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Lesson

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Abstract

Biotelemetry is used by researchers to track the interactions of animals with each other and the environment. While advancing technology has led to the development of numerous biotelemetry tools, radio telemetry remains the most common method for tracking small animals. Moreover, telemetry tracking of animal movement is an important skill for entry-level positions in wildlife biology. Thus, hands-on experience using radio telemetry provides students with an advantage as they pursue careers in wildlife biology, as well as an opportunity to build science process skills. We present a lesson in which students use radio telemetry to track animals; collect, analyze and interpret spatial data; and consider its applications to local wildlife management and conservation. Students submit their data to a national database collecting observations from multiple institutions as part of Squirrel-Net (http://squirrel-net.org). The aggregated data allows students to generate and test hypotheses across a broader variety of species and habitats than would be possible at any single institution. The lesson is designed for adaptation to diverse educational contexts, from a single two-hour laboratory period (basic skills acquisition) to a semester-long student-driven research project (open inquiry Course-based Undergraduate Research Experience, or CURE). Although this activity and the national database focus on spatial data for squirrels, which are diurnal, charismatic, easily identified, and present on most college campuses, the same methods and materials can be modified for any animal capable of carrying a radio transmitter and being safely tracked by students.

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Supporting Materials: Supporting File S1. Squirrels in space – Lecture slides on space use and movement; S2. Squirrels in space – List of resources for identifying focal species and field sites; S3. Squirrels in space – List of resources for purchasing equipment; S4. Squirrels in space – Example IACUC Protocol; S5. Squirrels in space – Lecture slides on tracking basics; S6. Squirrels in space – Worksheet for assessing preparation for equipment use; S7. Squirrels in space – Master datasheet and upload instructions; S8. Squirrels in space – Data collection instructions; S9. Squirrels in space – Example questions for summative assessment; S10. Squirrels in space – Instructions for creating simple maps; S11. Squirrels in space – R code for spatial analysis

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Learning Goal(s)

Students completing the lesson described in this article will understand:

- Costs and benefits of mark and recapture methods versus tracking animals.
- Similarities and differences among types of biotelemetry used to track the space use and movement of vertebrate animals.
- How researchers select the most appropriate method for tracking vertebrate animals, given the natural history of a species, the structure of its habitat, and the availability of funding.
- How researchers select the most appropriate method for attaching a transmitter to an animal based on species' characteristics.
- How location data are used for wildlife management and conservation.
- How to practice science process skills, such as making observations, analyzing data, interpreting results, and communicating results.

Learning Objective(s)

Students will be able to:

- Use VHF (Very High Frequency) radio telemetry to track the space use of a sciurid (squirrel) species in a study area.
- Explain why VHF radio telemetry is the most appropriate and widely used method for tracking the space use of sciurids.
- Discuss potential applications of data collected in class for wildlife management and conservation.

INTRODUCTION

For over 50 years, researchers have used biotelemetry to track the interactions of animals with each other and with their environment (1,2). As a result, the use of biotelemetry has provided important insight into the behavior, habitat use, and movement patterns produced by animals (3,4). While space use characteristics, such as the size and shape of home ranges, can indicate habitat preferences, and potentially habitat suitability, movement routes illustrate whether a species is restricted to a specific habitat or is able to use less desirable habitat and pinpoint where barriers to movement occur (5). Biotelemetry information can thus guide decisions about the types of management actions needed (e.g., establishing reserves, providing connectivity), how these actions are prioritized, and the spatial and temporal scales at which they are implemented (5).

Biotelemetry tools include transmitters that send very high frequency (VHF) radio signals to receivers within a few hundred meters, transmitters that send data thousands of kilometers using satellites, and devices that log data on animal physiology and environmental conditions. Rapidly improving technology is leading to ever-smaller tracking devices collecting higher-resolution data (6). However, many trade-offs still exist; devices with enough battery power to either transmit signals over long distances, collect high-resolution data, or collect data frequently or over extended time periods are bigger than many species can carry and often more costly than researchers can afford. As a result, VHF radio telemetry has remained the most common method for tracking small animals while maintaining high spatial and temporal precision (7).

VHF radio telemetry typically requires more frequent manual detection of tagged animals than other types of biotelemetry (e.g., GPS or ARGOS satellites), and can therefore be time- and labor-intensive (7). Much research using radio telemetry relies on workers in internships or entry-level positions to conduct tracking of animals in the field. A scan through a wildlife biology job board (e.g., Texas A & M Department of Wildlife and Fisheries Sciences Job Board; https://wfscjobs.tamu.edu/job-board/) will typically reveal a number of positions available for individuals able to use radio tracking for monitoring wildlife. Though often short-term, these positions commonly provide a “foot-in-the-door” to careers in state or federal agencies for biology or environmental science majors following graduation. Thus, lesson plans that allow first-hand experience using radio telemetry equipment provide students with a competitive advantage as they apply for these positions and enter the workforce.

