OVERVIEW

In this Click & Learn, students explore mathematical models that describe how populations change over time and apply these models to the invasive lionfish population in the Bahamas. They also use data from other species to learn how density-dependent factors limit population size.

The Click & Learn includes realistic and actual data from lionfish and other case studies. It provides opportunities to use the logistic growth model, graph data, and interpret figures from published scientific research.

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

- Mathematical population models are used to study how populations of organisms, including invasive species, change over time.
- Discrete-time models describe how populations change over specific time periods.
- Continuous-time models describe populations that change instantaneously.
- Logistic models describe population growth that is limited by negative density-dependent factors. In a logistic model, the growth rate changes depending on the population's density.
- Negative density-dependent factors include competition, predation, disease and parasites, and social behaviors.

STUDENT LEARNING TARGETS

- Describe invasive species and their impacts on ecosystems.
- Define carrying capacity and explain how it relates to density-dependent population growth.
- Use discrete-time and continuous-time logistic equations to model population dynamics.
- Interpret data and graphs to describe how the population growth rate varies with population density in a logistic model.
- Compare realistic field data to projections from models.
- Use data from case studies to explain how various negative density-dependent factors regulate population size.

PRIOR KNOWLEDGE

Students should be familiar with:
- basic algebra
- reading and interpreting graphs (in particular, line graphs, bar graphs, and scatterplots)
- basic ecological interactions (in particular, competition, predation, parasitism, and cannibalism) and how these can influence birth and death rates

MATERIALS

- access to the Click & Learn
- (optional) copies of the "Student Worksheet" and "Case Study Handouts"

BACKGROUND

Density-dependent population dynamics

Understanding population dynamics is important for answering many questions with practical applications in ecology, conservation, environmental resource management, and numerous other areas of biology. These questions range from how to manage crops, livestock, and fisheries (e.g., "How much fish biomass can be removed from a fish stock sustainably?"), to how to help threatened and endangered species (e.g., "Are small populations of endangered species currently declining or growing, and, if so, at what rate? What is the risk that an endangered species will go extinct?"), to how to anticipate ecological impacts (e.g., "How does the removal or addition of a species affect the population growth rates and carrying capacities of other species in the ecosystem?").

Population dynamics often depend on **density-dependent** factors, which influence a population's growth rate based on the population's size. Many of these factors are *negative* density-dependent, meaning that they *reduce* the population growth rate as the population gets bigger and thus limit the population's size. This type of population growth can be described using a common mathematical population model called the logistic growth model.

Logistic growth model

The Click & Learn presents both continuous-time and discrete-time logistic growth models. It begins with the discrete-time model because the calculations involved are more accessible to students and the results are easier to visualize. It later introduces the continuous-time model, which is better suited for modeling continuously reproducing species.

Additional background on both the continuous-time and discrete-time logistic growth models can be found in the "Logistic Growth Model" tab of the *Population Dynamics* Click & Learn.

Lionfish

Lionfish (*Pterois volitans*), the main species discussed in the Click & Learn, are native to tropical waters of the Indo-Pacific. They were introduced in the Atlantic in the early 1990s and have since spread throughout the Caribbean, the Gulf of Mexico, and the east coast of the United States. Biologists predict that lionfish will continue to spread extensively throughout the eastern coast of South America.

Lionfish have been extremely successful in their invaded range, reaching much higher densities than in their native range. They are voracious predators that prey on over 100 other species — in fact, 1000 lionfish can eat over 5 million prey fish in one year. As a result, lionfish have led to the decline of many reef fishes through predation or competition for similar food sources.

This Click & Learn uses the logistic growth model to explore the growth of the invasive lionfish population in the Bahamas, which scientists have been surveying since 2004. This example is used to explore how population growth rates change with population size, ranging from very small sizes to what appears to be a maximum size (carrying capacity).

