From Ants to Grizzlies: A General Rule for Saving Biodiversity

hhmi | BioInteractive

Film Activity
Educator Materials

OVERVIEW

The short film *From Ants to Grizzlies: A General Rule for Saving Biodiversity* explores the species-area relationship — a general ecological principle, or "rule," that describes how the number of species in a habitat changes with area — and demonstrates how this knowledge has been applied to the conservation of protected areas. The film highlights the work of several scientists, including Edward Wilson and Daniel Simberloff, who tested the species-area relationship on mangrove islands; Kellen Gilbert, who studied how this relationship applies to forest fragments in the Amazon; and Jodi Hilty and Whisper Camel-Means, who are working to connect the fragmented habitats of large mammals.

This document contains multiple resources for using the film with students, including the following (click links to go directly to each section in the document):

- specific pause points for the film with content summaries and discussion questions
- general teaching tips and discussion points for the film
- an answer key for the accompanying "Student Handout"
- an appendix that provides more background on the science in the film

Additional information related to pedagogy and implementation can be found on this resource's webpage, including suggested audience, estimated time, and curriculum connections.

KEY CONCEPTS

- The species-area relationship describes how the number of species that can be supported by a habitat increases as the area of the habitat increases.
- If the area of a habitat does not change, the (equilibrium) *number* of species in that habitat will remain stable in the long term. However, the *types* of species may vary over time.
- Many human activities are reducing the areas of natural habitats, which decreases the number of species they can support.
- Connecting habitats — for example, by using wildlife corridors or crossing structures — can increase their overall area, which increases the number of species that these habitats can support.
- Mathematical models can be used to describe, analyze, and project patterns in nature.

STUDENT LEARNING TARGETS

- Describe the species-area relationship and its implications for biodiversity.
- Apply the species-area relationship to both islands and fragmented habitats.
- Explain the role of wildlife corridors and crossing structures in supporting biodiversity.
- Interpret graphs and equations to make claims based on evidence.

PRIOR KNOWLEDGE

Students should be familiar with:

- basic concepts of biodiversity and habitat fragmentation
- interpreting scatterplots and lines of best fit, including those with logarithmic scales

For the "Extension" only, students should also be familiar with:

- working with basic algebraic expressions, including simplifying expressions with variables

PAUSE POINTS

The film may be viewed in its entirety or paused at specific points to give students an opportunity to ask questions, construct explanations, and make predictions. The table below lists suggested pause points, including the beginning and end times in minutes in the film.

Before starting the film, you may also ask students the following questions. (Some questions are also included in the "Student Handout."):

- What is a habitat?
- What are some specific examples of habitats that you know about?
- What do you think determines the number of species in a habitat?
- Why would we care about the number of species in a habitat?

	Begin	End	Content Description	Discussion Questions
1	0:00	1:15	• Human activities are making many natural habitats smaller and more fragmented (broken up into smaller areas). • These changes make it harder for wildlife to survive.	• What is "biodiversity"? • What is meant by habitats becoming "fragmented"? Which human activities make habitats more fragmented? • What are some ways we could "protect the wildlife and wild places that remain"?
2	1:16	3:46	• Edward Wilson's work played an important role in conservation. As a child, he was fascinated by insects. • In 1955, Wilson started surveying the types and numbers of ant species on South Pacific islands.	• What inspired Wilson to study insects? Do you have any personal experiences that inspired you to learn about something in science? • Why do you think different islands have different types and numbers of species?
3	3:47	4:37	• Wilson observed a relationship between the number of species on an island and its area. An island that was 10 times larger had about twice as many species. • This relationship applied to both the ant species Wilson studied (graph at 3:55) and to reptiles and amphibians on other islands (graph at 4:10). (Both graphs use logarithmic scales.)	• Summarize the species-area relationship that Wilson described. • Explain the parts of the graph shown at 3:55. What do the dots and the blue line represent? Are the numbers on the axes what you expect? Why do you think the data are shown this way? • How could you determine that the species-area relationship is indeed a general relationship? What other tests or experiments could you do to confirm this?
4	4:38	6:22	• Wilson predicted that if all species were removed from an island, the same number of species would eventually repopulate it (assuming that the island's area did not change).	• What did Wilson predict would happen on Krakatoa? How did he reach this prediction from the species-area relationship? • What is meant by the terms "repopulate" and "colonize"?