Here, we present a lesson in which students use radio telemetry to track sciurid mammals (e.g., squirrels, chipmunks, prairie dogs) on or near an institution’s campus, interpret spatial data, and consider the applications of these techniques to wildlife management and conservation. While radio telemetry has previously been used in course lesson plans (8,9), these lessons are often not shared among instructors since transferability of methods is frequently limited by specialization to species or habitats, and the number of instructors with access to telemetry equipment is limited. Here, we overcome these barriers by focusing on sciurids, which are found across a variety of habitats, including nearly all college campuses across North America, making the methods described in our lesson plan easily transferable. We expect that demonstrating successful implementation of the lesson and/or collecting preliminary data will increase the availability of funding opportunities for instructors to purchase their own radio telemetry equipment, thereby increasing learning opportunities for students across institutions.

Rationale and Origin of Lesson

Squirrel-Net is a group of teacher-scholars that share a common goal to promote authentic course-based research experiences, or CUREs, for undergraduate students. We are mammalogists that hold research and teaching positions at higher educational institutions across the United States, which range from R1 universities to primarily undergraduate institutions and colleges serving under-served and/or underrepresented populations. Our goals are to create flexible, inquiry-based lesson plans that take students out of the classroom and engage them in research on locally relevant and widely distributed mammals, while also collecting data with standardized protocols to test a wide-array of ecological questions across spatial and temporal scales.

This lesson is part of the Squirrel-Net module series (http://squirrel-net.org). All of the Squirrel-Net modules are designed for adaptation to diverse educational contexts, from a single two-hour laboratory period (basic skills acquisition) to a semester-long student-driven research project (open inquiry CURE). In each module, students can submit data to a national dataset that aggregates observations from multiple institutions. Students can therefore access and analyze the freely available national database, which allows them to explore the focal questions of the module across a broader variety of habitats and species than would be possible at a single institution. Finally, the four Squirrel-Net modules published in this set (10-13) are designed so that they can be scaffolded into multiple levels in a curriculum, allowing students to return to similar taxa and themes and uniting inquiry across multiple courses.

In the current lesson plan, we describe the most basic implementation of the Squirrels in Space module; however, for more advanced students and/or courses, instructors might consider including some of the lesson preparation (e.g., live trapping and radio collaring sciurids) during the class. Furthermore, additional class periods could be devoted to conducting additional tracking of radio-collared sciurids or querying and analyzing the national dataset to test hypotheses about how the space use of squirrels differs among habitats or species.

Intended Audience

This lesson is intended for upper-division undergraduates in elective courses in biology, zoology, ecology, wildlife management, or environmental science. It has been tested in vertebrate natural history and mammalogy laboratory courses (n = 24 students each) at California State University, Monterey Bay, an undergraduate-focused, Hispanic-serving, four-year institution. Students in these courses vary greatly in their prior experience with field ecology, as well as their quantitative and verbal skills.

Required Learning Time

This lesson was designed for either a single two-hour laboratory or two 50-min periods; however, it can be easily expanded to cover multiple class periods or taught in combination with other Squirrel-Net CURE modules (10-13). See Teaching Discussion for more details on expanding the lesson to include structured and open-inquiry activities.

Prerequisite Student Knowledge

We recommend that students are familiar with basic concepts related to animal space use and movement (e.g., potential risks and benefits to animals during movements in home ranges or dispersal outside home ranges). Students should understand how information on animal space use and movement can be used in management and conservation. If students are not familiar with these concepts, content could be provided via lecture and discussion in a preceding class (Supporting File S1. Squirrels in space – Lecture slides on space use and movement) or as assigned reading. Text books on vertebrate biology, animal behavior, or mammalogy typically include sections on home ranges and dispersal, often within chapters on ecology, movement, and/or behavior (14-17). The Wildlife Techniques Manual also includes chapters on radio telemetry methods (18) and analysis of radio telemetry data (19). The utility of location data for management and conservation is demonstrated in numerous studies, but well summarized by Allen and Singh (5).