The Click & Learn includes estimates of lionfish population densities over time, which can be used to estimate the carrying capacity of lionfish in the Bahamas. These population densities are based on realistic data compiled from studies using underwater surveys by divers (Green et al. 2012, Benkwitt et al. 2017, and Côté et al. 2018; the end of this document lists additional references). The data shown in the Click & Learn have been simplified from the original published data in order to make them more accessible to students and to better meet the key

learning goals. In particular, the data were converted to units that are easier for students to interpret, and outlier data from a year with a high degree of measurement uncertainty were excluded.

Notation for growth rates

The notation used in the equations of this Click & Learn may vary from what is used in some textbooks. You may need to clarify any discrepancies with your students.

The Click & Learn uses this equation for the **discrete-time logistic model**:

$$\frac{\Delta N}{\Delta t} = r_{\text{max,d}} N_t \left(\frac{K - N_t}{K}\right)$$

In some textbooks, $r_{\text{max,d}}$ (the discrete-time maximum per capita growth rate; also known as the discrete growth factor) is written simply as r_d; we have added the subscript "max" to emphasize that it is a *maximum* rate. $r_{\text{max,d}}$ may also be written in terms of another variable, **λ** (lambda), where $\lambda = r_{\text{max,d}} + 1$.

The Click & Learn uses this equation for the **continuous-time logistic model**:

$$\frac{dN}{dt} = r_{\text{max}} N \left(\frac{K - N}{K}\right)$$

In many textbooks, r_{max} (the continuous-time maximum per capita growth rate; also known as the instantaneous rate of increase, intrinsic growth rate, intrinsic capacity for increase, etc.) is written simply as *r*. Again, we have added the subscript "max" to emphasize that it is a *maximum* rate.

The discrete-time and continuous-time maximum per capita growth rates are related as follows:

$$r_{\text{max}} = \ln(r_{\text{max,d}} + 1)$$

A derivation of this equation is provided in the "Background" section of the "Educator Materials" for the *Population Dynamics* Click & Learn.

The *Lionfish Invasion* Click & Learn also uses r_{realized} to refer to the realized or "actual" per capita growth rate of the population. r_{realized} is defined as the overall population growth rate (*dN/dt*) divided by the population size (*N*) in the continuous-time model:

$$r_{\text{realized}} = r_{\text{max}} \left(\frac{K - N}{K}\right)$$

This notation is introduced to make a clear distinction between the *maximum* per capita population growth rate (r_{max}), which is a constant, and the *actual* population growth rate (r_{realized}), which varies with population size.

TEACHING TIPS

- The Click & Learn is designed so that students can complete it entirely on their own. You could ask students to complete the Click & Learn as homework, assign some or all questions as homework, and/or eliminate some of the questions.

- **Some of the questions in the "Student Worksheet" are identical to those embedded in the Click & Learn.** See the "Answer Key" below for more information. It is not necessary for students to do the same questions in both the Click & Learn and the worksheet.

- There are multiple ways to assess students' mastery of the concepts in the Click & Learn. Some suggestions are as follows:
  - o Have students submit the **PDF document generated by the Click & Learn**. The PDF records students' answers to the questions embedded in the Click & Learn. Students can generate this PDF by submitting their answers on the "Further Study" page of the Click & Learn. If needed, they can revise their answers on the appropriate pages and resubmit them.
  - o Have students complete the **"Student Worksheet"** for the Click & Learn. As noted above, the worksheet includes the same questions that are embedded in the Click & Learn, as well as some additional questions not in the Click & Learn. If students have already answered the questions in the Click & Learn, they can skip the corresponding questions in the worksheet or vice versa.
  - o Have students **answer questions in class** using clickers or other classroom response systems. You could walk students through the Click & Learn (or part of it) in class by projecting it on a screen. Students could then complete the questions in the Click & Learn or worksheet in class, and "vote" on the answers to the multiple-choice questions.
  - o **Create your own quiz or assignment** for the Click & Learn to better fit your class's needs and learning objectives.
- The **"Case Studies"** section of the Click & Learn contains five different case studies that demonstrate various mechanisms of negative density-dependence.
  - o The "Case Study Handouts" download contains printable handouts for each case study. The content in the handouts is identical to the content in the Click & Learn and can be used if students do not have access to the Click & Learn.
  - o Consider using a jigsaw approach where students complete one or two case studies in small groups, then work with students in other groups to learn about the other case studies and compare the mechanisms at play in the different examples.