			• Wilson tested his predictions with data from the island of Krakatoa. Bird species on Krakatoa were removed by a volcanic eruption. They repopulated over time in a way consistent with his predictions.	• Wilson wanted to test the species-area relationship in a more controlled experiment. Propose such an experiment. What type of habitat could you use to conduct this experiment?
5	6:23	8:31	• Wilson and his student, Daniel Simberloff, replicated what had happened on Krakatoa by fumigating mangrove islands, which killed all the insect species. • Over time, the islands were repopulated by similar numbers, but different types, of insect species as before fumigation. • Simberloff decreased the areas of some islands by sawing off mangrove tree limbs. The number of species decreased with area, as predicted by the species-area relationship.	• How did the fumigation experiments support the species-area relationship? • How did Simberloff's experiment with the sawed-off mangrove trees support the species-area relationship? • Wilson thought these experiments had "big implications." What do you think these implications could be?
6	8:32	11:01	• Research in the Amazon rainforest showed that habitat fragments on land function similarly to islands. • Kellen Gilbert, a scientist involved in this research, found that larger animal species with large ranges, such as monkeys, are more strongly affected by fragmentation.	• What is a habitat fragment, and how is it similar to an island? • Describe the Amazon experiment. How did its findings support or expand knowledge about the species-area relationship? • What kinds of species are more strongly affected by habitat fragmentation? Why?
7	11:02	13:07	• Protected areas are often too small for animals with large ranges to thrive. However, smaller protected areas can be connected to create larger ones. • The Yellowstone to Yukon Conservation Initiative (Y2Y), led by Jodi Hilty, helps protect and connect habitats in northwestern North America. • Wildlife corridors are one way of connecting fragmented habitats.	• Why do you think larger animals, such as wolves, need more "room to roam" (that is, have larger ranges)? • What is Y2Y, and what is its goal? • What is a wildlife corridor? Explain why it works based on the species-area relationship.
8	13:08	18:05	• Habitats can also be connected using wildlife crossing structures, such as overpasses and underpasses. • Crossing structures are researched and monitored by biologists such as Whisper Camel-Means, who works for the Confederated Salish and Kootenai Tribes.	• What is a "wildlife crossing structure"? Explain why it works based on the species-area relationship. • Camel-Means describes the wildlife crossing project as a "mix of science, politics, and tribal culture values." How did science, government, and

				culture each contribute to this project? • How might science, government, and culture contribute to other projects that you're familiar with?

BACKGROUND

The first part of the *Ants to Grizzlies* film focuses on the species-area relationship, which is a foundational part of island biogeography. **Island biogeography** is a theory and associated research area that examines factors affecting the numbers and types of species on islands. This includes not just literal islands surrounded by water but *any* isolated habitats — whether they are surrounded by ocean, mountains, deserts, or even cities and agricultural lands.

Many findings from island biogeography theory have been used to conserve habitats fragmented by human development. Later parts of the film show how island biogeography has been applied to, and advanced by, forest fragmentation research in the Amazon and the conservation of protected areas in the northwestern United States.

Additional background on island biogeography is provided in the appendix at the end of this document.

TEACHING TIPS

- Consider the following ways to **increase accessibility** for students:
  - Turn on closed captioning while playing the film. Captions are available in English, Spanish, and Auto-translate on YouTube.
  - Provide copies of the transcript, which can be downloaded from the film's webpage.
  - Use an audio descriptive version of the film if needed.
- Encourage students to **apply the concepts in the film to their personal contexts**.
  - For example, students could consider parks (or other spaces with wild animals) in their own neighborhoods, cities, etc. They could think about whether these parks are connected or are separated by roads, parking lots, buildings, etc., and how this might affect the number of species.
- **Provide context for the locations** mentioned in the film. For example, you could present a map of these major places:
  - Melanesia in the South Pacific (the site of Wilson's ant studies)
  - Krakatoa in Indonesia
  - The Florida Keys in the United States
  - The Amazon in northern South America (the research in the film took place near Manaus, Brazil)
  - The Yellowstone and Yukon regions in northwestern North America
- Help students learn **key vocabulary** from the film, including terms that may be unfamiliar in a scientific context, using strategies such as the following:
  - Provide students with a short list of specific terms they will be expected to know for your class (if any). Terms in the film include biodiversity, habitat, fragment/fragmented, conservation, repopulate, colonize, fumigate, replication, and hypothesis.
  - Have students define the key terms in their own words and create related sentences, images, etc. They can do this by making their own vocabulary cards or by using a graphic organizer.
  - Create a "word wall" for the key terms. This is a collection of vocabulary terms in a visible place, such as on a classroom wall, to which students may refer or add new terms.

DISCUSSION POINTS

Connecting to Students' Contexts

- The film shows multiple examples of scientists making **personal connections** to what they are studying or working on. These examples can be used as opportunities for students to reflect on and discuss their own personal connections to science, and how science is relevant to their interests, lives, and society in general.
  - Early in the film, for example, Edward Wilson tells the story of how he became interested in studying insects after a childhood accident. You may ask students to share experiences that have inspired or motivated them to learn about something in science.
- Near the end of the film, Whisper Camel-Means describes her work as a "mix of science, politics, and tribal culture values." Ask students to share their own examples of how science, politics, and culture have contributed to something they are interested in or are learning about. They can also discuss how they think culture and political ideas influence science and vice versa.

Graph Interpretation

- The film presents several graphs showing examples of the **species-area relationship**. You can pause the film at these points, then have students analyze and interpret these graphs to demonstrate their understanding of the species-area relationship.
  - Timestamps for these graphs are as follows. Each graph is also provided, with references, in the appendix at the end of this document.
    - **3:55** shows ant species. Appears in the appendix as Figure 1a.
    - **4:10** shows reptile and amphibian species. Appears in the appendix as Figure 1b.
    - **8:05** shows Simberloff's mangrove experiment. Appears in the appendix as Figure 2.
  - All of these graphs are **log-log plots**, meaning that they use logarithmic scales on both axes. If students are unfamiliar with logarithms or interpreting log-log graphs, consider discussing them as a class.
    - Students may have the misconception that the species-area relationship is linear because it appears as a straight line on these graphs. If so, explain that the relationship is actually nonlinear, with species number increasing more slowly at larger areas. (As stated in the film, an island that was *10* times larger had *twice* as many species.)
    - Consider having students replot one or more of the graphs with linear axes for comparison. Straight lines on the log-log plots will appear curved on linear axes.
    - Ask students why the nonlinear nature of the species-area relationship makes it so important to have large areas for conserving more species. (Species number increases more slowly at larger areas, so the area needed to conserve a majority of species may be larger than expected.)

