How Do Scientists Know? Answering High School Students’ Questions with an Ecological Sampling Unit

Lisa A. Pike

Abstract
What do animals eat? What animals are present in a habitat? How many animals are present? How was the habitat different years ago? How old is this animal? These are all questions that scientists want to answer. We know the answers to questions like these from data collected by scientists in a variety of ways. Science is evidence-based, and conclusions are arrived at after multiple replicable experiments. Presented here are six ecological scenarios that demonstrate how scientists arrive at answers to population ecology questions. These lessons can be implemented as single activities that supplement a high school ecology or environmental science curricular unit or as a midday rotation of stations in which students practice field sampling techniques used in population and community ecology, designed to answer ecological questions. Student scientists learn how to use indirect sampling methods to estimate abundance, density, age, and population size using mark–recapture, transects, and quadrats to model authentic field methods. They calculate species richness and biodiversity with a simplified Simpson’s diversity index and describe species age structure and distribution using tree rings, sheep horns, and camera trap images. Students also learn to display population data appropriately, graphing survivorship and richness vs. area and studying trophic pyramids.

Key Words: ecology; sampling; environment; populations; data collection.

Introduction
Population ecologists use a variety of quantitative methods to sample populations, in order to determine the presence of a species in a habitat, its abundance, and how resource availability, climate change, natural disaster, or removal or addition of predators or invasive species affects the native species. Why is species X abundant, or why is species Y declining? How do scientists know? How do they answer these questions? Especially in today’s political climate, it is always good to remind students that scientists don’t say things just on a whim—they have data, that is, evidence, to back up their claims. A scientist doesn’t use the word theory lightly, and when scientists generate a valid conclusion they then send that conclusion out for peer review, where other scientists in the same field of study can evaluate the conclusion and the methods used to test the hypothesis. Evidence-based conclusions get published only after having passed rigorous peer review. Scientists “know” things because of the extensive and rigorous testing of hypotheses, but scientists also can learn things in other ways, beginning at a different starting point, sometimes termed “discovery science.” How do we know what species lives in a habitat? Sometimes hypothesis testing can answer this question, sometimes you just need to get out in the habitat and see for yourself. How do you discover the answer? There are a variety of field sampling techniques designed to answer these questions, but it is not always easy to fit all the techniques into a packed teaching schedule. In this set of activities, targeted for high school biology or AP environmental science classes, student scientists rotate through stations designed to teach some of these methods. They learn how to use indirect sampling methods to estimate abundance, density, population size, age structure, species richness, biodiversity, diet, and distribution, and explore ways to display population data appropriately. In this way the activities become an engaging comprehensive curricular piece focused on ecological sampling methods as a way to teach ecological concepts.

This series of activities works well as a station rotation, but each station can also be used individually, especially when students are not strong in mathematics. While math is integral to several of the stations, students really just need to know how to add, subtract, multiply, and divide, and they need to be able to compute simple formulas and create and analyze both bar and line graphs. If students are not confident in the math associated with the lessons, then instead of a rotation these lessons should be used individually to supplement an existing ecology curriculum, where a teacher can take the time to walk students through calculations. As Davis-Berg and Jordan (2018) noted, the goal is to have students use quantitative reasoning and graphical analysis as aids to understanding concepts without getting bogged down in calculations or turned off by seemingly difficult formulas. The point isn’t so much the math itself (though I’ve heard math described as the “language of science”) as it is getting students actively engaged in figuring out ecological
The stations are each briefly described in Table 1, and the online version of this article is linked to extensive Supplemental Material (including background information for the teacher, data sheets that walk students through the math, procedures, and assessment ideas). A computer is needed for station 5 (abundance), which ties in a citizen science project and contributes to a real database. Each station requires approximately an hour of work, so students can cycle through the six stations over several days.