PROCEDURE

Usage of the Click & Learn and its materials is flexible and can be adapted based on your classroom context. The overall sequence in the Click & Learn, with some supplementary discussion points and activities, is as follows:

1. In the **"Introduction"** tab, students learn about lionfish, an invasive species in the Atlantic Ocean. Students view an animated map showing the spread of lionfish over time and watch a video interview with marine biologist Stephanie Green.
   a. Consider using the animated map to engage student interest in this phenomenon. Stimulate student thinking by asking them about the patterns they see in the growth of the lionfish's range and what they think might cause these patterns.
2. In the **"Lionfish estimates"** section under the "Models" tab, students watch a second video interview with Stephanie Green. This video explains common techniques used to estimate the size of fish populations. It highlights two types of underwater visual surveys commonly done in coral reefs: transect surveys and roving surveys.
   a. You may want to discuss other methods for estimating the size of animal populations, both underwater and on land. Examples include mark-recapture, fisheries catch, fisheries-independent monitoring (i.e., surveys carried out on research vessels, often done with the same kind of fishing gear as used on fishing vessels), or proxies for density (e.g., fecal pellets, vocalization).

b. The *Survey Methods* Click & Learn explores several methods used to survey populations of large terrestrial animals (in particular, African elephants). Students could compare and contrast these methods with the ones used for lionfish populations.

3. At the end of the **"Lionfish estimates"** section, students examine a graph of lionfish population densities over time.

   a. This graph is based on realistic data aggregated from several sources on lionfish population densities from 2004 to 2014 in the Bahamas. As described in the "Background" section above, some of the data were simplified in order to make them more accessible to students. You may want your students to engage with the original data (e.g., Green et al. 2012, Benkwitt et al. 2017, and Côté et al. 2018) if they have the appropriate background. You could use this opportunity to discuss "messiness" and uncertainty in real data.

   b. Students are asked to estimate carrying capacity (*K*) for the population based on the graph. An estimate from 450 to 550 will be marked as correct. If students provide an estimate outside this range, they will receive a pop-up message to help them better understand carrying capacity and revise their estimate. Many students may choose the highest point on the graph rather than the population size where the lionfish population seems to stabilize. This is a good opportunity to discuss how populations can sometimes overshoot their carrying capacity and how that leads to negative population growth.

4. In the **"Modeling change"** section, students are introduced to a discrete-time logistic model for the lionfish population.

   a. If students are unfamiliar with mathematical population models, you may need to provide additional scaffolding and support. For example, the *Population Dynamics* Click & Learn can be used to introduce students to basic population models. It provides more background on both discrete-time and continuous-time logistic growth models, as well as an interactive simulator for exploring the latter.

5. In the **"Lionfish calculations"** section, students use the discrete-time logistic model to project the size of the lionfish population over yearly increments. They record results from each step of their calculations in a table within the Click & Learn. Each time students successfully fill in one row of the table, the population size they calculated will appear on the adjacent graph.

   a. For this table to work, students must **round their result to two decimal places** at each step in their calculation and **immediately use the rounded result in the next step** of the calculation. This is not typically best practice for multistep calculations, as it can propagate rounding errors, but was done here as a simplification. Note that if students are using *unrounded* results in their calculations, the table may not work even though they are using the correct method.

   b. Students can click on each term in the header of the table to learn more about that term. They can also click on each number in the first row of the table (for 2004) to learn more about how that number was calculated.

   c. Students are asked to do calculations for three years (2005, 2006, 2007) only. Once they have completed these calculations, the rest of the table will be filled in automatically.