Science Practices

- The film demonstrates multiple types of science practices, including **observation, modeling, and experimentation**. This variety provides the opportunity to discuss the roles of different practices and how each can make important contributions to scientific research.
  - Students could reflect on how these approaches complement one another when trying to understand a phenomenon or solve a problem. For example, Wilson and colleagues used multiple approaches to study the species-area relationship:
    - They considered observational data on ants in the South Pacific, reptiles and amphibians in the West Indies, and birds from Krakatoa (a "natural" experiment where species were removed by a volcanic eruption).
    - They developed a mathematical model to describe the relationship.
    - They obtained experimental data from a controlled experiment in the Florida Keys.

- In particular, the film provides an opportunity to explore the importance of **mathematical modeling** in science. Although not explicitly mentioned in the film, modeling played a major role in the research shown.
  - Students may get the impression from the film that the data from Krakatoa and the Florida Keys were only used to confirm the existence of the species-area relationship. You may want to explain that these data were actually used to assess a mathematical model (not shown in the film) that Wilson and his colleagues developed to help explain the species-area relationship. More details about this model are provided in the appendix.
  - Consider asking students how scientists use mathematical models in general, why they might "test" certain models using experiments, and how models can be applied to answer questions or solve problems.
  - The "Extension" section of the "Student Handout" allows students to explore a mathematical description of the species-area relationship and its applications, as well as reflect on why mathematical equations can be useful for describing natural processes.

Specific Biological Concepts

- The species-area relationship is a foundational part of **island biogeography**; more details are provided in the appendix and the BioInteractive activity "Exploring Island Biogeography through Data." Although this film does not discuss island biogeography in detail, it can be used as an introduction to island biogeography and its applications.
- The film focuses on increasing the overall number of species, also known as **species richness**, as a strategy for protecting biodiversity and conserving wildlife. You may want to discuss the relationship between species richness and biodiversity, as well as what other factors should be considered in conservation.
  - Species richness is an indicator of biodiversity and an important metric to consider when determining the ecological health of a habitat. However, biodiversity is *not* equivalent to species richness, because metrics of biodiversity also account for the relative abundance of different species within a community. (A community with similar numbers of individuals among many species has higher biodiversity than a community dominated by individuals from one or two species. The latter community may be more vulnerable to habitat changes, as species with smaller populations are at higher risk of local extinction.)
  - In upper-level courses, students may be interested in learning about other methods for quantifying biodiversity, such as Simpson's diversity index and Shannon's diversity index.
- The film could provide an opportunity to discuss other consequences of **habitat fragmentation**.
  - One consequence that could be discussed in upper-level classes is edge effects. Fragmentation increases the proportion of edges to habitat area and can separate or isolate existing communities. When edges between habitats are natural, such as the transition between forest and meadow, species diversity may increase along the edges (as the edge itself can provide a different type of habitat that benefits some species). However, when the edges are created by habitat destruction and human development, species diversity tends to decrease along the edges. Conservationists are studying these edge effects and how they impact biodiversity.
  - The Scientists at Work film *Seed Dispersal and Habitat Fragmentation* shows how habitat fragmentation can affect seed dispersal in tropical forests.

STUDENT HANDOUT

The "Student Handout" is designed as a learning assessment that probes students' understanding of the key concepts addressed in the film. Part 1 of the handout should be used *before* the film to assess students' prior knowledge. You may modify the handout to better fit your learning objectives and your students' needs (e.g., changing which parts are done before or after the film, reducing the number of questions, adding more explanations of vocabulary, etc.).

ANSWER KEY

PART 1: Before the Film

1. The title of the film uses the phrase "saving biodiversity."
   a. Explain what biodiversity means in your own words.
   Student answers will vary based on prior knowledge. Depending on their answers, you may want to discuss the difference between biodiversity and species richness, as mentioned in the "Discussion Points" above.
   b. Why do you think saving biodiversity might be important? What are the benefits of biodiversity for wild ecosystems and human societies?
   Students may know that biodiversity is important for ecosystem function. More biodiverse ecosystems are often better at handling environmental stress and can provide more resources and services for humans. Students may also mention the intrinsic value of nature or future discoveries that would not be possible if species went extinct.
2. The start of the film will mention that, as human populations expand, habitats are shrinking and becoming more **fragmented**: broken into smaller, separated areas.
   a. Describe at least one specific way in which human activities or development are making habitats more fragmented.
   There are many possible answers. For example, humans directly reduce or divide up natural habitats by developing roads, cities, agricultural fields, etc. Humans can also indirectly fragment natural habitats by causing forest fires, pollution, climate change, etc.
   b. What do you think happens to wildlife when their habitats become more fragmented? How might these changes affect the biodiversity in a particular area?
   Student answers will vary based on prior knowledge; they will learn more about these ideas while watching the film.