| Station | What Do You Want to Know? | How Do You Answer This Question? | Student Activity | Methods, Materials & Costa |
|---------|---------------------------|---------------------------------|-----------------|---------------------------|
| 1       | Population size           | Mark–recapture and transects    | Students estimate population size using Lego transects. Students then pull a sample of beans (or live mealworms) from a bag and then use Lincoln-Peterson formula to estimate population size. | • Mealworms $35, or 6 bags of Lima beans $25  
• Paint pens $45 (6 colors, 2–4 of each color)  
• Plastic cups, paper plates or newspaper, $10  
• Lego transects: Legos $30 and string $2 |
| 2       | Species richness and diversity | Transects and quadrat sampling | Students learn how to sample a large area using quadrats, then calculate species richness and graphically display species richness versus area. | • Tape and craft materials (pom poms, felt creatures), or beans, rubber erasers, plastic beads, etc. $15–25 |
| 3       | Diet                      | Analyze scat, or stomach contents | Students dissect owl pellets, sort and classify bones, and set up a trophic pyramid. | • Owl Pellets, $2–3 each (1 pellet per 1–2 students = total $25–35)  
• Bone Chart |
| 4       | Age and survivorship      | Analyze growth rings           | Students count tree rings to determine age of trees, then create a survivorship curve for Dall sheep. | • Tree Rings (real or photographs, a downloaded resource)  
• Tree Cores (from UCAR center for science education, free download)  
• Age Data for Dall Sheep (a downloaded resource)  
• Jumbo straws and markers ($5) |
| 5       | Abundance                 | Camera traps                   | Students determine number of big cat species at Wildsumaco, Ecuador, using camera trap images, then log on to Zooniverse to analyze photos from the Grumeti Reserve in Tanzania. | • Big cat photos from Wildsumaco, a downloaded resource  
• Zooniverse (computer or internet needed) |
| 6       | Historical presence and distribution of species | Analyze cores                  | Students analyze graphic “cores” and determine which layer is the top, bottom, and middle by aging the Foraminifera tests found within each layer. | • Download and laminate core images |

* Per lab of 24 students (6 groups of 4).
Station 1: Population Size Estimates

Population ecologists look at many types of descriptive data, including population size and density, age structure, sex ratio, and survivorship (Ricklefs, 1990; Raven et al., 2014). When the population being studied is human, we call this demography, and the population estimate is a census. With wild populations of highly mobile animals, however, it isn’t as easy as knocking on a door and asking questions like “How many people live here?” In fact, it is not always easy to determine what species, and how many of each, are in a particular habitat, especially if the habitat is large. Biologists often use transects and quadrats to sample communities and habitats. With plants, which tend not to run or hide from scientists, transects are most often used to calculate species richness and abundance. A transect is a line across the habitat over which the number and types of organisms are documented at regular intervals. Quadrats are small plots placed randomly within a larger habitat, and the plants (or slow-moving animals, like slugs) within are counted. A total number can be extrapolated from several smaller quadrat samples.

At this station, students first use the transect method to calculate the population size of plant species, using Legos scattered over a flat Lego base (Figure 1). Then students use the mark–recapture method to estimate the size of a mealworm (or bean) population (Figures 2 and 3). Population size estimates vary (see sample data in Table 2).

Worksheets walk students through questions such as “How should I lay out the transects – what distance apart should they be?” and “Should they be parallel, or is it OK for transects to cross?” and “How would I capture and mark a black bear, or a butterfly?” After collecting the data, you can ask the students if their data reflect what they see on the Lego board (for instance, are some species more common than others?), if there might be better ways to set up the transects to collect a more representative, and unbiased, sample, and if the actual count of mealworms was close to the estimate. Some groups have an extremely large percent error for mark–recapture. Did they do anything wrong? Not usually – it was mostly luck of the draw, and due to a small sample size. How might this be a problem for a wildlife manager?

Station 2: Species Richness & Diversity

Knowing a population’s size, distribution, and density is important for predicting how that population will change in the future (Ricklefs, 1990). If the population has a low density, then organisms might have trouble finding mates. If the population is clustered around a resource (such as a pond) and the resource disappears, the population will most likely decline or move. Putting it into this frame or context helps students understand the importance of taking quantitative data.

