VertNet dataset. Datasets include over 150 columns, requiring students to choose appropriate variables while accounting for errors that might occur in large datasets collected across many institutions. Students flex their statistical skills to examine their research question and present their results to the class, perhaps discovering that "Rules" were meant to be broken. By completing this module, students become familiar with how museums aid in research, gain confidence in asking and pursuing their own scientific questions, and practice managing and analyzing large datasets.

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Supporting Materials: S1. Teaching biodiversity-VertNet Instructions; S2. Teaching biodiversity-Presentation rubric; S3. Teaching biodiversity-Exam Assessment; S4. Teaching biodiversity-Survey and results; S5. Teaching biodiversity-Lecture 1; S6. Teaching biodiversity-Lecture 1 Script; S7. Teaching biodiversity-Student Module; S8. Teaching biodiversity-Instructional Team Presentation; S9. Teaching biodiversity-Activity 1 Lecture; S10. Teaching biodiversity-Hypothesis Handout; S11. Teaching biodiversity-Lecture 2; S12. Teaching biodiversity-Lecture 2 Script; S13. Teaching biodiversity-Lab Activity 2 Introduction; S14. Teaching biodiversity-Excel Variation Instructions; S15. Teaching biodiversity-Statistics Instructions; and S16. Teaching biodiversity-Excel ANOVA Instructions.

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Learning Goal(s)

Students completing this lab module will:

- Become familiar with biodiversity at the species level and see the diversity of specimens housed in research museums (including both taxa and preparation types).
- Discover the scientific resources that museum collections provide.
- View zoology museums as active research facilities rather than warehouses or exhibit spaces.
- Gain an appreciation for the biodiversity of animals, including those in their local geographic area.
- Understand that there are many exceptions to biological "Rules."
- Actively engage in the scientific process through inquiry, including hypothesis development, data collection, statistical analysis, data presentation, and science communication.

Learning Objective(s)

Students completing this lab module will:

- Learn how to appropriately handle and measure museum specimens.
- Develop the necessary statistical skills to analyze museum specimen data.
- Become familiar with how to search an online museum database and integrate supplemental data with their own dataset.
- Strengthen scientific communication skills by presenting research to their peers.
- Demonstrate ability to investigate scientific questions and address obstacles that occur during data collection and integration.
- Increase proficiency in managing and using large datasets for scientific research.
- Make connections between natural history knowledge and morphology of organisms in developing and testing hypotheses.

INTRODUCTION

Natural history museums provide a window into the past and a picture of biodiversity that is at a tipping point as we approach a sixth mass extinction (1). Most specimens in herbaria and zoology museums are vouchered research specimens. These are permanently archived specimens that allow curators to verify the identity of the species from a particular geographic location at a particular time (2). For example, especially in areas with high levels of biodiversity, there can be numerous beetle species at a single field site that resemble each other and are impossible to differentiate with the naked eye. Individuals collected in the field can be examined under the microscope to determine species and population-level differences that are not matched by photography of individuals. In the case of mammals, some species can only be differentiated by examining attributes of the skull, such as number and shape of teeth, position and size of holes for blood vessels, and the extent to which bones of the skull touch. Voucher specimens can be preserved with formalin and stored in ethanol, or may be prepared in a “dry” form: mammal and bird carcasses are often skinned and stuffed with cotton and their skeletons are cleaned, while insects are pinned. In addition to serving as a warehouse of diversity that allows for the discovery of new species [e.g., Olinguito (*Bassaricyon neblina*), a recently discovered carnivore species, 3], zoological museums serve a vital role in ongoing research for a variety of fields (4,5).

Most natural history museums were founded in response to early biological surveys. Many specimens were collected in the late 1800s and early 1900s, when field excursions were common and the preservation of populations of little concern. More recent field work often involves trapping a large number of specimens, measuring all individuals and taking subsamples for genetic work (e.g., buccal swab or ear punch), and releasing most back into the wild (6). A small number of specimens are euthanized according to ethical committee standards in order to verify the species trapped at a site and maintain additional records via museum specimen vouchering and cataloguing (7). Vouchering is the act of taking or preparing a physical specimen. Vouchers are the gold standard in systematics and taxonomy and the basis for describing all biodiversity. Cataloguing is the act of formally accessioning those specimens into a museum, adding the voucher as a permanent record in a curated collection. Because of the long history of sample collection, museums provide us with snapshots of biodiversity and organisms’ traits through time.

Museum collections serve as both focal points and supplementary data for research in ecology, evolution, and conservation (8,9). Because of historical sampling efforts, species that have become extinct can still be studied via museum specimen collections. For example, US research collections house over 600 Carolina parakeet (*Conuropsis carolinensis*) specimens (http://portal.vertnet.org/search?q=Conuropsis+carolinensis). Recently, an ecologist combined anecdotal records and museum collection data to draw a hypothesized historical distribution map of the species (10). Another research team sequenced the genome of the extinct passenger pigeon (*Ectopistes migratorius*), subsequently evaluating the genetic diversity and variation thanks to collection efforts while the species was extant (11).

As a result of decades of biological survey work by museum curators, today’s researchers can evaluate changes in a variety of traits across a broad geographic range and more than 100 years. Museum specimens play a vital role in evaluating how climate change and industrialization impact animal populations. For example, researchers measured the change in feather color in five bird species to track the change in atmospheric black carbon from 1880 to 2015 in response to industrialization and clean air policies (12). In a separate study, mercury concentration in ivory gull feathers from 14 different museum collections showed a 45-fold increase from 1877 to 2007 (13). Museum collections also allow for analysis of geographic variation - chipmunks housed in three museums were found to vary in cranial morphology and coat color across their range due to gradients in habitat (14). The number and variety of research questions that can be explored using museum specimens continues to grow, even as support for such institutions has decreased (5).