Prerequisite Teacher Knowledge

We recommend that instructors have either observed or conducted live trapping and radio collaring of sciurids or other small mammals. We also recommend instructors have experience tracking vertebrate animals, although not necessarily sciurids, using VHF radio telemetry. However, numerous videos demonstrating radio tracking can be found online, and some may serve well as a form of instruction when in-person training is not feasible. Instructors will also need a basic knowledge of the ecology and natural history of the focal species. Instructor resources for selecting a focal species of sciurid, identifying the species and its sign (e.g., nests, burrows), and locating an appropriate study site are provided in Supporting File S2. Squirrels in space – List of resources for identifying focal species and field sites.

SCIENTIFIC TEACHING THEMES

Active Learning

Students participate in multiple active learning activities. For example, think-pair-shares during an introductory lecture provide students with time to verbalize thoughts about a question before comparing ideas with a partner, and then sharing with the whole class (20). A whip around during a discussion following data collection asks every student to take a turn (e.g., while sitting/standing in a circle) providing a short response to a question; answers can repeat previous ideas, but wording should differ (20). Additionally, students collaborate in small groups to collect data during class and submit it to a national dataset. Students may also work in groups to develop questions about the space use of sciurids, address the questions through analyzing the national dataset, and prepare scientific lab reports.

Assessment

Students prepare a scientific lab report in which they describe their research question, methods for examining their research question, interpretation of data, and the potential importance of their data for wildlife management and conservation. Reports can be written in small groups to provide students with the type of collaborative experience typical of modern research in the ecological/environmental sciences and to reduce instructor grading load. Assessment of individual students can be conducted through short essay questions on exams that prompt comparisons of various tracking methods based on a given scenario (e.g., a specific project question, species, habitat) or interpretation of figures representing data on animal space use or movement.

Inclusive Teaching

Squirrel-Net modules are designed to act as CUREs that allow all students an authentic research experience in class, thereby overcoming the time and financial limitations that prevent many students from engaging in research outside of class (21). Such equal access to research experiences may help women and minorities overcome the structural barriers that reduce their numbers in the sciences (22). Participation in a CURE has been linked to student gains in research skills, self-efficacy, and persistence in science (23-25). Additionally, our CURE modules are implemented through a national network that not only creates broad-scale datasets, but will also help students feel a sense of belonging to a scientific community outside their class, as well as validation for contributions to this broader community (26).

In this specific lesson, a variety of strategies, such as think-pair-share, multiple hands, multiple voices (i.e., requiring multiple raised hands or responses to a question before any responses are shared), and whip around are used to foster participation of all students in discussion activities (20). While inclusive instruction is sometimes difficult in field sciences, this lesson provides ample opportunity for including students with disabilities. Because sciurids are broadly distributed across diverse natural and urban habitats and are present on nearly all university and college campuses in North America (27) this lesson can be implemented in locations that allow participation of students with mobility disabilities. Additionally, because data collection requires both listening to radio telemetry receivers and visually locating sciurids or their sign (i.e., nests, burrows), collaboration of students in small groups allows participation of students with either visual or hearing impairments during field activities. This lesson can also provide flexibility in how activities are conducted outside of class. As an extension option, students sign-up to track radio-collared sciurids outside of class by choosing times that fit their schedules, thereby avoiding timing conflicts with work or family obligations.

LESSON PLAN

Preparation for Class

This lesson requires a population of radio-collared sciurids on/near campus; it will therefore require that instructors are either comfortable capturing and radio collaring sciurids or aware of local wildlife biologists with whom collaborations can be established. Once instructors have identified individual(s) who will capture and radio collar sciurids, as well as a focal species and field sites (Supporting File S2. Squirrels in space – List of resources for identifying focal species and field sites), they will need to ensure access to live trapping and telemetry equipment. We provide a list of necessary equipment, estimates of cost, and potential purchase sites in Supporting File S3. Squirrels in space – List of resources for purchasing equipment. Some companies selling telemetry equipment have grant programs that will donate equipment for research and educational projects. Additionally, Squirrel-Net hopes to establish a loan system that will provide access to telemetry equipment for instructors/classes unable to afford these purchases. Instructors can visit the Squirrel-Net homepage (http://squirrel-net.org) to check for availability of telemetry equipment. Finally, instructors will need approval to work with sciurids on or near campus. Approvals will typically include a scientific collecting permit from a state agency, a protocol approved by the university's Institutional Animal Care and Use Committee (IACUC), and any site access permits for reserves, parks, or universities. We provide an example IACUC protocol in Supporting File S4. Squirrels in space – Example IACUC Protocol. The process of applying for permits, gaining IACUC approval, and purchasing equipment can take many months; depending on experience with these activities, we recommend instructors allow 3-6 months for this pre-class preparation.

