Predicting Patterns & Testing Predictions Using a Biogeography Lesson

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Abstract
Generating ideas and then testing predictions are important parts of the scientific process. In this laboratory exercise, I begin by challenging students to think about the reasons that the number of species on an island will increase or decrease. In small groups, students discuss how species richness changes over time and how rates of extinction and colonization will change depending on island size, distance from the mainland, and number of species already on the island. Students will make and test predictions using model islands and bean “species” only after they have come up with their own ideas of how species number changes over time and made predictions in the form of a graph. Last, students go outside and test the effect of area on the number of species found on a nonisland “island” (such as a wooded patch between sidewalks). This quick exercise allows students to differentiate between hypotheses and predictions and introduces such terms as sample size and replication while allowing for discussions about when the data don’t always match predictions.

Key Words: population biology; conservation; ecology; biogeography; ecology; AP environmental science.

Introduction
This year I skipped my standard description of island biogeography theory, where I “tell” students the patterns that island biogeography predicts, do a short activity to “prove” it, and, utilizing guided discussion, ask them to think about why different localities support different numbers of animal or plant species. Narrowing it down, I asked the students to list factors that can lead to the number of species on an island changing. We generated ideas first and did the activity second. I propose that helping the students come up with the theory on their own, and then doing the activity to test their own predictions, will cement the now iconic theory into their frame of learning.

I did this in response to an article I read in Nature, one that resonated with me, where the author stated, “Biological theory must generate ideas as well as data” (Nurse, 2021). It isn’t all about the data, Nurse claims—ideas are useful, and theorizing should be encouraged as a way to integrate knowledge, frame the big picture, and show why the data are being collected. Ideas change as evidence is collected, and it is important for students to see this. Here, I start by having students generate their own ideas and predictions, then they graph what they believe the pattern of number of species versus area, and then distance, should be, and only then do we do some follow-up activities with data collection to see if their predictions were correct. This helps students understand how scientists think and reason (Rafanelli & Osborne, 2020).

What Is Island Biogeography Theory?
In 1963 ecologists Robert MacArthur and E. O. Wilson first presented their theory describing the interplay between immigration, or colonization, rates (adding species) and local extinction rates (subtracting species), which results in an equilibrium number of species on an island. Colonization rates are high when islands contain few species, and nearly every species that encounters the island is “new”; conversely, extinction rates are low when there are few species, because each species has enough space and resources to survive (competition is low), and there just aren’t that many to go extinct. As islands become more populated, colonization rates decline (any new individual that encounters the island is likely already represented on the island by other individuals) and extinction rates increase (as populations become smaller and competition more intense). Imagining this on a graph (Figure 1) you see an X shape, and the point where the two lines cross is the equilibrium point. Though MacArthur and Wilson didn’t test these predictions (testing was done later, in 1969), their work was important because they developed a mathematical equation to enable them to predict species richness in a particular place, and they recognized that there were factors other than speciation that would increase the number of species on an island. In fact, they thought the equilibrium number of species on an island would be reached much sooner than could be explained by speciation or evolution alone. Colonization was a key part of their theory. They also recognized that there would be turnover, that the actual species may change over time, but that the number of species would remain relatively constant, at an equilibrium.

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MacArthur and Wilson proposed that larger islands would have a greater biodiversity at equilibrium (indicated by the total number of species found on the island) than smaller islands if the two islands were of equal distance from a source population (the mainland). They also generalized that if there were two islands of equal size, the island closer to the mainland source would have a greater biodiversity. These patterns hold true because of differences in colonization rates and extinction rates, with larger and closer islands having greater colonization (they are easier to find) and smaller islands having higher extinction rates (because of their necessarily smaller population sizes).