Since the 1950s, access to natural history courses in universities has declined, representing a larger shift in the scientific community away from specimen collection and research (15). In early 2017, the University of Louisiana at Monroe chose to divest their natural history collections (16). The administration found no value in the collection, which included over 6 million fish specimens (Doug Yanega, 28 March 2017, personal communication). However, scientists in multiple fields recognize the value of museum collections, as recently evidenced by the large federal grant awarded across a network of museums to scan and digitize specimens (17). With new technological advances sparking a renewed interest in museum collections, and decline in worldwide biodiversity becoming an increasing concern (e.g., 18), natural history may soon be a re-burgeoning field that scientists can leverage to improve general awareness of biodiversity (19-20). With this in mind, we believe it is important to begin developing course materials to introduce a new generation of undergraduate students to the field of biodiversity museum research. Advancing Integration of Museums into Undergraduate Programs (AIM-UP!) provides online educational resources with this goal in mind. One such module introduces students to an array of research areas that can take place thanks to ornithology collections (https://issuu.com/coevolution/docs/ornithological). Linton et al. (2019) designed a module for undergraduate students to compare mammal body masses on an Alaskan island and Canadian mainland to explore Island Biogeography through museum specimens (21). In this activity, students explore similar questions to one another, but with different mammal species.

The Ecology and Evolutionary Biology major at University of Michigan was recently renamed to Ecology, Evolution, and Biodiversity, indicating that the institution recognizes the importance of biodiversity. In addition, four museums including the University of Michigan Museum of Zoology (UMMZ), which houses approximately 13 million animal specimens, received over 40 million dollars from the University of Michigan to relocate to a state-of-the art collections research facility (22). With institutional attention turned toward raising awareness of biodiversity, we designed this laboratory module to allow undergraduate students in an introductory biology course to conduct inquiry-based biodiversity research while improving their understanding of the scientific process and strengthening their quantitative reasoning skills (23).

Within the broader context of introductory biology labs, there has been a push to replace cookbook activities with inquiry-based labs to provide students with a better introduction to scientific research and to help them integrate foundational material with hands-on application (23-25). Students introduced to research at an early stage in their academic path are more likely to persist in science and typically receive higher grades in STEM courses (25). Persistence in STEM is also strengthened by active learning environments in both lecture and lab-based courses (25,26). A lab module designed around museum specimens immerses students in the diversity of animals while they craft research questions for animals that they are likely to find intriguing and familiar (e.g., campus squirrel species).

A secondary aim for this lab module is to expose students to the study of natural history and biodiversity that goes beyond memorizing taxonomic classifications. As many have observed, most current undergraduate students have spent little time outdoors, exploring the natural world in their own backyards (27-29). Natural history coursework and classes with field experiences have decreased due to lack of interest, funding, or both, leading to a widespread lack of knowledge about existing biodiversity, evolutionary history of diverse groups of organisms, and an ability to integrate between molecular and organismal fields (29-33). Taking a deep dive into a monophyletic group in this lab module requires students to engage in the process of science while they explore evolutionary relationships within a group and between the chosen group and close relatives (34). This approach grounds student understanding in evolutionary concepts and allows for practice with applications of phylogeny.

Ecology provides the real-life context within which students can explore evolution of a group of organisms. Patterns that have long been observed by natural historians provide an accessible entrée into the world of museum research. These patterns, especially in endotherms, are largely associated with latitudinal gradients. Within and between species, adaptations to various climates are evident when morphological characteristics are compared between a species' northern and southern populations. Bergmann's Rule (35) states that animals have larger body sizes in colder environments. This decrease in surface area to volume ratio is an adaptation for endotherms that must conserve energy in less temperate climates. As the ratio between surface area and volume decreases, heat loss decreases. This logic also explains Allen's Rule (36), which states that endotherms in colder environments will have shorter extremities (e.g., ears, tails, limbs). Longer extremities would increase an animal's surface area to volume ratio, thus increasing heat dissipation. In deserts, some species such as hares use this to their advantage to better thermoregulate in extreme heat (37).

These ecogeographic patterns provide a springboard for students to begin developing their own research questions regarding variation between or within species and seamlessly draws connections between two core life science concepts outlined in Vision and Change: evolution and structure and function (23). Students can evaluate these rules or pursue alternative questions by measuring research or teaching collection specimens. They can examine the extent and direction of sexual selection, evaluate the impact of urbanization on populations, or examine how a species has changed over time. The UMMZ, along with approximately 120 other natural history museums around the world, have uploaded their inventories of vertebrate collections on the NSF-funded VertNet online database (http://vertnet.org/). Individual specimen records include spatial, temporal, and often, morphometric measurement data. VertNet allows students to explore a much larger dataset than the specimens available at any one college or university. Provided the appropriate dataset is available on VertNet, museum specimens offer an ideal resource for inquiry-based research in the classroom because students can pursue an unlimited number of unique research questions.

Intended Audience

This lab module is intended to target undergraduates early in their college career to introduce them to hands-on museum research. The intended audience includes freshman and sophomore students considering a biology or environmental studies major. In the course, students either had AP Biology credit, had previously taken a general introductory biology course, or were simultaneously enrolled in a general introductory biology course. This activity can also be used for courses on vertebrate biodiversity, in which ecogeographic patterns are likely to be addressed in lecture.

Required Learning Time

Two hours of lecture and 6-7 hours of lab time were devoted to the activity as presented. Ninety minutes of the lab were spent touring museum collections, and this can be altered depending on the size and scope of an institution's natural history collection(s). A visit to an exhibit at a natural history museum could be substituted, as could an internet-searching activity about a group of organisms for an institution without a collection. Students spent 30 minutes planning three potential projects in small groups. Following instructor feedback and consultation, student groups finalized their research question and collected data in one three-hour lab period and spent two hours on statistical analysis and presentation development in a second lab period. As needed, student groups spent additional time outside of class preparing for their presentation. For this activity, each student group delivered a 10-15 minute presentation on which they were assessed.