Figure 1. Students use Legos to model a forest or field, and then they learn to use the transect method to count Lego plant species.

Figure 2. Live mealworms are a hit in the classroom and can be used in a mark–recapture exercise to estimate population size.
In this station, we continue the theme of sampling populations to estimate population size, and we use quadrats to introduce the concepts of species richness and species diversity. Species diversity is a measure that combines what species are present and how abundant each species is, while richness is simply a count of how many species are present. It is generally accepted that ecosystems that have higher richness and diversity values have higher ecosystem health and stability, and that these ecosystems are more resilient in the face of change (man-made or natural). Having a variety of species not only can help provide us food, but can also contribute to clean water, breathable air, fertile soils, climate stability, pollution absorption, building materials for our homes, prevention of disease outbreaks, medicinal resources, and more. Diversity indices can be used to compare different communities or one community at different points in time, with a higher diversity indicating a healthier community (Kormondy, 1996; Cleland, 2011).

How do we measure richness and diversity? Biologists obtain data on organism abundance, richness, and density by marking off smaller plots, or quadrats, within the habitat. Multiple quadrats are used for replication, and quadrats need to be of equal size, and selected randomly from within the larger habitat. Your number of quadrats should equal at least 10% of your total area. The station setup features a large area divided into quadrats by masking

**Figure 3.** An alternative to mealworms in the mark–recapture exercise would be to use large white lima beans and permanent markers.

**Table 2.** Sample data for the Lincoln-Peterson mark–recapture estimator. You want a separate (different) color for each group, with as many colors as you have groups. Groups of four students work well.

| Group | M | t | R | Ne | %E |
|-------|---|---|---|----|----|
| Blue  | 109 | 71 | 14 | 552.7 | 34.1 |
| Red   | 36  | 51 | 4  | 459  | 11.4 |
| Green | 90  | 72 | 20 | 324  | 21.4 |
| Purple| 89  | 99 | 21 | 419.6 | 1.8 |
| Black | 51  | 64 | 8  | 408  | 0.97 |
| White | 37  | 51 | 10 | 185  | 54.2 |

$N_e =$ Total (actual size of population) 412

**Figure 4.** Ecology and environmental science teachers have created quadrats in the lab for many years. Students learn how to randomly select a few quadrats out of the whole, and then they calculate species richness and diversity (photo credit: Jon Guston, AP Environmental Science).
tape, with different species represented by various craft materials or beads (Figure 4).

Within each quadrat, student biologists count the number of species and the number of individuals of each species (population size), then calculate population size, species richness, and species diversity for the larger habitat. Next, students will create a species richness vs. area (number of quadrats) graph, and calculate the Simpson’s diversity index (modified as seen in Paterno et al., 2017) using their quadrat data.

Students will hypothesize that increasing habitat size (or area) can increase species richness. This is generally true; the larger an area is, the more species it will contain (up to an equilibrium point – the carrying capacity for number of species in a given habitat). This relationship can be graphed (Figure 5). As you can see, at some given habitat size there will be no more increase in number of species. Ask students: Can you think why this may be?

Station 3: Diet

To get a good indication of what an animal eats, you can dissect out the gut from a dead animal (roadkill, scientific samples); capture an animal and force it to regurgitate; or look at its scat for any undigestible remains. We will focus on a variation of the scat method that is very popular as a science extension: owl pellets. Owls are nocturnal raptors, and they are predatory, eating small rodents and sometimes other birds, reptiles, even fish and crayfish (Cornell Lab of Ornithology, https://www.allaboutbirds.org). They generally eat their prey items whole, digest the muscle, fat, and skin, and regurgitate, in the form of a pellet, anything they can’t digest (such as whole bones, fur, or feathers). While you can sometimes find pellets in the wild (fresh ones are moist), it is easy to purchase sterilized dry pellets in a variety of sizes, from a variety of species, and from owls from different locations around the United States (e.g., North vs. South). These pellets often come from zoos or bird rehabilitation facilities where owls are fed small rodents.