PART 2: After the Film

3. Figure 1 uses a **logarithmic scale** on both axes of the graph.
   a. Carefully examine the axes and then describe what a logarithmic scale is.
   Student answers will depend on their familiarity with logarithmic scales. They may observe that equal intervals on an axis with a logarithmic scale do not represent equal differences in the numbers. For example, an interval on the higher end of the axis represents a larger increase than an interval of equal size on the lower end. Some students may recognize that each equal interval represents multiplication by a specific factor; for example, each subsequent interval on the x-axis of Figure 1 represents multiplication by 10. They may also realize that intervals on the logarithmic scale correspond to powers of 10 or another factor.

   (If students struggle with this question, provide them with additional support for understanding logarithmic scales and log-log plots, mentioned in the "Discussion Points" above.)
   b. Why do you think a logarithmic scale was chosen to show these data?
   A logarithmic scale is useful for showing data over a large range of values. In Figure 1, for example, the island areas range from less than 10 km^2 to around 100,000 km^2. It would be hard to show all of these data points together on a graph with a more typical linear scale, since the data points would be very far apart.
4. Fill in the following table with numerical values estimated from Figure 1.

Island	Area of island (km^2)	Number of reptile and amphibian species

Montserrat	***100***	***9***
Puerto Rico	***10,000***	***40***
Cuba	***100,000***	***70***

5. Complete the following statements based on Figure 1. Briefly support each answer with a specific example from the figure.
   Statement: An island that is about ***10*** times larger has about ***2*** times as many species.
   Example: ***Cuba is about 10 times larger than Puerto Rico. Cuba has about 70 species, which is about 2 times as many species as the 40 species on Puerto Rico.***

   Statement: An island that is about ***100*** times larger has about ***4*** times as many species.
   Example: ***Puerto Rico is about 100 times larger than Montserrat. Puerto Rico has about 40 species, which is about 4 times as many species as the 9 species on Montserrat.***
6. Imagine that 90% of Cuba's area became unsuitable for wildlife due to human activities. How many reptile and amphibian species would you expect to find in Cuba then? Support your answer with evidence from Figure 1.
   Answers may vary; be open to a range of reasonable responses. Students could say that, based on the pattern in Figure 1, an island that is 10 times larger has about twice as many species. So, if the suitable area of Cuba is reduced by a factor of 10, we'd expect the current number of species (70 species) to be reduced by a factor of 2, resulting in 35 species.

   Students could also argue that 10% of Cuba is about 10,000 km^2, which is similar to the area of Puerto Rico. If we assume that most of Puerto Rico's area is suitable for wildlife, 10% of Cuba could support around the same number of species as on Puerto Rico: 40 species.
7. Wilson and his colleagues compared their mathematical model of the species-area relationship to real data. They used data from the *natural* removal of species from the island of Krakatoa and an *experimental* removal of species from islands in the Florida Keys.
   a. Think about why the scientists decided to use both natural and experimental data. What are some advantages of natural data? What are some advantages of experimental data?
      Data from natural environments can indicate how biological principles operate under real environmental conditions. A natural event, like the volcanic eruption on Krakatoa, can show if a natural environment responds as you predicted (e.g., based on a controlled experiment or mathematical model).

      Obtaining data from experiments may give you more control over which variables are constant or changing, which makes it easier to study the specific variables you are interested in. Experimental data can also be obtained more quickly, since you don't have to find or wait for a specific type of event (like a volcanic eruption).
   b. Complete the following statement based on what happened in both the Krakatoa and the Florida Keys examples.
      Although the ***number*** of species on an island tends to stay the same, the ***type*** of species can change over time.
8. In 1979, scientists started an experiment in the Amazon to determine whether habitat fragments on land behaved like the islands studied by Wilson and his colleagues.
   a. How is a habitat fragment on land similar to an island in the ocean?
      Both are isolated from other habitats. Islands in the ocean are isolated by water. Habitat fragments on land are isolated by areas of human development, such as farms, roads, and towns.

b. The scientists in the Amazon found that certain types of species were more likely to be lost from small habitat fragments. According to the film, which types of species were more likely to be lost, and why?
Larger species with larger range requirements were more likely to be lost, because the fragments were too small to support the resources and space they needed to survive.

c. Kellen Gilbert, one of the scientists in the film, and her colleagues have found that monkey species with a higher proportion of fruit in their diet are rarer in smaller fragments, possibly because it's harder to find enough fruit in smaller areas. Describe **two** other things that could be difficult for a species to find or do in a smaller area, which could cause the species to disappear from that area.
There are many possible answers. For example, in a smaller area, it could be harder to find enough food/prey, water, shelter, and other resources to survive. Based on their prior knowledge, students may also mention more conflicts over territory, increased inbreeding, smaller population sizes that are more vulnerable to extinction, etc.

9. Fill in the following table to describe two of the strategies presented in the film.

Strategy	What is it?	How does it help conserve species?
wildlife corridor	***a large, continuous wild area through which animals can move***	***It connects fragmented habitats and gives animals access to a larger overall area.***
wildlife crossing structure	***a structure built over or under a road to help animals cross safely***	***Similar to a wildlife corridor, it connects fragmented habitats. It also reduces the risk of animals being hit and killed by cars.***

10. Explain why the very large size of the Y2Y corridor is important. Support your answer using evidence from the research done in the Amazon.
Research from the Amazon showed that large animals with large range requirements often cannot survive in small areas. Many animals in the Y2Y region, such as wolves and bears, are large and have large range requirements. So, it's important for the Y2Y corridor to be very large in order to have enough resources and space to support these kinds of animals.