Prerequisite Student Knowledge

Students should have working knowledge of how to read a phylogenetic tree and should be familiar with the general groups of animals (e.g., birds, fish, invertebrates). Students should know how to use measuring tape and rulers in the appropriate units. For very small specimens, instruction and practice with calipers may be helpful. If needed, students should receive instructor guidance on basic spreadsheet organizing tools and statistical tests.

Prerequisite Teacher Knowledge

For this lab activity, the instructor should be generally familiar with animal diversity and the tree of life, along with the biological underpinnings of ecogeographic rules. Prior to the lab, instructors should familiarize themselves with VertNet to gauge the datasets available and the covariates provided for mammal species of interest (See Supporting File S1: Teaching biodiversity - VertNet Instructions). It is helpful to have a set of back-up datasets already downloaded in case of internet access problems. Instructors should be able to coach students on how standard measurements are taken for mammal specimens (see Before Lab 2 section) and should be able to discuss the scientific process from hypothesis development to scientific communication with both their students and instructional team. For life history information, we recommend the invaluable Animal Diversity Web (https://animaldiversity.org/).

SCIENTIFIC TEACHING THEMES

Active Learning

Active learning strategies are used throughout the module, including group discussion and inquiry-based research. In small groups, students develop questions they would like to pursue with museum specimens and the online database. Students then examine the available specimens and data, allowing them to evaluate the feasibility of the various questions they want to pursue. Once each group chooses a scientific question to evaluate, they design methodology to collect and analyze their data, and work together to evaluate and present their results. Depending on the complexity of the intended final product, students might need to find and obtain other datasets (e.g., climate records) as part of their project. This inquiry-driven activity allows students to apply what they learn in lecture to their data and pursue additional resources to better interpret results.

Assessment

Student groups are assessed in a formative way as they talk through their proposed scientific questions and design their research protocol. This allows instructors to promote creativity while steering student groups toward more feasible projects. As students are interpreting their results, they are also verbally assessed to ensure they are drawing connections between their data and the life history traits of the species they are examining. Students are evaluated in summative way first, as a group during a 10-15 minute presentation to the class, and second, individually based on their responses to 6 short answer and multiple choice exam questions (for assessment resources, see Supporting Files S2: Teaching biodiversity - Presentation rubric and S3: Teaching biodiversity - Exam Assessment). To evaluate if student knowledge of biodiversity and museum research improved, students completed 6 survey questions before and after the module for course credit (Supporting File S4: Teaching biodiversity - Survey and results).

Inclusive Teaching

The module allows for multiple learning styles to be simultaneously addressed. Students see the diversity and variation of animals, discuss their research projects with the instructor and their peers, and are given the opportunity to handle and measure specimens. In addition, the research project allows students to fill numerous roles including specimen handler, measurer, data collector, data sifter, statistician, graphic designer, and presenter. Based on the geographic range made possible by VertNet, students can also leverage the diversity of their group to form predictions on nationwide or even global variation in a species. For students with little outdoor experience, the urban ecology of a university's campus provides for rich hypotheses regarding urban vs. suburban vs. rural populations. By choosing charismatic species that are found on or near campus such as squirrels, the lesson includes every student, even those with limited previous engagement with wildlife.

LESSON PLAN

Please see Table 1 for the teaching timeline of the two-week module. Students all attend lecture as one large group (~110 students) and attend lab in sections of 16-20 students. Students are broken into small groups of 3-4 students for each lab module. Laboratory sections are taught by graduate student instructors (GSIs) who are responsible for much of the one-on-one and small group feedback, teaching practical skills such as caliper operation and statistical analysis, as well as grading assessments. All lesson documents are provided as supporting materials.

Before Lab 1

The instructor introduces the biodiversity module with a one-hour lecture preceding the activity (see Supporting Files S5: Teaching biodiversity - Lecture 1 and S6: Teaching biodiversity - Lecture 1 Script). The lecture script provides a scaffold on which to build, depending on the audience. Students should read the module (pages 1-6 of Supporting File S7: Teaching biodiversity - Student Module) prior to the lecture. Prior to lecture, the instructor reviews the concepts of the lab with their instructional team (Supporting File S8: Teaching biodiversity - Instructional Team Presentation).

In-class: Lecture 1

In the lecture, the instructor's main goal is to provide students with background on diversity of the group of taxa the students will be investigating, along with instruction on how to read a phylogenetic tree and what information can be gleaned from proper reading of a phylogenetic tree. In addition, the lecture provides an introduction to museum research and gives the instructor an opportunity to modify the students' conception of what a natural history museum is and does.

Instruction in both basic biodiversity and the tree of life as well as reading phylogenetic trees will be more or less in-depth depending on previous course material and student background knowledge. It is important to give students adequate background on the animals used in lab (i.e., Table 2), especially if these taxa are uncommon or unfamiliar to your students. This lab is flexible enough to allow an instructor to choose species students are more likely to be familiar with or expand students' biodiversity knowledge by focusing on species students might have never heard about before.

Lab 1: Museum tour & hypothesis development

Tour

Students tour the museum collection to encounter a vast array of diverse animals. If possible, this should be led by museum staff for authenticity and a unique perspective. Our students saw the bird, insect, fish, and herpetological collections. During the tour, instructors should encourage students to ask the museum staff questions, but also should not hesitate to ask their own questions. The tour lasted 45-60 minutes, but could be longer or shorter depending on the size of the available collection. If the tour ends early, students can work in small groups to answer questions in the Module (Supporting File S7: Teaching biodiversity - Student Module, pages 7-8) and review the research project instructions (Supporting File S7: Teaching biodiversity - Student Module, pages 9-10).