Once equipment is available and approvals are established, instructors can begin live trapping and radio-collaring sciurids. To determine the number of animals that should receive radio collars, instructors should carefully consider the objectives of the lesson plan and any related research projects, availability of funding/equipment, and availability of people who can conduct tracking. For example, when we used this lesson, we aimed to provide students with radio tracking knowledge and experience, and also to investigate space use of sciurids along an urbanization gradient. To meet our objectives, we radio collared 10 sciurids on campus, 10 in an adjacent suburban neighborhood, and 10 at nearby reserves (students in our research labs tracked sciurids on off-campus sites). Instructors should also consider the sex and age/size of the individuals receiving radio collars, as the timing of seasonal activity (e.g., hibernation) can vary with these factors. As a general rule, researchers typically place radio collars on individuals only when mass of the radio collar is < 5% of the individual's body mass (28). Instructors should consider the timing of live trapping and radio-collaring activities in relation to when the lesson plan will be implemented in class. Finally, instructors should plan on tracking radio-collared sciurids every 1-3 days prior to class to ensure familiarity with the study animals and habitat, to be aware of any missing individuals or collars, and to practice recording data using the datasheet (Supporting File S7. Squirrels in space – Master datasheet) and instructions (Supporting File S8. Squirrels in space – Data collection instructions). When we taught this lesson, we conducted the majority of our live trapping and radio collaring during a week-long spring break, and then followed the lesson plan when classes resumed.

Before students begin the lesson plan, they can be split into the number of teams for which telemetry receivers and antennas are available, and radio frequencies associated with radio-collared squirrels can be evenly split amongst the teams. If the lesson plan is being taught as a CURE, a pre-assessment survey and instructions for compliance with the Institutional Review Board for Protection of Human Subjects in Research (IRB) can be requested via the Squirrel-Net homepage (http://squirrel-net.org), and students can complete the survey prior to class. We also recommend that students are familiar with basic concepts related to animal space use and movement (e.g., home ranges, dispersal), as well as how these concepts are applied to the management and conservation of wildlife. If students are not familiar with these concepts, content can be provided in a preceding class or as assigned reading.

An Introduction to Biotelemetry

Instructors begin the lesson by presenting a short lecture on the types of biotelemetry tagging and tracking (Supporting File S5. Squirrels in space – Lecture slides on tracking basics). We used think-pair-share and multiple hands, multiple voices as inclusive teaching strategies (20) to allow opportunities for participation of all students in discussions. For example, after providing information on the advantages and disadvantages of different types of biotelemetry tracking, we asked students to think for a moment about which tracking methods they would apply in various scenarios (e.g., examining dispersal of urban raccoons versus migration of Arctic caribou) before sharing ideas with a partner, and then the class as a whole. After illustrating common methods for attaching radio transmitters to animals, we asked students to generate ideas about how to attach a transmitter to a burrowing animal without a prominent neck, such as a badger or a snake. We requested at least 5 students raise their hands before we proceeded with the discussion.

Next, instructors bring telemetry and GPS-locating equipment to class to introduce components (i.e., receiver, antenna, GPS unit or smartphone application) and demonstrate steps followed to track an animal (i.e., power on, select radio frequency, adjust volume and gain, scan with antenna, follow loudest signals) and record location data in field notebooks (i.e., power on, track satellites, save waypoint and/or record GPS coordinates in a notebook). Instructors also note helpful tracking strategies based on the natural history of the focal species (e.g., circling burrows or trees to home in on a radio-collared individual). At this point, we asked students to complete a worksheet to ensure they understood use of telemetry equipment and methods for tracking an animal using homing (Supporting File S6. Squirrels in space – Worksheet for assessing preparation for equipment use). We answered any questions that arose while students completed the worksheet before continuing.

Finally, instructors introduce assignments associated with radio tracking and data collection activities that will be completed outside of class. Assignments should include entry of data into the national dataset (Supporting File S7. Squirrels in space – Master datasheet), following instructions (Supporting File S8. Squirrels in space – Data collection instructions), but the level of inquiry may vary from simple interpretation of maps and other figures derived from the data to development and testing of hypotheses and formal communication of results (Table 2). Example assessment and reflection questions to include within an assignment or on later quizzes/exams are included in Supporting File S9. Squirrels in space – Example questions for summative assessment.