11. Think of a habitat *not* mentioned in the film that is fragmented by human development, maybe one you have learned about or are personally familiar with. Propose a specific way to help conserve the species in this habitat, based on what you learned from the film.
Student answers will vary; be open to a range of reasonable responses. Ideally, students should apply concepts they have learned from the film, such as the species-area relationship, the importance of large areas for many species, and potentially also specific strategies such as wildlife corridors and crossing structures.

EXTENSION: Half-Earth and the Species-Area Relationship

1. Why might it be useful to describe natural processes and patterns, such as the species-area relationship, using mathematical equations?
There are many possible answers. For example, models can be used to investigate the factors involved in natural processes or patterns. Models can also be used to project the outcomes of different scenarios — for instance, what might happen to species under future environmental changes or management actions.

2. Without using the equation, what proportion of Earth's species would you expect to be supported by *half* of Earth's area?
Student answers will vary. They will revisit their prediction in Question 5.

3. Rewrite the right side of the equation to represent the number of species in *half* of Earth's area. (*Hint*: Remember that *A* represents the *total* area of Earth. How could you adjust *A* in the equation to represent *half* of Earth's area?)
   To represent half of Earth's area, students just need to change A to A/2. The equation is thus:

$$\text{number of species in half of Earth's area} = c\left(\frac{A}{2}\right)^{0.3}$$

4. Calculate what proportion of species on Earth would be supported by half its area. Round your answer to two decimal places. (*Hint:* You can use the equation below as a starting point. Fill in the numerator "?" with your answer from Question 3, then simplify the fraction. Neither *A* nor *c* should appear in your final answer.)
   Students can complete and simplify the equation as follows:

$$\begin{aligned}\text{proportion of species} &= \frac{\text{number of species in half of Earth's area}}{\text{total number of species on Earth}}\\ &= \frac{c\left(\frac{A}{2}\right)^{0.3}}{c(A)^{0.3}}\\ &= \frac{c(A)^{0.3}\left(\frac{1}{2}\right)^{0.3}}{c(A)^{0.3}}\\ &= \left(\frac{1}{2}\right)^{0.3}\end{aligned}$$

   The result is $(1/2)^{0.3}$, which can be rounded to 0.81.
5. Is your answer to Question 4 smaller, larger, or similar to what you expected in Question 2? Why do you think this is?
   Student answers will vary depending on their answer to Question 2. Some students may have expected only half the species to be supported by half of Earth's area, which is smaller than what is shown by the calculation (0.81 or 81%). If so, consider taking the opportunity to discuss the nonlinear nature of the species-area relationship.
6. Why do you think Wilson proposed saving half of Earth's area and not more?
   Student answers will vary. They may say that saving more than half of Earth's area would be unfeasible because human societies also need space, there might not be enough money or support for saving more, etc. They could also say that 81% of species may be enough to keep ecosystems functioning and saving more would have greater costs than benefits.

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APPENDIX: Additional Information on Island Biogeography

This appendix has the following sections:

The Species-Area Relationship

An early driving question in the study of island biogeography was how to explain the species-area relationship (called the "species-area rule" in the film): a pattern where the number of species on islands increases with island area. One of the scientists who observed this relationship was entomologist Edward Wilson (also known as E. O. Wilson), the first scientist introduced in the film and one of the founders of the theory of island biogeography. Wilson is also known for popularizing the term "biodiversity."

In 1955, Wilson began cataloging ant species on the South Pacific islands of Melanesia. As Wilson examined his data, he noted how the number of ant species on an island increased with the island's area (Figure 1a). Although it may seem intuitive that larger islands would support more species because they have more resources and habitats, this pattern was surprisingly nonlinear (an island that was *10* times larger typically had about *twice* as many species) and appeared across a broad range of organisms and locations. For example, Wilson's mentor, Philip Darlington, had found a similar relationship for West Indian reptiles and amphibians (Figure 1b).

This pattern, the species-area relationship, can be described by a power function:

$$S = cA^z$$

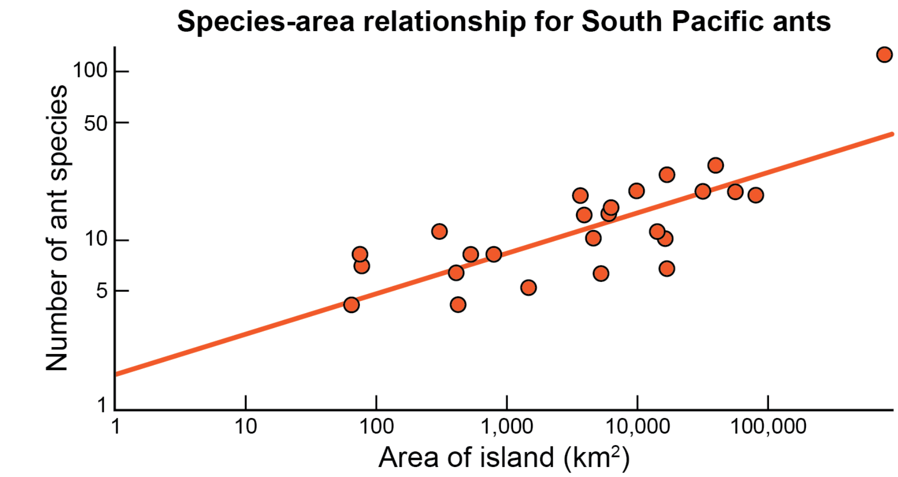
where *S* is the number of species, *A* is the area of the island, and *c* and *z* are constants fitted from the data. Both *c* and *z* may vary depending on the types of species and islands; *z* tends to vary less and typically ranges from around 0.2 to 0.4 (MacArthur and Wilson 1967).