At this station, students work in groups to dissect a pellet and identify and quantify the bones within one barn owl pellet (Figure 6). Ask: How are the bones alike? Different? Do any of the bones provide clues about the type of animal they came from? Then students calculate how many of each prey item the owls eat per week and year, and, given the number and mass of prey per year and the energy content of each prey type, they calculate the amount of energy per kilogram of prey (Table 3). (See Carolina Biological Supply, under Further Resources below.)

This can be extended into a lesson on trophic pyramids and thermodynamics. The energy loss from the prey to the owl often ends up being 99%, which leads to a discussion about the 10% transfer of energy and 90% loss of energy being averages, and, with the mass of the owl being so low (for a top predator), the math usually comes out at 99% loss (Shertz, n.d.). I like to see students question this number, as it means they really understand the concept of energy loss and aren’t just plugging in numbers without understanding the concept.

Station 4: Age & Survivorship

Students begin this station by estimating the ages of trees and of Dall sheep using photographs of tree rings (Figure 7) and Dall sheep horns, respectively. Knowing the age structure and sex ratio of a population helps researchers predict the growth of populations (Kramer, 2013). Ages – and life spans – are limited by genetics and environment. Maximum life spans are measured by looking for the longest-lived organism of the species, but a more meaningful measurement is average life expectancy, which is a statistic derived from...
Table 3. Sample data for the owl pellet investigation.

| Prey            | Number eaten per year ($Y_I$) | Mass (g) ($M$) | Mass of Prey (g) ($PM = Y_I \times M$) | Mass of Prey (kg) ($PM/1000$) | Mass (kg) of Producers Eaten by Prey ($= Prod$) | Biomass (BM) of Producers (kg) ($BM = PM(kg) \times Prod$) |
|-----------------|-------------------------------|----------------|----------------------------------------|-------------------------------|-----------------------------------------------|----------------------------------------------------------|
| Mouse/vole      | 900                           | 20             | 18,000                                 | 18                            | 45.6 kg                                       | 820.8                                                   |
| Mole            | 0                             | 55             | 0                                      | 0                             | 365 kg                                        | 0                                                       |
| Shrew           | 0                             | 5              | 0                                      | 0                             | 1168 kg                                       | 0                                                       |
| Rat             | 2730                          | 240            | 655,200                                | 655.2                         | 12.8 kg                                       | 8386.56                                                 |
| Bird            | 0                             | 20             | 0                                      | 0                             | 127 kg                                        | 0                                                       |
| **Total PM$_I$ (kg)** = 673.2 |                      |                |                                        |                                |                                               |                                                          |

**Figure 7.** Tree rings can be used to estimate the age of a tree.

Wildlife Sanctuary in Ecuador and the Grumeti Reserve in Tanzania. You can then link this station with stations 1 and 2 and answer questions about how scientists count the number of animal species in a quadrat, especially for a highly mobile, secretive, or nocturnal animal. Included in this station are photographs of big cats taken from camera traps at the Wildsumaco Biological Station. Student scientists determine the number, and sex, of big cats within the range covered by the cameras (Figure 8; Vanderhoff et al., 2011). Second, using a computer with internet access, the station includes a citizen science opportunity from the University of Minnesota Lion Center and Zooniverse. Using the “Zooniverse” website (https://www.zooniverse.org), “Snapshot Grumeti” lets participants identify animals in camera-trap photos and upload the data to scientists.