After-tour lecture

A short 10-minute lecture by the instructor wraps up the biodiversity tour (see Supporting File S9: Teaching biodiversity - Activity 1 Lecture). In our case, a GSI with curatorial experience and museum research presented the lecture. First, students are asked about why specimens are prepared lying flat, rather than positioned in a life-like taxidermy-style pose. Students learn that the flat positioning allows for measurements and manipulation more easily than a positioned taxidermy mount and allows for the storage of more specimens. When a mammalian research specimen is prepared, scientists will try to collect as much data about the animal as possible. Data collected include the weight, specimen's entire body length (tip of nose to tip of tail), length of tail, length of right hind foot, length of ear (from the ear notch to tip of the ear), life stage, sex, reproductive status, and location where the specimen was collected. Mammals are prepared by removing the skin from the carcass, subsampling organs for genetic material, stuffing the skin with cotton, placing wires in limbs to stabilize, and sewing the skin shut. The skeleton is cleaned with dermestid beetles.

The importance of museum collections is emphasized to students when we discuss the Tasmanian tiger, which became extinct in 1936. There are 249 specimens of Tasmanian tiger found in research museums today. Because of a well-preserved pup, conservation biologists are working toward bringing this species back to life, a process referred to as "de-extinction" (38). Contrast the 249 Tasmanian tiger specimens to only 76 specimens of the Caribbean monk seal, which went extinct later in 1952. With fewer specimens collected, there are fewer questions we can ask and statistical analyses will not be as robust for this species.

It is very important to remind students frequently about proper specimen handling. Specimens should be held from the center of gravity but should not be squeezed tightly. Only pencils should be used around the specimens to avoid marking them up.

Hypothesis development

Students then break into groups of 3-5 for their research project. Each team of students chooses a different mammal group to research: Soricidae (shrews); Sciuridae (squirrels) other than chipmunks; Muridae (Old World mice) and Cricetidae (New World mice); and *Tamias* (chipmunks). Once assigned to a mammal group, student teams can choose to research a single species or compare multiple species. These groups were chosen because of the number and diversity of specimens we had available for student use. The available specimens are divided among four lab rooms (Table 2) to keep student traffic to a minimum and allow enough space for the safe examination of specimens. Student groups move between rooms as necessary. For instructors less familiar with the scope of VertNet, we recommend using mammalian families that students might recognize as mammal groups (e.g., Sciuridae, Muridae, Cricetidae, Soricidae, Leporidae [rabbits and hares], Didelphidae [American opossums], Procyonidae [raccoons], and Mephitidae [skunks]).

Each group is assigned a different mammal group (Table 2) in order to keep presentations and research unique and informative; students teach one another about their group of interest during presentations. Groups use the lecture background on ecogeographic patterns and suggestions in the lab manual to brainstorm research questions with the help of a handout (Supporting File S10: Teaching biodiversity - Hypothesis Handout). They can also do online searching to learn more about their assigned taxon. Each group should develop at least three hypotheses they are keen to pursue with museum specimens and the online database. They receive feedback from instructors on the feasibility of addressing the various questions posited. If time permits, they can share their hypotheses with the class to receive feedback from their peers.

Before Lab 2

Before the second lab activity, the instructor builds on the first lecture, reviewing standard measurements taken for research specimens and discussing scientific discoveries made due to museum collections available to scientists (see Supporting Files S10: Teaching biodiversity - Hypothesis Handout, S11: Teaching biodiversity - Lecture 2, and S12: Teaching biodiversity - Lecture 2 Script).

Preparation for Lab 2

Before Activity 2, measuring devices such as tape measures and calipers should be put in the classroom. Each table or lab bench should have one group's skin specimens placed on it (Table 2). Because we run 4 labs simultaneously, each laboratory room contained one group of taxa: chipmunks, other squirrels, mice, and shrews. Because large datasets delay the download process, instructors should begin the download process for all relevant VertNet datasets at least three days prior to Lab 2 (for instructions, see Supporting file S1: Teaching biodiversity - VertNet Instructions).

In-class: Lecture 2

In lecture 2, the instructor checks in with students about their research questions and gives guidance on how to choose one question to pursue from their initial ideas. A main goal of this lecture is to show students how to properly measure specimens and what the measurements found in VertNet mean. This lecture allows instructors to introduce students to VertNet and walk them through an example of quality-filtering their data. The instructor should emphasize data quality control and encourage at least two students from a group to measure each specimen to compare measurements and ensure the data are not biased by different measuring techniques.

The lecture allows the instructor to share some interesting and compelling museum research results related to ecogeographic rules and beyond, to help students start to imagine the types of questions they can investigate. An emphasis in this lab module allowing students to do "real" research substantially increases student enthusiasm and interest.

Lab 2: Data collection

Introducing the lab

At the beginning of lab, instructors demonstrate how to properly handle museum specimens and how to use calipers.

The instructor also projects a sample VertNet dataset to show students how they can quickly organize their data using the Sort function and remove columns that do not contain covariates of interest. Instructors may also present this via PowerPoint (Supporting File S13: Teaching biodiversity - Lab Activity 2 Introduction). Columns that students should pay particular attention to are titled: Year, Occurenceremarks, Dynamicproperties, Sex, LifeStage, Scientificname, Country, stateprovince, county, and decimallatitude. Year is important for groups interested in changes through time. Occurenceremarks and Dynamicproperties both often includes notes on the specimen's measurements, formatted in the following way unless otherwise noted: Total length (mm) – tail – hind foot – ear = weight (g). Sex is important for groups interested in sexual dimorphism. All groups should be mindful of the LifeStage, removing subadults to avoid biasing the data. If the VertNet data file includes multiple species, the Scientificname column allows the species to be separated. Groups interested in geographic variation should be mindful of the appropriate geographic variable columns. In our example, students were provided with specimens from our Mammal Teaching Collection, a museum collection that is not on VertNet. If specimens provided to students are also on VertNet, instructors should guide students to remove duplicates from their dataset.