6. In the **"Revising the model"** section, students are introduced to a continuous-time logistic growth model for the lionfish population. From this point on, the Click & Learn uses only the continuous-time model for lionfish.

   a. You may want to discuss the differences between continuous-time and discrete-time models in more depth, including what types of populations or questions each type of model is best suited for. In this case with lionfish, the continuous-time model was used to capture the fact that lionfish reproduce continuously throughout the year.

7. In the **"Visualizing a population growth model"** section, students explore how the "actual" growth rate per individual (called $r_{realized}$ in the Click & Learn) changes with population size. This section was designed to help students reflect on the ecological factors that cause a population to grow more slowly at small and large population sizes.

    a. $r_{realized}$ is defined as the overall population growth rate (dN/dt) divided by the population size (N). In the logistic growth model:

    $$r_{realized} = r_{max}\left(\frac{K - N}{K}\right)$$

    b. Students can click three points on the graph of lionfish population size over time. These points represent a small population size (2005), an intermediate population size (2008), and a large population size (2010). Clicking a point displays a pop-up describing the factors that influence $r_{realized}$ and the overall population growth rate (dN/dt) at that point.

        i.   For the sake of simplicity, the pop-ups focus on the role of resource availability and births. Consider discussing other factors (predators, deaths, etc.) that could also affect population growth rates and yield similar patterns.

        ii. The pop-up for 2005 highlights that population growth rate is the result of both birth rate and death rate with the following statement: "Note that population growth rate is the result of both births and deaths but for simplicity, the growth is represented with just births. For example, in reality, 4 new lionfish could also mean 5 lionfish being born and 1 dying, or other combinations of births and deaths." You may want to review and unpack this important concept with your students.

        iii. Students will need to close the pop-ups in order to see the images that appear behind them. These images are visual representations of the population size at the start of a year (shown as adult lionfish) and the change in population size between that year and the next (shown as juvenile lionfish).

8. In the **"Changing rates"** section, students explore how the overall population growth rate (dN/dt) changes with population size (N). This section was designed to help students see that dN/dt is small when population size is low, increases with N to a maximum value at $N = K/2$, and declines to zero as N reaches K.

    a. Students can toggle between two graphs: one showing the lionfish population size over time (N vs. t) and the other showing how the population growth rate changes with population size (dN/dt vs. N). There is also a table that compares the values of N and dN/dt at different times.

    b. Students should observe that the population grows the fastest when $N = K/2$. Depending on students' background, you may want to connect this to the concept of maximum sustainable yield (MSY). MSY is the population size at which the population growth rate is maximized (in this case, $N = K/2$). Fisheries often maintain populations at MSY because it produces the largest catch that can be repeatedly removed without decreasing the population.

        i.   Students often struggle with the concept that MSY does not occur at $N = K$, because they intuitively think that the larger the population, the greater the population growth rate. This is an opportunity to surface student thinking on this topic and directly address this common misconception.

    c. At the end of this section, students answer multiple-choice questions about why the population growth rate (dN/dt) is low at certain times. Students are not expected to know the correct answers at this point and will be exploring these ideas more in the next section. Encourage students to predict answers on their own, but don't penalize them for wrong initial answers. This practice encourages students to reflect on their prior ideas and check their understanding, a useful metacognitive habit.

9. In the **"Growth limits"** section, students read about various factors that can lead to negative density-dependent population growth. They are then presented with five case studies based on published scientific research, which show different negative density-dependent factors at work.

10. The **"Case Studies"** tab has sections for each of the five case studies. In each section, students read a description of the study, analyze a related graph (based on a published scientific figure), and answer questions. In the **"Match mechanism to study"** section that follows, students identify the main density-dependent factor at play in each case study.

   a. As described in the "Teaching Tips" above, it may be helpful to have students engage with the case studies using a jigsaw approach rather than having all students do all five case studies.