Data Collection

Next, instructors distribute telemetry and GPS-locating equipment among student teams and begin travel to the field site. Upon arrival at the field site, instructors should announce a meeting time and place for holding a final discussion. Students then collaborate in teams to track sciurids using radio frequencies. When radio telemetry receivers produce loud signals indicating proximity to a radio-collared sciurid, students look for the sciurid or sign of where it is hidden (i.e., burrow or nest) and record location data (i.e., GPS coordinates), as well as other data describing the location environment, on data sheets (Supporting File S7. Squirrels in space – Master datasheet) following instructions (Supporting File S8. Squirrels in space – Data collection instructions). To describe the local environment, students describe the weather and note the type of habitat in which their radio-collared sciurid is located. Students also estimate the distance to any edges delineating the presence of a second type of habitat (e.g., where campus transitions to urban development or where forest transitions to agricultural habitat), the distance to the nearest refuge (i.e., tree for tree squirrels, burrow for ground squirrels), and the distance to any human structures present. If other animals are in the vicinity, students record data on the species (e.g., squirrels, humans, dogs), number of individuals, and distances from the radio-collared sciurid, as well as note any interactions among animals. Last, students record information that can be used to infer the quality of collected data, including level of confidence that the radio-collared sciurid is present at the recorded GPS coordinates and factors disrupting reception of radio signals, such as hills and buildings.

If radio-collared sciurids are in close proximity to one another, instructors can easily visit each team to check progress during tracking and encourage team members to switch roles (i.e., who holds antenna and receiver, who records data). At the designated time and place, instructors use strategies such as a whip around (20) to guide student discussion describing and reflecting on experiences tracking animals (e.g., Was it difficult to locate your radio-collared squirrel? Why or why not? How would you change your tracking strategy in the future?), as well as potential uses for collected data (e.g., How would resource managers use these data if they were collected from an endangered species? Could these data be used to describe the habitat preferences of the species? How might campus planners use these data if they consider the species a pest?). Instructors may also remind students that radio tracking experiences are valuable skills that can be noted on curriculum vitae or résumés (Figure 1).

Relevant coursework

Mammalogy (BIO 364) **Spring 2017**
- Set and baited Sherman and Tomahawk traps
- Applied ear tags and recorded data on small mammals (species, body mass, sex, reproductive condition)
- Tracked radio-collared ground squirrels using radio telemetry

Landscape Ecology (ENVS 446) **Fall 2017**
- Used ArcGIS to calculate home range sizes from location data collected for squirrels
- Used Fragstats to calculate common landscape metrics (e.g., edge density, contagion) for study sites

Figure 1. Example section of a curriculum vitae/résumé noting experiences using radio telemetry and calculating home ranges.

Last, instructors address any remaining questions about assignments related to tracking activities and remind students to enter data from data sheets into the national dataset. At the simplest level of inquiry, we recommend asking students to reflect on the applicability of different types of biotelemetry to the tracking of local sciurids and to interpret any potential relationships between sciurid location data and landscape features/cover types (see Supporting File S9. Squirrels in space – Example questions for summative assessment). For example, in a structured inquiry activity, an instructor might ask students to use a map of squirrel locations on their campus to determine if squirrels avoided campus buildings (i.e., most locations were at distances greater than 10 m from human structures). In a more advanced course, an instructor might plan a free inquiry activity in which students generate hypotheses based on primary literature (e.g., Are squirrels found on campuses more likely to be found within 10 m of human structures in the summer when fewer humans are present than in winter? Are squirrels in urban habitats, which may be habituated to humans, found at greater distances from refuge than squirrels in natural habitats?), test predictions using the national dataset, and then communicate research in a manuscript-style paper. If the lesson plan is being taught as a CURE, a post-assessment survey and instructions for compliance with Institutional Review Boards can be requested via the Squirrel-Net homepage (http://squirrel-net.org), and students can complete the survey when their research experiences are complete.

TEACHING DISCUSSION

All Squirrel-Net modules are designed for implementation in a variety of classroom settings (e.g., variation in instructional level, class size, type of institution). In all cases, the most basic level of the assignment (described in the lesson plan for *CourseSource*) is structured inquiry, where students are focused on learning data collection skills (10-13). Although students are not engaged in a full research experience at this level, they are still collecting and submitting authentic data to a national dataset. For assignments at the highest level of inquiry, students are provided only with Squirrel-Net protocols for data collection. They are expected to use literature to generate hypotheses explaining patterns in space use and movement by sciurids and to test these hypotheses using the national dataset, which will include the data that they themselves collect.