Although the species-area relationship is nonlinear, it will appear linear when using logarithmic scales. This is because taking the logarithm of both sides of the function above gives a linear equation:

$$\log(S) = \log(c) + z\log(A)$$

Thus, plotting species (*S*) vs. area (*A*) on a log-log plot (a graph that uses logarithmic scales on both axes) will produce a straight line with the slope of *z,* as shown in both Figures 1a and 1b.

a



b

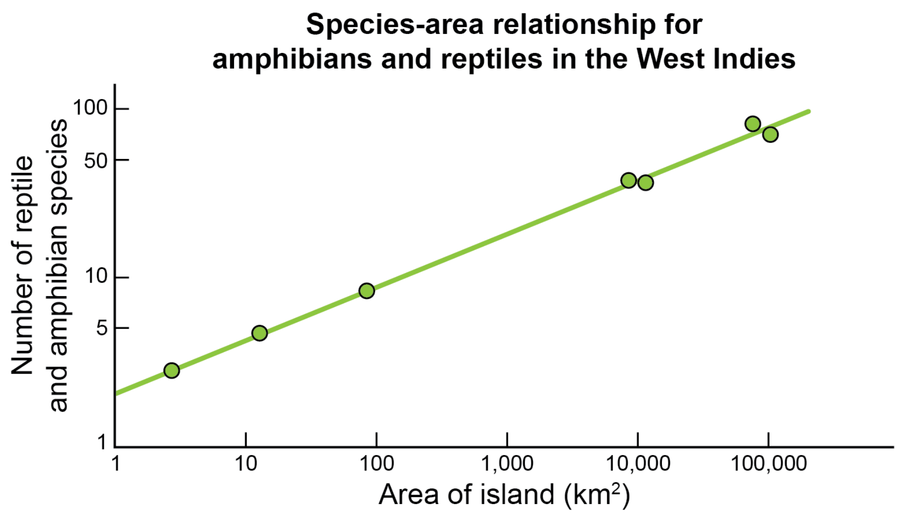


Figure 1. Species-area relationships for **(a)** ant species in the South Pacific (figure based on Wilson 1961; appears in the film at 3:55) and **(b)** reptile and amphibian species in the West Indies (original data from Darlington 1957, figure based on MacArthur and Wilson 1967; appears in the film at 4:10). Note that both graphs are log-log plots.

Based on the species-area relationship, if the area of an island does not change, the number of species on that island should be stable over time. Wilson and his colleague, mathematician Robert MacArthur, created a mathematical model to explain *how* an island can maintain a stable number of species, and *why* this number would depend on the island's area. Their model, the **dynamic equilibrium model**, became a cornerstone of island biogeography theory.

In brief, the model focuses on two major processes that affect the number of species on an island: immigration and (local) extinction. When a new species arrives on an island through **immigration**, it competes with the species already there for resources. Species that are outcompeted die out through local **extinction**. When the rates of immigration and extinction are equal, the total *number* of species remains stable (fluctuates around a constant number of species) and is at an **equilibrium**. Since the *types* of species can still change as new species move in or die out, this equilibrium is **dynamic**.

In the model, the equilibrium number of species on an island depends on immigration and extinction rates. These rates depend on two main features of the island: area and isolation.

- The effects of *area* on immigration and extinction cause the equilibrium number of species to increase with area, resulting in the **species-area relationship**.
- The effects of *isolation* on immigration and extinction cause the equilibrium number of species to decrease with an island's distance from a source pool of species. This is called the **distance effect**.

For a full explanation of the dynamic equilibrium model, as well as resources for unpacking this model with students, refer to the "Exploring Island Biogeography through Data" activity.

Testing the Model: Krakatoa and the Florida Keys

The dynamic equilibrium model can be used to predict the equilibrium number of species for an island — as well as how long it will take to reach equilibrium — based on factors such as the island's area and distance from the mainland.

MacArthur and Wilson compared predictions from the model to historical data from the volcanic island of Krakatoa (also called Krakatau) in Indonesia. An eruption in 1883 wiped out most of Krakatoa's species and destroyed much of its land. In the decades after the eruption, scientists recorded the bird species that repopulated the now-smaller island. The number of species that the island eventually returned to supporting, as well as the length of time it took to reach this number, were consistent with the predictions of the dynamic equilibrium model (MacArthur and Wilson 1963).

The model also predicted that once the island reached equilibrium, the *number* of species would remain stable, but the *types* of species would change over time. Again, this prediction was confirmed by the historical records: the number of bird species on Krakatoa stayed relatively constant for over a decade, with several old species being replaced by new species over time.