Questions that camera trapping can answer include, among others, the following: Are the animals solitary? Are there young? What is the ratio of males to females? Is species $X$ found in this

○ **Station 5: Abundance**

Cameras are a great tool when you want to identify individuals but not necessarily capture them – or when the species you want to identify are secretive. Marine biologists have long used photographs of whale flukes and dorsal fins to identify pod members and follow them from year to year, assessing health and birth rates. Cameras don’t have to be operated by a researcher; you can set out motion-sensitive camera “traps” that take photographs of animals as they pass in front of the lens and store the images until the researcher returns and downloads the images. In fact, this is happening right now in many places, including Wildsumaco

**Figure 8.** Camera traps at the Wildsumaco Biological Station in Ecuador allow scientists to estimate size and sex ratio of the resident margay population.
area? How often does an individual return to the same place (do they have a set “patrol”)?

**Station 6: Historical Distribution & Using Fossils to Age Sediment Layers**

Tiny ocean creatures called Foraminifera (forams, for short) can tell a multitude of stories about the ocean bottom, because changes going on in the ocean affect foram groupings and distribution. Benthic ocean sediments contain remnants of once living organisms (in this case the test, or calcium carbonate shell, of a protist in the foram group), and because foram species segregate themselves in regard to water depth, latitude, and water temperature, and because they contain chemical signatures that can indicate glacial and interglacial periods, forams are often used by geologists as a climatic indicator species (DeMarco, 2009; Wetmore, 2017). Scientists can also tell the age of sediments, reconstruct past climate, determine the feasibility of drilling for oil, and take a pretty good guess as to what ancient habitats were like in terms of food availability, salinity, water depth, water temperature, and so forth by looking at what fossil foram species are present in a given sediment layer.

In station 6, we will look at foram species present in three geological layers to assess the age of the layer and the species’ historical distribution. Information is included for an extension to look at climate as well. This hands-on exercise may sound familiar at first, and you have probably seen students “mining” cookies in lessons on economics or resource extraction, or you may have done cupcake geology where students investigate layers, or strata, of a cupcake Earth. I have put these geology exercises in the framework of a real-life situation, with real organisms that existed on Earth in the past, and I’ve used color-coded images instead of cookies to keep this station at about 30 minutes of analysis.

Using the data sheet on foram species, ask students: What is different about the layers? Which one was laid down first? Which one is newest? How can you tell? When students struggle, I ask them to look at the geological time scale and consider: If you have a foram that lived from ancient times up to more modern times, over a wide range, will it be easy to use it to identify the age of the sediment sample? Why or why not? What if you had a foram that is found only in a narrow time range, say, only in the early Cenozoic (65–33 mya) – would you then be able to narrow down the age of the sediment sample in which that foram species was found? Could that foram species be used as an indicator of a geological time frame? And, just because a foram could have been alive and present in a geological period, does that mean you will necessarily find fossil evidence of it?

At the station, each student in a group is assigned a core. The core divides into three layers, distinguished by sediment color (Figure 9). Students are asked to determine which layer is the oldest. Tell them: You have three sediment layers from 10 deep ocean cores – but the layers got mixed up in transit back to the lab. Put them in chronological order, then defend your claim by explaining the evidence you found that caused you to arrange the layers as you did. While “dissecting” these layers they should note what species, and how many of each, they find. From this they can try to figure out the age of each layer and thus the order the layers belong in. Students will use group data to defend their claims about which oceanic sediments layer are the oldest and youngest (Table 4). Follow up by linking this station with station 2 to discuss species richness and biodiversity, which, given time, could also be calculated for each layer.

**Summary**

The station rotation exercise presented here is an active, hands-on way to teach ecological concepts by teaching a variety of quantitative methods for sampling and investigating populations. Student
scientists learn how to use indirect sampling methods to estimate abundance, density, population size, age structure, species richness, biodiversity, and distribution, and then they learn to display population data appropriately. They learn about bias and random sampling. They practice “doing” science and analyzing results. Extensions are numerous and include lessons on classification keys and species identification, or doing a biodiversity blitz on your campus. All in all, it is fun, informative, easy – and interdisciplinary.