We implemented the "Squirrels in Space" lesson in two classes of 24 upper-division students during the Spring of 2017: mammalogy and vertebrate natural history. In both classes, we implemented the lesson as a guided inquiry project spanning multiple weeks. Students were happy to spend time outdoors and excited to gain first-hand experience using technical equipment often seen in wildlife documentaries. In fact, after our students answered questions from campus bystanders about our telemetry activity and equipment, the non-science students and facility workers expressed a desire to try tracking. Students were pleased by the enthusiasm for field science and happy to share their newfound knowledge. Comments on course evaluations at the end of the semester indicated that students believed the experience using radio telemetry would improve their chances of finding employment in the field of wildlife biology. We have some anecdotal evidence suggesting this was true. For example, one student contacted us a year after the class ended to thank us for the telemetry experience and report that she'd been having fun working as a sea otter tracker and behaviorist during the filming of a television series on animals.

Extensions and Modifications

Because we implemented our lesson over multiple weeks, it included multiple extensions and modifications. First, prior to data collection, we used a jigsaw activity in which each student prepares part of an assignment outside class to later share with a group of students in class (29). We assigned students to four different groups based on the first letter of their surname and tasked each group with reading a different scientific article prior to class (e.g., 30-33). All four articles described studies in which telemetry was used to track an animal species along an urbanization gradient; they differed in that some reported a positive relationship between home range size (i.e., area used during food gathering mating, and caring for young) and urbanization and others found the reverse. In class, students first met in small groups with students who had read the same article to discuss their understanding of the article's main points. Next, students met in groups in which each member had read a different article, and they used peer teaching to share what they had discussed in their first groups. Meeting first with those who had read the same article allowed students to peer teach with confidence to those who had not read the same article. Students were generally surprised by the contrasting results reported in the articles, and this fueled them to think critically while generating their own hypotheses about the responses of local sciurids to urbanization.

An extension commonly used in wildlife courses with access to radio telemetry equipment is a "hide and seek" activity which allows students to practice using telemetry equipment outdoors. This activity can be used in classes preparing students for collection of data from radio-collared animals, but is also useful as a stand-alone activity in classes that do not have access to radio-collared animals. We started this activity by asking for a volunteer to play the role of a radio-collared squirrel. The volunteer then took a radio transmitter and hid his or herself on campus. We note that instructors may want to quickly discuss hiding locations with volunteers to ensure they do not hide in places that will take more than 20 min to locate on foot. The remaining students were divided into groups, and each group received a telemetry receiver and antenna and was assigned a starting location within a ~2-min walking distance of the instructor. To track the volunteer, one student in each group held the telemetry receiver and antenna, scanning with the antenna to search for a signal. Once a signal was detected, the entire group listened to the volume of signals received as the antenna was moved about and came to a consensus on which direction to move in order to home in on the volunteer. As each group tracked the radio signal, they took turns carrying the equipment so that multiple students could practice focusing the antenna on the loudest signals and fine-tuning reception with the receiver. Typically, student groups located the volunteer at approximately the same time, since groups could usually see one another and verify that they were all homing in on a similar location. If a group went astray, however, students who had successfully tracked the volunteer were happy to call or text their lost classmates and get them back on track. This entire process was repeated a few times so that all students were able to practice handling telemetry receivers and antennas. If desired, the difficulty of searches can be increased by having volunteers hide near tall buildings where radio signals may be deflected or continue moving (slowly) so that groups must track a moving target.

If students are able to practice using telemetry equipment in class, data collection can be modified so that students sign up to track radio-collared ground squirrels on or near campus with a partner outside of class. We used a shared Google Calendar to have students sign up for either early (7:00-12:00) or late shifts (12:00-17:00) each day over a 15-day period. To meet the minimum 30 location points recommended for kernel analyses of home range (34), some students volunteered to conduct tracking for more than one shift. Our calendar included instructions directing students to transfer equipment to groups scheduled after them. This system worked surprisingly well; having just one team (i.e., one receiver and antenna) tracking at any one time on campus allowed student researchers in our lab to use additional receivers and antennas to track ground squirrels on off-campus sites. We were able to accumulate the recommended minimum number of location points for individual squirrels quickly and efficiently. Occasionally, students were unable to locate an individual squirrel, but these difficulties served as opportunities for class discussions about the unpredictability of field work, error associated with tracking methods, and strategies for troubleshooting and overcoming such setbacks.

Many modifications can be applied to the analysis and interpretation of data, as well as assessment. While we used Google My Maps (35) to quickly create maps illustrating the location points collected by students (Figure 2), student groups could easily use this application to create their own maps of any subset of the national dataset they choose. Instructions for creating a simple map using Google My Maps (35) are provided in Supporting File S10. Squirrels in space – Instructions for creating simple maps. As data analysis and interpretation become more specific to groups, opportunities arise for groups to share their results in more conference-like presentations with the rest of the class, and for assessment to cover science communication.