Student activity

Students evaluate their VertNet dataset and the three research questions they developed during Lab Activity 1. This will allow them to evaluate the feasibility of the various hypotheses and refine the question they ultimately pursue. If time permits, it can be a good idea for students to pursue their two most interesting or reasonable questions, in case one or the other does not result in sufficient data from VertNet. The instructor should visit each group to help them when they encounter obstacles. For example, one group might have hypothesized that a squirrel's legs would be shorter at higher latitudes. Data on leg length is not currently available on VertNet. The instructor could ask them what length data is available, leading the group to change their research question slightly. We do not think the following types of questions are likely to become successful research projects, because of current data limitations: questions on fur color, questions related to specific geographic locations unless sampling was extensive, questions that rely on skulls or skeletons, and questions related to teeth. Skins are a better choice for use in this lab, rather than skulls or skeletons, because skins are more durable and tend to be more abundant in museum teaching collections. Skins are the best museum preparation type to directly address ecogeographic rules - body length vs. latitude, limb length vs. latitude, and interspecific comparisons between low and high latitude species. Skulls and skeletons of small mammals could be used to examine dentition and locomotion, but are extremely fragile, and cannot easily be repaired. Once a group has finalized their research question, they should design a methodology: what they are measuring and how, keeping in mind that each group should have at least two students measure each available specimen.

Students take measurements from museum specimens and then sift through their VertNet dataset to collect additional data (for instructions, see Supporting File S14: Teaching biodiversity - Excel Variation Instructions). This allows them to see the extent of data and variables collected from museum specimens. It also requires them to find the variables they are interested in while accounting for errors that might occur in large datasets collected across many institutions. Groups looking at small specimens with small features (i.e., hind foot of different mouse species) will need instruction on how to use calipers, and supervised practice by the lab instructor before using the calipers on specimens. If there is time remaining after data collection is complete, student groups can begin looking for patterns. Instructions on simple statistical analyses are available in Supporting Files S15: Teaching biodiversity - Statistics Instructions and S16: Teaching biodiversity - Excel ANOVA Instructions. Any statistical program that the students or instructor is familiar with should work for this activity.

Lab 3: Data analysis & presentation preparation

Students flex their statistical skills to examine their research question. If statistical analyses have not been introduced yet in the semester, we have provided step-by-step instructions to help guide students in the Supplemental Materials. Students interpret results by researching their animal's life history. They collaborate in their small groups to design a 10-15 minute PowerPoint presentation for the class. Some groups may need to complete the presentation and rehearse outside of class hours.

Lab 4: Research presentations

Student groups present on their different mammals, so that they become the experts in the room on their chosen group. The reasoning behind measurements they chose should be well-articulated and the analysis both rigorous and thoughtful (Supporting File S2: Teaching biodiversity - Presentation rubric). After each presentation, the student audience is encouraged to ask questions.

TEACHING DISCUSSION

This lab activity was conducted with 110 students who are majoring in the life sciences at the University of Michigan taking Introduction to Biology Lab in the Spring 2017 semester. According to the syllabus, "The purpose of this course is to show you how science is done and to have you do some yourself. It covers some big topics in biology — enzymatic activity, genetic manipulation by recombinant DNA techniques, interactions between organisms, evolutionary change in populations of microbes due to selective pressure, and biodiversity and functional morphology of animals." In this course, students attend lecture led by a professor and one of four laboratory sections led by a GSI.

At this point in the semester, students have already learned how to analyze ecological data with linear regressions, t-tests, and ANOVAs. Therefore, they were expected to complete statistical analyses for their project independently outside of class if necessary. This activity could be modified to be the lab where statistical analysis is introduced; the quantity of data available online make accessing a suitable dataset fairly easy. One challenging aspect for our students was determining a systematic way to sort through VertNet data to determine which records to keep and which to delete, on the basis of a set of criteria they had to define. The instructors identified encouraging students to get as much useable data as possible and helping students through data management issues as major challenges in this lab. To provide additional scaffolding for this activity, students could first be introduced to museum research with Linton et al.'s Island Biogeography Activity (21). This would allow students to become comfortable with museum data before tackling the larger VertNet dataset.

A sample of projects presented included tail length vs. latitude in the least chipmunk, body length vs. latitude in the fox squirrel, tail length in chipmunks in urban vs. rural areas, and the variation in hind foot to body length ratios between tree squirrels and ground squirrels. To evaluate the efficacy of the laboratory exercises in increasing student knowledge of biodiversity and museum research, the students were surveyed before and after the lab activity with six questions (Supporting File S4: Teaching biodiversity - Survey and results). Seventy-four percent of students showed an increase in biodiversity and museum research knowledge after the lab, with an average improvement of 1.2 correct answers. Biodiversity knowledge improved more than museum research knowledge, but this could in part be because fewer students answered the biodiversity knowledge questions correctly before the module (Supporting File S4: Teaching biodiversity - Survey and results). After the module, at least 20% of students struggled with museum research questions related to diet and behavior, which were not directly addressed in their lab activity. Students were surprised that the museum was not an exhibit space; a working research museum was completely new to most students, and further expands students' vision of what constitutes research in the biological sciences. While students enjoyed the research museum tour, the instructors thought an exhibit museum plus a "behind-the-scenes" look at the research museum might have been more interesting to students.