Krakatoa inspired Wilson to design an experiment to eliminate species from small islands, to see if they also returned to equilibrium in line with the model's predictions. In the 1960s, he found the ideal habitat for such an experiment: a set of tiny mangrove islands in the Florida Keys. These islands were very small, which meant they would reach equilibrium quickly, and they had mainly insect species, which could be easily eliminated through fumigation. (Since islands in this region are often struck by hurricanes, which also eliminate most insects, Wilson did not think the fumigations would cause long-term harm to the ecosystem.) After fumigation, new insects could immigrate to the empty islands by flying, riding on birds, arriving on driftwood, etc.

Wilson and his graduate student, Daniel Simberloff, worked with an exterminator to fumigate the mangrove islands. They then observed the insect species that repopulated the islands over time. Within eight months, most of the islands had reached an equilibrium species number in line with the predictions of the dynamic equilibrium model. The numbers of species on most of the islands held steady thereafter, and many of the species that repopulated the islands were different from the species observed before fumigation (Wilson and Simberloff 1969; Simberloff and Wilson 1969). The more remote islands took longer to reach equilibrium, and they had fewer species at equilibrium than less remote islands of similar size; this was consistent with the distance effect in the dynamic equilibrium model.

The dynamic equilibrium model also suggested that smaller islands would have fewer species at equilibrium (consistent with the species-area relationship). It was difficult to test this prediction with the islands selected for fumigation, as they did not significantly differ in area. So Simberloff undertook another experiment. He measured the number of species on several new mangrove islands, then reduced the areas of the islands by sawing off large sections of the mangrove trees. Several months after each island's area was reduced, the number of species on that island had also decreased (Figure 2), as predicted by the dynamic equilibrium model and species-area relationship.

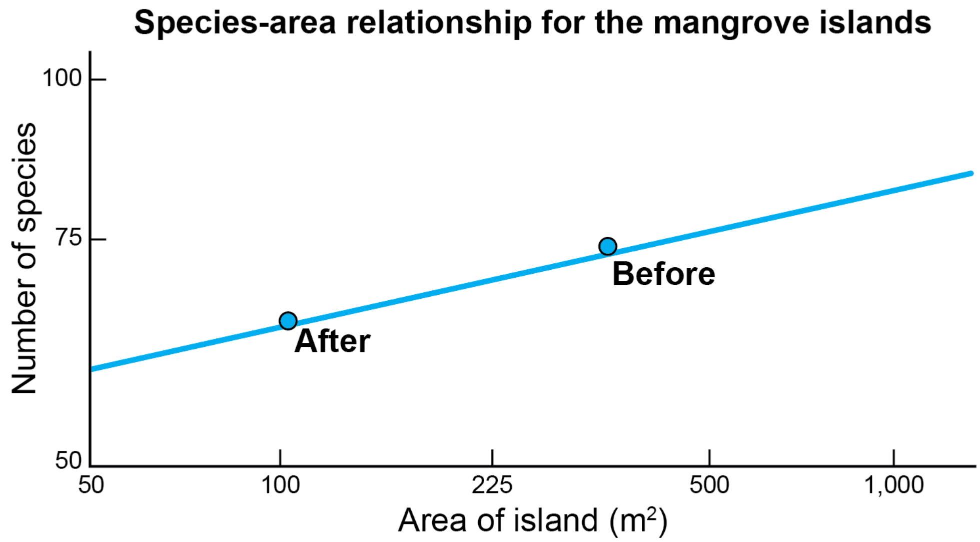


Figure 2. The species-area relationship for one island (CR1) in Simberloff's mangrove experiment (figure based on Simberloff 1976; appears in the film at 8:05).

Backed by both natural and experimental data, the dynamic equilibrium model became highly influential among ecologists. Its principles are now known as the theory of island biogeography and have sparked many new scientific discoveries and questions. One major question that emerged was whether the models and theories of island biogeography would also apply to habitats on land isolated by human activities and development, rather than by water.

For example, one of the largest ecosystems in the world, the Amazon rainforest, contains many "islands" of isolated forest patches. These patches, called **fragments**, are often created by ranchers and loggers cutting down trees. Do these forest fragments also follow principles from island biogeography?

To test this idea, scientists began one of the largest, longest-running projects in ecology: the **Biological Dynamics of Forest Fragments Project (BDFFP)**. This project has been ongoing since 1979 and spans about 1,000 square kilometers of the Amazon rainforest near Manaus, Brazil. Scientists in the BDFFP are closely monitoring 11 Amazon forest fragments of different areas (ranging from 1 to 100 hectares) at various distances from each other. The scientists have collected data on the species before and after the fragments were created, to see how the biodiversity has changed over time.

So far, this large collection of data has suggested several key patterns, many of which support principles from the theory of island biogeography. For example, both fragment area and remoteness seem to be critical factors in determining the total number of species that a fragment can support. Smaller, more remote fragments support fewer species. The species in these smaller, more remote fragments also have a greater risk of going locally extinct and no longer being found in the fragment (Hance 2011; Laurance et al. 2011; Stouffer et al. 2009).