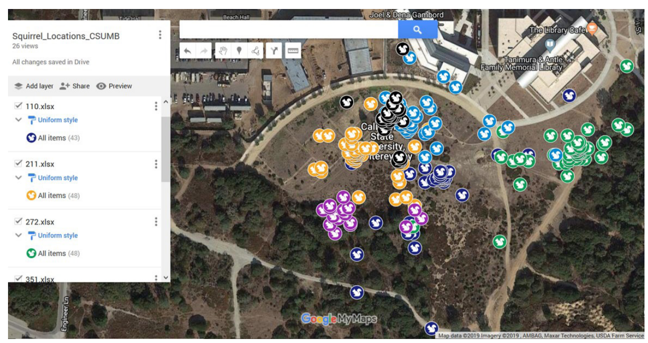

Figure 2. Example map created in Google My Maps illustrating location data collected for six sciurids (yellow, purple, black, light blue, dark blue, and green squirrel icons) on the California State University, Monterey Bay campus.

Additionally, classes with access to computers can use specialized tools for conducting analyses. For example, students can use R software to calculate home range sizes using multiple estimators or GIS software to conduct additional visualizations and spatial analyses. We provide code to calculate home ranges and distances between neighboring squirrels using R software (Supporting File S11. Squirrels in space – R code for spatial analysis), but also note sample data and R code are available through an online tracking workshop (https://github.com/jamesepaterson/trackingworkshop; 36). At our institution, data collected by students in mammalogy and vertebrate natural history courses were used by students learning to estimate home ranges in a landscape ecology course the following semester. Students examined the relationship between home range size and urbanization and shared findings with both campus planners interested in improving management of the squirrels as pests on campus and local reserve managers interested in expanding populations of the same species on local reserves. Some students were in both a data collecting class and the landscape ecology class, and thus experienced extended exposure to this lesson plan over a full academic year. Indeed, this extended exposure to research working with a particular study system/hypothesis could be scaffolded into curricula, as extended exposure to research may increase student gains in research skills, confidence, and identification as a scientist to an even greater extent than a single research experience (37,38).

Last, instructors may wish to adapt this lesson plan to other species beyond squirrels. Although our national dataset is specific to sciurids, tracking data for any animal can be shared, and potentially accessed, through movebank.org, an online repository of animal tracking data hosted by the Max Planck Institute of Animal Behavior (39). Although the field site identification, equipment needs, and capture and handling methods described in the supporting files will vary with species, this lesson plan can be applied with little modification to the radio tracking of most terrestrial animals.

SUPPORTING MATERIALS

- S1. Squirrels in space – Lecture slides on space use and movement
- S2. Squirrels in space – List of resources for identifying focal species and field sites
- S3. Squirrels in space – List of resources for purchasing equipment
- S4. Squirrels in space – Example IACUC Protocol
- S5. Squirrels in space – Lecture slides on tracking basics
- S6. Squirrels in space – Worksheet for assessing preparation for equipment use
- S7. Squirrels in space – Master datasheet and upload instructions
- S8. Squirrels in space – Data collection instructions
- S9. Squirrels in space – Example questions for summative assessment
- S10. Squirrels in space – Instructions for creating simple maps
- S11. Squirrels in space – R code for spatial analysis

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Table 1. Squirrels in space teaching timeline