If a college does not have any research museum collections to tour, a tour could be scheduled at the nearest natural history museum. Alternatively, there are multiple videos available to introduce students to the research museum setting and see what goes on behind the scenes. We recommend the highly-subscribed YouTube channel, Brain Scoop, offered by the Field Museum of Natural History:

- https://www.youtube.com/watch?v=JZTTckEIaDI
- https://www.youtube.com/watch?v=heiyGjUko8M
- https://www.youtube.com/watch?v=nS8suhK-c5I).

If there are no specimens available to measure, the activity can be modified to focus solely on VertNet data. Alternatively, there are additional museum databases with media files of specimens that can be used to replace in-lab specimens. These online databases include iDigBio (https://www.idigbio.org/), GBIF (https://www.gbif.org/), and Arctos (https://arctos.database.museum/). We would like to highlight the Arctos mammal collection from Chicago Academy of Sciences (CHAS) which has pictures of mammal skins with a scale bar that would allow students to take body measurements in ImageJ (https://imagej.nih.gov/ij/).

For instructors interested in leveraging the novel technology of 3D printing, MorphoSource (https://www.morphosource.org/) is an online repository of 3D specimen data that allows users to download files for specific taxa. Some of the data is "raw", meaning that it would require some effort to prepare for printing, whereas other data have been manipulated to create the 3D representation of the specimen that could be used for printing. Software such as Dragonfly (https://www.theobjects.com/dragonfly/) may offer free education licenses and can be used to manipulate raw data and create 3D models of the users' choosing.

Species included in the mammal groups for this activity include the five most common mammals on 536 US college campuses surveyed [Table 2 (39)]. Because of their visibility on college campuses, these five species could each be assigned as the focal species for student groups to evaluate. Instructors can focus on any group of vertebrate taxa (or let students choose), so that the activity fits well within an existing course structure. We think this lab might be an ideal way to get students to learn more about an unfamiliar group of taxa; focusing on a particular biome might offer a way to increase knowledge of biodiversity while addressing global climate patterns and associated vegetation types. We found that student groups teaching one another about their organisms was an effective way to help students stay engaged during lab presentations.

SUPPORTING MATERIALS

- S1.Teaching biodiversity-VertNet Instructions. Provides instructor and student instructions to navigate VertNet and successfully download relevant datasets.
- S2.Teaching biodiversity-Presentation rubric. Rubric for instructor to grade group presentations to assess student groups.
- S3.Teaching biodiversity-Exam Assessment. Exam questions and key to individually assess students; these are provided as a sample for what we expected students to achieve given the stated learning objectives.
- S4.Teaching biodiversity-Survey and results. Results from six survey questions administered before and after the module.
- S5.Teaching biodiversity-Lecture 1. Lecture before Lab 1.
- S6.Teaching biodiversity-Lecture 1 Script. Instructor's script that aligns with the lecture 1 slides.
- S7.Teaching biodiversity-Student Module. Student handout for the lab activity to be read before the opening lecture and used throughout the activity.
- S8.Teaching biodiversity-Instructional Team Presentation. Slides to introduce instructional team to the activities and learning goals.
- S9.Teaching biodiversity-Activity 1 Lecture. Mini lecture to present immediately following museum tour.
- S10.Teaching biodiversity-Hypothesis Handout. Handout that students complete during Activity 1 to allow instructor to assess potential directions of student projects.
- S11.Teaching biodiversity-Lecture 2. Lecture before Lab 2.
- S12.Teaching biodiversity-Lecture 2 Script. Instructor's script that aligns with the lecture 2 slides.
- S13.Teaching biodiversity-Lab Activity 2 Introduction. Optional lecture to begin Lab 2 for instructors wishing to provide more structured help with Excel and VertNet.
- S14.Teaching biodiversity-Excel Variation Instructions. Resource for students who may need instructions on how to sort data in Excel.
- S15.Teaching biodiversity-Statistics Instructions. Resource for classes that have not been introduced to statistical analysis or may require a refresher.
- S16.Teaching biodiversity-Excel ANOVA Instructions. Resource for classes that have not been introduced to statistical analysis or may require a refresher.