MacArthur and Wilson’s iconic graph (Figure 2) where a decrease in colonization rates and an increase in extinction rates is plotted against the number of species present on an island, and effects of island size and distance are accounted for, is the result of their “thought experiment” and is prominent in most introductory biology and ecology classes—classes where the theory is described and then students test the theory by a variety of means, sometimes going into the field to count number of species in plots of different sizes, or in the classroom by throwing beans or erasers at “islands.” However, it is more beneficial to have students puzzle out and construct their own graph themselves first, as MacArthur and Wilson did—they will generate ideas and, in doing so, practice the brainstorming and collaboration and consensus building that is common in actual science laboratories and educational facilities all over the world. This is scientific reasoning at its best—students demonstrate their own understanding of the implications of a scientific idea by developing their own explanations, and then they test their idea in a variety of ways. It is another way of doing science, one that may not start out with the traditional scientific method of hypothesis-forming first, and it can demonstrate how biologists think and reason. Rafanelli and Osborne (2020) outline six styles of reasoning in biology, including evolutionary reasoning, which our students use when they evaluate complex island ecosystems and the changes that occur over time; hypothetical modeling and probabilistic reasoning, when students develop hypothetical models and predict how the number of species will change with distance or size; and mathematical deduction, when they analyze their data from the activities presented here.

MacArthur and Wilson published their theory and mathematical equation without testing it right away, though they fit their equation to some previously collected data sets. Later, Simberloff and Wilson (1969, 1970) did some extensive testing of the theory on small mangrove islands off the coast of Florida by wiping out arthropod populations and recording subsequent recolonization. Jared Diamond further refined the theory when he estimated turnover rates for birds in the Channel Islands and found that while some species left the islands, other species colonized, leaving a stable equilibrium (Diamond, 1969; Jones and Diamond, 1976). Brown (1971) did the same with analogous nonislands, the isolated montane forests on mountaintops, where mammal species’ turnover was found to be inversely related to “island” size and to distance from a source population. Wright confirmed this on islands in a freshwater lake in Panama, at least for birds.

Other researchers continued to test the theory: Power, in 1976, discovered that habitat complexity was a very important predictor of the number of bird species found on islands off California, in fact more so than island size—and he thought that habitat complexity (and perhaps altitude) should be included in the calculation of the equilibrium number of species. Lomolino and colleagues (1989), again looking at land islands on top of mountains, found that when something disrupts the normal equilibrium between immigration and extinction, the number of species will “relax” back to the equilibrium when the disruption is removed.

Scientists use island biogeography theory to predict biodiversity, which is an indicator of the health of an ecosystem. Ecosystems with higher biodiversity numbers tend to be more resilient and recover better if there is a natural disaster. And since this theory applies to nonislands as well, for example state parks, national wilderness areas, prairie potholes, mountaintop cloud forests, and so on, it has been used widely to help conservation biologists design and size protected areas so that parks and preserves more effectively maintain populations of threatened or endangered species. Some species have large home ranges, and a park large enough to hold many individuals isn’t feasible because of space, finances, or staffing—but several smaller parks might work, particularly if they were connected. Smaller parks...
with connections to others have greater amounts of “edge,” which can be an important habitat. This is the SLOSS debate—a single large preserve, or several smaller ones, which is better? This gives a real-world application to what the students are learning. And, sizing a park correctly for the number of species you want to protect is important—once you hit that number you don’t need to make the protected area any larger to get the same benefit (thus saving money). As the protected area gets larger, you may not see a corresponding increase in number of species, as there is, in effect, a carrying capacity—the equilibrium number of species an area can hold.

Table 1. Eight targeted questions to jump-start student idea generation.