One illustrative example comes from the work of anthropologist and primatologist Kellen Gilbert, one of the scientists in the film. Gilbert surveyed the six primate species that inhabit the BDFFP region and determined how many of these species lived in forest fragments of different areas. She and others have discovered that, as one might expect from island biogeography, smaller fragments have fewer primate species. However, the species that are absent from the smaller fragments are not random: they tend to be larger primates with high proportions of fruit in their diet. (This may be because fruit-eating primates need to roam large areas to consistently find available fruit, which changes seasonally.) The species that *do* live in the smaller fragments typically do not eat as much fruit and have smaller range requirements (Gilbert 2003; Boyle and Smith 2010).

Similar findings from other BDFFP research have supported the idea that certain species — in particular, larger animals with large range requirements — simply cannot thrive in small, isolated habitat fragments. These species may need a larger minimum area to obtain enough resources to survive. As a result, one large fragment of habitat may be able to support more species than multiple small, isolated fragments of similar total area. This is known as the "single large or several small" (SLOSS) debate in conservation.

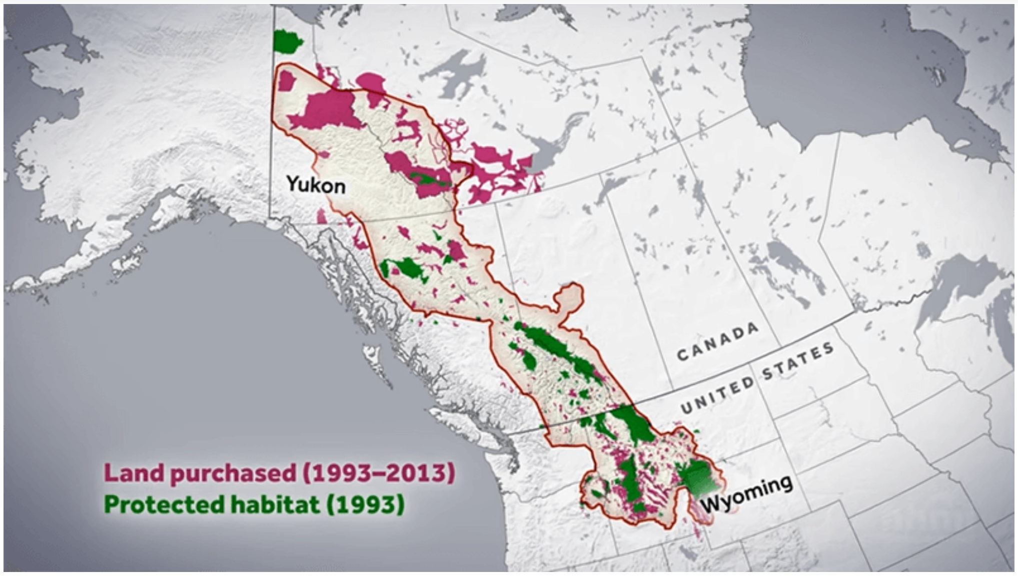
Conservation Applications: Corridor Ecology and Protected Areas

The lessons learned from island biogeography and the BDFFP have been put into practice by conservation scientists designing protected areas, such as wildlife reserves. These include reserves in the western United States and Canada, such as Yellowstone and Jasper national parks. These parks are home to many large species, such as grizzly bears and wolves, that are threatened by habitat fragmentation. As mentioned in the film, the natural ranges of these animals may extend hundreds of miles.

Based on findings from island biogeography and the BDFFP, one way to help these animals survive is to increase the overall area of their habitat. This is the goal of an organization called the Yellowstone to Yukon Conservation Initiative (Y2Y). Ecologist Jodi Hilty serves as president and chief scientist for Y2Y. As Hilty explains in the film, Y2Y is working to create a **wildlife corridor**, a large continuous area through which animals can travel safely, from the Yellowstone ecosystem in the south to the Greater Mackenzie Mountains of the Yukon (a territory in northwest Canada) in the north — an area that covers over 50,000 square miles (Figure 3a).

a

b



Hilty and her colleagues use the principles of **corridor ecology**, the study of ecological connectivity and corridors, to connect smaller habitat fragments — thereby creating larger continuous protected lands, effectively expanding the areas of suitable habitats, and ultimately increasing the number of species that these areas can support. Y2Y creates these connections by working with state and local governments to increase the protection of federal land, purchasing private land (Figure 3b), and working with landowners to create conservation easements and promote land management practices that support wildlife.

Another strategy for connecting fragmented areas involves helping wildlife cross roads, highways, and other areas of human development that separate natural habitats. Some species cannot easily cross roads, and others face the risk of getting hit by cars while crossing. **Wildlife crossings** are bridges (overpasses) and tunnels (underpasses) that are constructed to allow animals to safely cross roads and move freely between the habitats on different sides.

Whisper Camel-Means, a wildlife biologist for the Confederated Salish and Kootenai Tribes (CSKT) Wildlife Management Program, studies how animals use wildlife crossings on U.S. Highway 93 in Montana. As mentioned in the film, she is dedicated to upholding Tribal cultural values, which include allowing animals, and their energy, to safely flow across their native landscapes. Camel-Means uses motion-detecting camera traps to take photos of animals as they move through the crossings. She and her colleagues have found a substantial increase in animal movements across the highway, and a decrease in vehicle collisions with wildlife, after the construction of the crossings (Huijser et al. 2015).