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REFERENCES

1. Ceballos G, Ehrlich PR, Barnosky AD, García A, Pringle RM, Palmer TM. 2015. Accelerated modern human-induced species losses: Entering the sixth mass extinction. Sci Adv 1: e1400253.
2. Culley TM. 2013. Why vouchers matter in botanical research. Appl Plant Sci. 1:apps.1300076.
3. Helgen KM, Pinto CM, Kays R, Helgen LE, Tsuchiya MTN, Quinn A, Wilson DE, Maldonado JE. 2013. Taxonomic revision of the olingos (Bassaricyon), with description of a new species, the Olinguito. ZooKeys 324:1-83.
4. Suarez AV, Tsutsui NL. 2004. The value of museum collections for research and society. BioScience 54:66-74.
5. Pyke GH, Ehrlich PR. 2010. Biological collections and ecological/ environmental research: a review, some observations and a look to the future. Biol Rev 85:247-266.
6. Clemann N, Rowe KMC, Rowe KC, Raadik T, Goman M, Menkhorst Peter, Sumner J, Bray D, Norman M, Melville J. 2014. Value and impacts of collecting vertebrate voucher specimens, with guidelines for ethical collection. Mem Mus Vic 72:141-151.
7. Martin NA. 1990. Voucher specimens: A way to protect the value of your research. Biol Fertil Soils 9:93-94.
8. Rocha LA, Aleixo A, Allen G, Almeda F, Baldwin CC, Barclay MVL, Bates JM, Bauer AM, Benzoni F, Berns CM, Berumen ML, Blackburn DC, Blum S, Bola?os F, Bowie RCK, Britz R, Brown RM, Cadena CD, Carpenter K, Ceríaco LM, Chakrabarty P, Chaves G, Choat JH, Clements KD, Collette BB, Collins A, Coyne J, Cracraft J, Daniel T, de Carvalho MR, de Queiroz K, Di Dario F, Drewes R, Dumbacher JP, Engilis A, Erdmann MV, Eschmeyer W, Feldman CR, Fisher BL, Fjeldså J, Fritsch PW, Fuchs J, Getahun A, Gill A, Gomon M, Gosliner T, Graves GR, Griswold CE, Guralnick R, Hartel K, Helgen KM, Ho H, Iskandar DT, Iwamoto T, Jaafar Z, James HF, Johnson D, Kavanaugh D, Knowlton N, Lacey E, Larson HK, Last P, Leis JM, Lessios H, Liebherr J, Lowman M, Mahler DL, Mamonekene V, Matsuura K, Mayer GC, Mays H., McCosker J, McDiarmid RW, McGuire J, Miller MJ, Mooi R, Mooi RD, Moritz C, Myers P, Nachman MW, Nussbaum RA, Ó'Foighil D, Parenti LR, Parham JF, Paul E, Paulay G, Pérez-Emán J, Pérez-Matus A, Poe S, Pogonoski J, Rabosky DL, Randall JE, Reimer JD, Robertson DR, Rödel M-O, Rodrigues MT, Roopnarine P, Rüber L, Ryan MJ, Sheldon F, Shinohara G, Short A, Simison WB, Smith-Vaniz WF, Springer VG, Stiassny M, Tello JG, Thompson CW, Trnski T, Tucker P, Valqui T, Vecchione M, Verheyen E, Wainwright PC, Wheeler TA, White WT, Will K, Williams JT, Williams G, Wilson EO, Winker K, Winterbottom R, Witt CC. 2014. Specimen collection: An essential tool. Science. 344:814-815.
9. Yeates DK, Zwick A, Mikheyev AS. 2016. Museums are biobanks: unlocking the genetic potential of the three billion specimens in the world's biological collections. Curr Opin Insect Sci 18:83-88.
10. Burgio KR, Carlson CJ, Tingley MW. 2017. Lazarus ecology: Recovering the distribution and migratory patterns of the extinct Carolina parakeet. Ecol Evol 7:5467-5475.
11. Murray GGR, Soares AER, Novak BJ, Schaefer NK, Cahill JA, Baker AJ, Demboski JR, Doll A, Da Fonseca RR, Fulton TL, Gilbert MTP, Heintzman PD, Letts B, McIntosh G, O'Connell BL, Peck M, Pipes M, Rice ES, Santos KM, Sohrweide AG, Vohr SH, Russell B, Briggs JC. 2017. Emergence of a sixth mass extinction? Biol J Linn Soc Lond 122: 243-248.
12. DuBay SG, Fuldner CC. 2017. Bird specimens track 135 years of atmospheric black carbon and environmental policy. Proc Natl Acad Sci U S A 114:11321-11326.
13. Bond AL, Hobson KA, Branfireum BA. 2015. Rapidly increasing methyl mercury in endangered ivory gull (Pagophila eburnea) feathers over a 130 year record. Proc Biol Sci 282: 20150032.
14. Sutton DA, Patterson BD. 2000. Geographic variation of the western chipmunks Tamias Senex and T. Siskiyou, with two new subspecies from California. J Mammal 81:299-316.
15. Tewksbury JJ, Anderson JGT, Bakker JD, Billo TJ, Dunwiddie PW, Groom MJ, Hampton SE, Herman SG, Levey DJ, Machnicki NJ, del Rio CM, Power ME, Rowell K, Salomon AK, Stacey L, Trombulak SC, Wheeler TA. 2014. Natural History's Place in Science and Society, BioScience. 64: 300-310.
16. Flaherty C. 30 March 2017, posting date. Louisiana Monroe getting rid of two major natural history collections to make way for a sports field. Inside Higher Ed 2017. Available from https://www.insidehighered.com/news/2017/03/30/louisiana-monroe-getting-ridtwo-major-natural-history-collections-make-way-sports.
17. Cross R. 2017. New 3D scanning campaign will reveal 20,000 animals in stunning details. Science. 10.1126/science.aap7604.
18. Briggs, JC. 2017. Emergence of a sixth mass extinction? Biol J Linn Soc Lond 122:243-248.
19. Hiller AE, Cicero C, Albe MJ, Barclay TLW, Spencer CL. 2017. Mutualism in museums: A model for engaging undergraduates in biodiversity science. PLoS Biol 15: e2003318.
20. Leadley PW, Krug CB, Alkemade R, Pereira HM, Sumaila UR., Walpole M, Marques A, Newbold T, Teh LSL, van Kolck J, Bellard C, Januchowski-Hartley SR, Mumby PJ. 2014. Progress towards the Aichi biodiversity targets: an assessment of biodiversity trends, policy scenarios and key actions. Secretariat of the Convention on Biological Diversity, Montreal, Canada.
21. Linton D, Monfils A, Phillips M, Ellwood L, Cook J. 2019. An investigation of island biogeography using data from online natural history collections. (Version 2.0). QUBES Educational Resources. doi:10.25334/Q4ST7D
22. Thompson CW, Duda TF, Hinshaw JC, Lee T, O'Brien MF, Rabosky DL, Schneider GE, Priscilla K. Tucker PK. 2016. Investing in biodiversity collections for the future: a new century at the UMMZ. Page 111 in Abstract Book - 96(th) Annual Meeting of the American Society of Mammalogists. American Society of Mammalogists, Minneapolis, Minnesota.
23. AAAS. 2011. Vision and Change in Undergraduate Biology Education: A Call to Action. Washington, DC: AAAS. Available from http://visionandchange.org/finalreport/.
24. Smith KA, Sheppard SD, Johnson DW, Johnson RT. 2005. Pedagogies of Engagement: Classroom- Based Practices. J Eng Educ 94:1-15.
25. President's Council of Advisors on Science and Technology (PCAST). 2012. Engage to excel: producing one million additional college graduates with degrees in science, technology, engineering, and mathematics. Washington, DC: U.S. Government Office of Science and Technology.
26. Freeman S, Eddy SL, McDonough M, Smith MK, Okoroafor N, Jordt H, Wenderoth MP. 2014. Active learning increases student performance in science, engineering, and mathematics. Proc Natl Acad Sci U S A 111:8410-8415.
27. Weigl PD. 2009. The natural history conundrum revisited: mammalogy begins at home. J Mammal 90(2): 265-269.
28. Louv R. 2005. Last child in the woods: saving our children from nature-deficit disorder. Algonquin Books of Chapel Hill, Chapel Hill, NC.
29. McCauley DJ. 2017. Digital nature: Are field trips a thing of the past? Science 358:298-300.
30. Wilcove DS, Eisner T. 2000. The impending extinction of natural history. Chron High Educ 47:B24.
31. Schmidly DJ. 2005. What it means to be a naturalist and the future of natural history and American universities. J Mammal 86:449-456.
32. Fleischner TL, Espinoza RE, Gerrish GA, Greene HW, Kimmerer RW, Lacey EA, Pace S, Parrish JK, Swain HM, Trombulak SC, Weisberg S, Winkler DW, Zander L. 2017. Teaching biology in the field: Importance, challenges, and solutions. BioScience 67:558-567.
33. Anderson JGT. 2017. Why ecology needs natural history. American Scientist 105:290.
34. Ballen CJ, Greene HW. 2017. Walking and talking the tree of life: Why and how to teach about biodiversity. PLoS Biol 15(3): e2001630.
35. Bergmann K. 1847. Ueber die verhältnisse der wärmeökonomie der thiere zu ihrer grösse. Gottinger Stud 3: 595-708.
36. Allen JA. 1877. The influence of physical conditions in the genesis of species. Radic Rev 1:108-140.