Activity	Description	Time	Notes
Preparation for Class			
Prepare to conduct field work with sciurids on/ near campus	1. Identify experienced individual(s) (e.g., local members of professional societies or natural resource agencies) or familiarize self with methods to capture and radio collar sciurids. 2. Ensure access to live trapping and telemetry equipment. 3. Gain approval for work with sciurids on/near campus.	Up to 6 months	• Helpful resources for identifying focal species and field sites included in Supporting File S2. Squirrels in Space – List of Resources for Identifying Focal Species and Field Sites. • Example equipment lists/costs and permit protocols are included in Supporting Files S3. Squirrels in space – List of resources for purchasing equipment and S4. Squirrels in space – Example IACUC Protocol.
Conduct initial field work	Live trap and radio collar select sciurids on/ near campus.	~2 weeks	Some initial field work can be incorporated into classes prior to the lesson, depending on time available in class.
Lecture and discussion on space use and movement (optional)	Interactive lecture with think-pair-shares.	25 minutes	Lecture slides provided in Supporting File S1. Squirrels in space – Lecture slides on space use and movement
Assign telemetry equipment and radio frequencies to student teams	1. Divide class into number of teams for which telemetry receivers and antennas are available. 2. Divide radio frequencies of collared squirrels among teams.	10 minutes	
Pre-CURE assessment survey	Students complete the pre-assessment survey.	15-30 minutes	Request access and information for approval by the Institutional Review Board for Protection of Human Subjects in Research (IRB) through the Squirrel-Net homepage (http://squirrel-net.org).
Class Session: An Introduction to Biotelemetry			
Mini-lecture on tracking methods	Interactive lecture with think-pair-shares.	25 minutes	Lecture slides with notes are in Supporting File S5. Squirrels in space – Lecture slides on tracking basics.
Introduction to telemetry equipment	1. Introduce components of radio telemetry equipment and GPS-locating device. 2. Demonstrate use of on/off switches, radio frequency selection, use of volume and gain, and saving location coordinates. 3. Discuss natural history of focal species and strategies for tracking it.	15 minutes	
Telemetry worksheet	Worksheet designed to assess understanding of telemetry equipment use.	10 minutes	Worksheet is provided in Supporting File S6. Squirrels in space – Worksheet for assessing preparation for equipment use.
Class Session: Data Collection			
Travel to field site on/near campus	1. Student teams gather telemetry equipment, GPS-locating devices, and field notebooks. 2. Class travels to field site.	10 minutes (varies by site)	If separated into two 50-min classes, students may meet at the field site at the beginning of the second class to increase time available for tracking.

Activity	Description	Time	Notes
Data collection	1. Student teams track sciurids using assigned radio frequencies. 2. Students use GPS-locating devices/ smartphone applications to assign coordinates to sciurid locations. 3. Students collect waypoints and record information on locations and environmental conditions in field notebooks or the master datasheet.	30 minutes	• Master datasheet is provided in Supporting File S7. Squirrels in space – Master datasheet and upload instructions. • Instructions are provided in S8. Squirrels in space – Data collection instructions. • Before tracking begins, the instructor should announce a meeting time and place for holding a discussion. • The instructor may check the progress of each team if radio-collared sciurids are in close proximity to one another.
Discussion	1. Students discuss their tracking experiences. 2. Students return equipment to instructor.	10 minutes	
Outside of Class			
Data entry into national dataset	Students submit data from data sheets into national dataset.	10 minutes	• Online submission form for national dataset is available by request through the Squirrel-Net homepage (http://squirrel-net.org).
Interpretive assignment	1. Instructor provides map(s) of national dataset locations. 2. Students use map(s) to complete interpretive assignment.	30 minutes	• Instructor may provide map of subset of national dataset locations, which can be quickly created using Google My Maps (Google LLC 2019). Instructions provided in Supporting File S10. Squirrels in space – Instructions for creating simple maps. • Potential interpretation questions are included in Supporting File S9. Squirrels in space – Example questions for summative assessment.
Post-CURE assessment survey	Students complete the post-CURE assessment survey.	15-30 minutes	Request access and information for approval by IRB through the Squirrel-Net homepage (http://squirrel-net.org).

Table 2. Examples of extensions and modifications for this lesson. Levels of inquiry are explained in more detail in the companion essay by Dizney et al. (11).

Level	Structured Inquiry	Controlled Inquiry	Guided Inquiry	Free Inquiry
Telemetry	Students track and collect locations for radio-collared sciurids in class. Students complete an assignment outside of class by interpreting a map of location points to address a question. Both map and question are provided by instructor.	Students track and collect locations for radio-collared sciurids in class. Students analyze (cleaned) national dataset and create maps to compare mean distance of squirrels to landscape features (e.g., roads, habitat edges) in two populations (e.g., ground vs tree squirrels, urban vs natural habitat). Students generate a specific hypothesis, test a prediction using an analysis selected by instructor, and write a short reflection or lab report on their experience.	After practice using equipment in class, students track and collect locations for radio-collared sciurids outside of class. Students analyze (cleaned) national dataset and create maps. Possible questions assess individual (e.g., sex), environmental (e.g., cover type), or temporal (morning vs evening) predictors of squirrel space use (e.g., distance to landscape feature). Students select appropriate analysis to test their own hypothesis and prediction. Communication of scientific process is assessed; students select format (e.g., poster or oral presentation).	After practice using equipment in class, students track and collect locations for radio-collared sciurids outside of class on multiple occasions. Students develop hypotheses, select analyses, and use (uncleaned) national dataset to create maps and to test hypotheses and predictions generated from literature. Communication of scientific process is assessed as a manuscript-style paper including literature references.