| Think-Pair-Share Questions | Sample Student Answers/Reasoning |
|-----------------------------|----------------------------------|
| 1 What causes a population (a group belonging to one species, in one place at one time) to increase in number/size? To decrease? | • Reproduction can increase how many there are, if more are being born. But if more are dying than being born, then the population will get smaller. • If someone moves into the area (immigration) [it could cause a decrease]. |
| 2 How does the number of species on the Earth change over time? | • I think the number is the same until a species goes extinct. A lot of species are going extinct. • Sometimes a new species is discovered. Or, on an island, a new species could immigrate or be blown in by a hurricane, or arrive in a shipwreck or something. • It would be the same on an island as the whole Earth. Earth is like one big island. • There are more species on Earth now than when life was created—the number increases over time. • Species could go extinct, and that would cause the number to decrease. |
| 3 How do plants and animals colonize (immigrate to) a newly formed island? How does the rate of colonization change as more species find the island? Graphically, how would this look? Use # species on the x-axis and rate of colonization on the y-axis. | • New species can come onto the island, like they could fly there or be washed there from a storm. That’s an increase. • Plants have seeds, which can float or the wind can blow them, and they could arrive on an island that way. • When the island is new or empty, just about anything that finds the island is a new species. But after some time, it’s harder to find new species, so colonization doesn’t happen as much. |
| 4 What causes island plants or animals to go extinct? How does the rate of extinction change as the number of species living on the island gets higher? Graphically, how would this look? Use # species on the x-axis and rate of extinction on the y-axis. | • If there aren’t enough resources, or there is a disaster, like a hurricane, a species could go extinct. • When a population gets too small, like from overhunting, it goes extinct. • Sometimes a species from somewhere else takes over and drives the native species out. • I think when there aren’t many species on the island, extinction would be lower, because there would still be enough resources for everyone. But with a lot of species, there’d be competition, and some species wouldn’t make it. |
| 5 If I had two islands, one large and one small (both the same distance from the mainland), would size make a difference in how many species the island could hold—how? What about the number of individuals within a population/species—does that change based on island size? | • I think a smaller island would hold less animals. And less species. There isn’t enough room for all of them. • If I had less space, then my population couldn’t be very big. I think there wouldn’t be enough food for them. Or space. |
| 6 How would the size of the island affect the rate of extinction? | • A species would disappear faster, go extinct, if there weren’t very many of them. So, the smaller island has higher extinction rates. |
| 7 If I had two equally sized islands, with one close to a mainland and one farther distant, would one island have more species? Which one? Why? | • Oh, the close one—it would be way easier for species to get to the close island. |
| 8 How would the distance of the island from the mainland affect the rate of colonization? | • If it is close, it would be easy to see from the mainland, and easier to get to and find it. |
The Two-Day Lesson Begins with Idea Generation

The activities that follow idea generation are modified from activities used in the Advanced Placement Environmental Science classes and are aligned with the NGSS Performance expectations MS-LS2 and 4, NGSS HS-LS2-2 and 6, and the NGSS Disciplinary Core Idea LS2 (Ecosystems: Interactions, Energy, and Dynamics). While I use the activities in high school and college classes, they can be used for middle school students as well. These activities are done over two days, where on day one I begin with targeted questions (Table 1) and have students first think-pair-share and then form groups of four to find consensus. Students begin to graphically display their ideas (Figure 3), and, last, we do a simple biogeography activity where a poster with a mainland and four islands (small and near, small and far, large and near, large and far) is placed on the ground and 50 bean “species” are dropped over the mainland (Figures 4 and 5).

Figure 3. Students graph their ideas about colonization and extinction rates on islands.

Figure 4. The poster islands for testing rates of colonization predictions.

Figure 5. Students drop bean “species” onto the poster islands to determine which islands are more likely to have high colonization rates.
The beans represent the likelihood of a species colonizing the island (Table 2), and the patterns we see usually hold up to the student-generated ideas that more distant islands and smaller islands will have fewer species colonize. As an extension, time permitting, I also introduce different materials to drop (for example, beans for birds, cotton balls for mammals, clothespins for amphibians, and popcorn seeds for insects) showing that different types of animals have different abilities to immigrate—birds can fly long distances, but mammals usually don’t get to the far islands, thus a nonbouncing material like a cotton ball works well to represent mammals. Again, we use class discussion to decide what material represents what type of animal, and why. On day two, we go outside and count the number of tree species within consecutively larger quadrats, then graph a species richness versus area curve.

My campus has a wooded area, so we count tree species in a one-meter square quadrat first, moving up to 16-meter square quadrats for the largest sample (Table 3). Without woods, this can be done in a grassy area, using smaller quadrats and looking at types of grasses and weeds.

Another extension is a computer simulation from East Tennessee State University that can be done to reinforce and extend their analysis of how latitude affects species richness on islands. This simulation is a stand-alone exercise where students design an experiment looking at two islands. They compare island size (diameter) and distance from a mainland, and they also alter habitat type (varying from tropical to tundra, including desert) and taxon (either birds, reptiles, mammals, or arthropods). Computer-generated data displays the average number of species on each island. This exercise reinforces past lectures on experimental design, specifically ensuring there is only one independent variable, and the rest are controlled variables. If a student selects to test island size, for example, then the hypothesis should describe the relationship between two variables (size and number of species) and the student should keep island distance constant. But what if they don’t? Is it a fair test? It is an opportunity for the class to discuss hypotheses and experimental designs made by their peers and to critique. It also allows students to predict differences if the island was tropical versus temperate (or if the taxon was birds versus mammals), to explain the basis for their prediction, and then to generate data to make a conclusion and defend, or reject, their claim.