37. Griffing JP. 1974. Body Measurements of Black-Tailed Jackrabbits of Southeastern New Mexico with Implications of Allen's Rule. J Mammal 55:674-678.
38. Pickrell J. 11 December 2017, posting date. Tasmanian Tiger Genome May Be First Step Toward De-Extinction. Natl Geogr 2017. Available from: https://news.nationalgeographic.com/2017/12/thylacine-genome-extinct-tasmanian-tiger-cloning-science.
39. Peplinski J, Brown JS. 2018. A guide to campus squirrels. Page 90 in Abstract Book - 98(th) Annual Meeting of the American Society of Mammalogists. 25-29 June 2018. Manhattan, Kansas.

Table 1. Teaching biodiversity with museum specimens – teaching timeline. Activities that occur in lab sections are led by graduate student instructors; the lecture is taught by a faculty instructor.

Activity	Description	Time	Notes
Preparation for Lab 1			
Module reading	Students read module pages 1-6.	20 minutes	Module is provided in S7.
Conceptual overview	• Instructional team meets to discuss lab philosophy and procedures. • Lead instructor prints out project descriptions.	45-60 minutes	Presentation for instructional team is provided in S8. Project description is provided in S10.
Lecture 1			
Introductory lecture	• Refresh students on tree reading. • Discuss biodiversity. • Introduce museum research.	About 50-minute interactive lecture	Lecture 1 is provided in S5 and Lecture 1 script is provided in S6.
Lab 1			
Museum tour	The goal is to show students a sample of collections.	1.5 hours	We found students were most interested in common species they recognized, and especially large collections of common specimens. We also exposed students to rarities in our collection, and even a mammal specimen undergoing preparation.
Mini lecture and hypothesis writing		30 minutes	Lecture slides for post-tour mini lecture provided in Supporting File S9.
Preparation for Lab 2			
Instructional prep	• Set out museum specimens. • Set out measuring devices.	30-60 minutes	Consider traffic flow around specimens in your classroom space; also think about clipboards and data collection sheets (or have students make their own).
Lecture 2			
Lecture	• Review data collection. • Review museum research.	50 minutes	Lecture 2 available in S11 and Lecture 2 script is provided in S12.
Lab 2			
Data collection	• Students collect data from specimens. • Students problem solve to finalize hypothesis. • Students collect digital data.	3 hours	The most intensive aspect of this lab is to help students with proper data collection, sorting VertNet data, and managing a spreadsheet with thousands of rows.
Lab 3			
Data analysis and presentation preparation		3 hours	Data analysis instructions for excel are found in S13-S16.
Lab 4			
Research presentations		1.5 hours	The rubric for presentations is found in S2.

Table 2. Museum skin specimens used in Lab 2. Species in **bold** are the five most commonly observed squirrel species on college campuses in US and Canada (39).

Group	Species	Common Name	No. specimens
Sciuridae (chipmunks)	***Tamias minimus***	Least chipmunk	8
	Tamias striatus	Eastern chipmunk	10
Soricidae	*Blarina brevicauda*	Northern short-tailed shrew	12
	Sorex cinereus	Masked shrew	5
Sciuridae (non-chipmunk squirrels)	***Sciurus carolinensis***	Eastern gray squirrel	2
	Sciurus niger	Fox squirrel	3
	Marmota monax	Groundhog	2
	Tamiasciurus hudsonicus	Red squirrel	8
	Glaucomys sabrinus	Northern flying squirrel	2
	Glaucomys volans	Southern flying squirrel	3
	Ictidomys tridecemlineatus	13-lined ground squirrel	5
Muridae + Cricetidae	*Mus musculus*	House mouse	9
	Peromyscus leucopus	White-footed mouse	15
	Peromyscus maniculatus	Deer mouse	12