There are great opportunities for tying in research skills, math, and ELA classes (reading informational texts, arguing from evidence), as students learn to look at the bigger picture: Why are some species, like frogs, declining? How do limiting resources, climate change, or invasive species influence species abundance and diversity? And how do we know if a population is impacted at all?

**Supplemental Material**

- Teacher setup guides/answer keys/student handouts:
  - Teacher setup notes.docx
  - Station 1 – Mark recapture population size.pdf
  - Station 2 – SpRich Biodiversity.pdf
  - Station 3 – Owl pellets diet
  - Station 4 – Tree rings dall sheep age.pdf
  - Station 5 – Camera traps for abundance.pdf
  - Station 6 – Cores forams.pdf
- Cores printable.pdf
- Tree ring photos.doc
- Dall sheep age photos.doc
- Margay images camera trap lab.pptx

- Owl pellet bone chart.png
- UCAR sample tree cores

**Further Resources**

- Carolina Biological Supply Company, “Owl Pellet Food Webs” activity, https://www.carolina.com/teacher-resources/Interactive/owl-pellet-food-webs-a-model-of-energy-and-mass-transfer/tr46115.tr
- Cornell Lab of Ornithology, All About Birds (Online Guide to Birds and Bird Watching), https://www.allaboutbirds.org
- Owl Brand Discovery Kits, https://obdk.com
- Zooniverse, “Snapshot Grumeti,” https://www.zooniverse.org
- University of Minnesota Lion Center “Snapshot Safari,” https://doi.org/10.13020/5r00-8c56
- International Ocean Discovery Program, Joides Resolution, https://joidesresolution.org
- Wildsumaco Biological Station, http://wildsumacobio.org/welcome

**References**

Cleland, E.E. (2011). Biodiversity and ecosystem stability. *Nature Education Knowledge*, 3(10), 14.

Davis-Berg, E. & Jordan, D. (2018). The innovative use of mathematica to teach biodiversity. *American Biology Teacher*, 80, 372–378.
DeMarco, G. (2009). Seafloor fossils provide clues on climate change. Green@Rensselaer, Rensselaer Polytechnic Institute, Troy, NY.

Kormondy, E. (1996). Concepts of Ecology, 4th ed. Prentice Hall, NJ: Pearson Education.

Kramer, M. (2013). How old is that lion? A guide to aging animals. National Geographic, July 30. https://news.nationalgeographic.com/news/2013/07/130730-aging-animals-fish-cats-science-primate-oldest-animal-clam/.

Murphy, E.C. & Whitten, K.R. (1976). Dall sheep demography in McKinley Park and a reevaluation of Murie’s data. Journal of Wildlife Management, 40, 597–609.

Paterno, J., Calvo, L., Jordan, R. & Bushek, D. (2017). Activity: One Fish, Two Fish – assessing the habitat value of restored oyster reefs. Current: The Journal of Marine Education, 31(1).

Raven, P.H., Johnson, G.B., Mason, K.A., Losos, J.B. & Singer, S.R. (2014). Population demography and dynamics. In Biology, 10th ed. (AP ed.). New York, NY: McGraw-Hill.

Ricklefs, R.E. (1990). The estimation of population size is critical to the study of population dynamics. In Ecology (3rd ed.). New York, NY: W.H. Freeman.

Shertz, K. (n.d.) Teaching A.P. Science – owl pellet dissection – trophic pyramid and energy loss. https://teachingapscience.com (accessed April 11, 2019).

Vanderhoff, N., Hodge, A.M., Arbogast, B. & Knowles, T. (2011). Abundance and activity patterns of the margay (Leopardus wiedii) at a mid-elevation site in the eastern Andes of Ecuador. Mastozoologia Neotropical, 18, 271–279.

Wetmore, K. (2017). Foram facts: an introduction to Foraminifera. University of California, Berkeley. http://www.ucmp.berkeley.edu/fosrec/Wetmore.html.

LISA A. PIKE is an Associate Professor of Biology at Francis Marion University, Florence, SC 29506; e-mail: LPike@fmarion.edu.