These exercises allow students to use many types of scientific reasoning to come up with their own ideas which they can then test. Coming up with ideas is an important step, sometimes skipped when time is short and cookbook labs with known answers are easily available. Taking the time to generate ideas and construct explanations is part of this lesson, as is mathematical thinking as students demonstrate an understanding of biodiversity and factors that affect species richness. Also a part of the lesson is the chance to reconsider and revise ideas when their tests sometimes don’t match their predictions. For example, often students expect to see the species richness continue to increase as habitat size increases; instead it comes to an equilibrium number and, graphically, levels out, providing an opportunity to discuss with students what happens when their predictions are incorrect, and that it is ok and still good science, even if their hypotheses and predictions aren’t supported. The data on colonization rates generally work out as MacArthur and Wilson predicted, although sometimes the numbers for the large/far and small/near islands (the middle of the island biogeography graph) are flip-flopped. Why is this? Just random chance—which reiterates the importance of doing the poster island exercise multiple times, with multiple groups, and collecting class data that can be averaged. It is a good time to discuss the importance of replicates and outliers.

Table 2. Sample data from the “Poster Islands” biogeography activity. Students had three replicates and averaged the results to get the means shown here. Beans that landed on the ocean/island boundary were counted as long as at least half the bean were on the island.

| Lab Group | Yellow (Large/Far) | Green (Large/Near) | Blue (Small/Far) | Red (Small/Near) |
|-----------|-------------------|--------------------|-----------------|-----------------|
| 1         | 1.3               | 3.0                | 0.30            | 1.50            |
| 2         | 1.0               | 2.3                | 0.30            | 1.00            |
| 3         | 1.3               | 4.0                | 1.30            | 0.67            |
| 4         | 2.0               | 4.7                | 1.10            | 0.75            |
| 5         | 1.8               | 3.9                | 0.75            | 1.20            |
| 6         | 1.5               | 4.0                | 1.10            | 0.60            |
| Mean      | 1.48              | 3.65               | 0.80            | 0.95            |

Table 3. Sample data for the field component, counting trees in successively larger quadrats. Students graph a species richness versus area curve from this data.

| Quadrat #  | Area (m²) | Number of Species (inclusive) |
|------------|-----------|-------------------------------|
| 1 (2 × 2 m)| 4         | 1                             |
| 2 (4 × 4 m)| 16        | 3                             |
| 3 (8 × 8 m)| 64        | 6                             |
| 4 (12 × 12 m) | 144    | 8                             |
| 5 (16 × 16 m) | 256    | 9                             |

○ Assessment

Along with the worksheet that students complete as we go through the exercise (Supplemental Material available with the online version of this article), I assess by having students research an endangered species and design a mixed-use nature preserve, using the species’ habitat requirements and island biogeography theory to decide on factors such as size and shape of the preserve, and where to locate the minimum of 20% land set aside for human nature-based activities. Students make a poster, and we do a gallery walk and critique. This allows us to talk about the classic debate between a single large preserve or several smaller preserves (that may or may not include connections such as wildlife corridors) and about habitat requirements of local endangered species.

Students enjoy both the consensus building (student Lucie says it is a form of “winning” if their idea “reigns supreme”) and the activities. I admit that doing the outside part in good weather is important as rainy season mosquitos generally have the students rushing to finish so they can go back in, and sometimes there is a little screaming if there are spider webs—but to be honest, for all the screaming, students are ready to go back out and do it again as a welcome break from the classroom and a chance to be able to scream at a bug and not get reprimanded for a lack of volume control.
**Supplemental Material**

Supplemental Material is available with the online version of this article:
- Student biogeography worksheet
- Teacher resource with answer key
- Worksheet for virtual computer simulation
- Design a Nature Preserve poster assignment (with scoring rubric)
- A PowerPoint slide, scaled to size (26 × 35 inches) for printing the island poster

**Additional Resource**

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