11. In the **"Further Study"** tab, students revisit the lionfish example to think about which negative density-dependent factor(s) may be important for regulating lionfish populations.

   a. One question has students outline an experiment to test their hypothesis. Choose a method for them to share their ideas that works with your class structure, such as having them submit a short research proposal, asking them to comment on other students' ideas in a discussion forum, making posters that are shared in a gallery walk, and so on.

   b. The end of the Click & Learn mentions that students can engage with the broader problem of invasive species even if they aren't in a place with invasive lionfish. Consider explicitly connecting what students have learned to other examples of invasive species that are more relevant, local, or interesting to them. For example, you could discuss how population dynamics and mathematical models could be used to inform management of local weeds or insect pests.

ANSWER KEY

Many questions in the "Student Worksheet" are equivalent to those embedded in the Click & Learn. The questions underlined and highlighted below are in the "Student Worksheet" only.

PART 1: Introduction to Lionfish

1. Which characteristics of lionfish helped them successfully invade the Atlantic Ocean?
   Lionfish have very few predators in the Atlantic Ocean and can eat a lot of the native fish. (Other relevant lionfish characteristics not mentioned in the Click & Learn, which you may also want to discuss with students, include the following: Lionfish eat many different types of prey and occupy many habitats. They produce a lot of eggs and reproduce often, which is what ecologists call an r-selected species. They can also disperse through buoyant eggs and a pelagic larval phase.)

2. In general, which characteristics do you think make an invasive species successful in its new environment?
   Student answers will vary depending on their prior knowledge; be open to a range of responses. Characteristics of invasive species can include lack of predators, fast growth to sexual maturity, rapid reproduction (with many offspring produced per reproductive cycle), strong dispersal abilities, and being a generalist species (can live in many environmental conditions and eat a variety of things).

3. Based on the graph at the bottom, estimate the carrying capacity for this lionfish population.
   around 500 lionfish per 10,000 m²

PART 2: Logistic Growth Models

4. Copy your values from the table in the Click & Learn into the table below, or insert a screenshot from the Click & Learn.

t	N_t	$r_{max,d}N_t$	$(K - N_t)/K$	$\Delta N/\Delta t$	N_{t+1}
2004	20	23	0.96	22.08	42.08
2005	*42.08*	*48.39*	*0.92*	*44.52*	*86.6*
2006	*86.6*	*99.59*	*0.83*	*82.66*	*169.26*
2007	*169.26*	*194.65*	*0.66*	*128.47*	*297.73*

5. Copy the N_{t+1} values for each year into the table below, or insert a screenshot from the Click & Learn.

2008	2009	2010	2011	2012	2013
297.73	*434.69*	*499.68*	*499.68*	*499.68*	*499.68*

6. <mark>Why is the continuous-time model more appropriate for modeling lionfish?</mark>
   Lionfish reproduce (and die) all throughout the year, so their population size is changing all the time. The continuous-time model is more appropriate for capturing these frequent changes.

7. <mark>Compare the three curves shown in the graph at the end of the section.</mark>

   a. How does the curve for the continuous-time model compare to the curve for the discrete-time model?
   The curve for the continuous-time model increases less steeply than the curve for the discrete-time model, but both level off at the same carrying capacity by 2014. (You may want to discuss with students why the models differ. Note that in the continuous-time model, the population growth rate updates constantly. In this particular discrete-time model, the population growth rate updates only once a year.)

   b. How do the curves for both models compare to the population estimates based on diver data? What might explain the differences?
   The curves based on the models are much smoother than the data-based estimates. The data-based estimates have much greater year-to-year variation, including a big spike in 2008 and fluctuations around the carrying capacity.

   Student explanations for these differences will vary. They may say that the variations in the data-based estimates could be due to the divers miscounting the fish or the fish not being evenly distributed between the places the divers sampled and the rest of the area (sampling errors). These variations could also be caused by real variations in the lionfish population size, which may be due to environmental changes or time lags between when a certain population size is reached and ecological consequences of this new population size (e.g., changes in survival and reproductive ability). The simple models used here do not include these types of errors or variations and therefore appear smoother and more idealized.

PART 3: Exploring Growth Rates

8. <mark>*Before* looking at the graph, predict the population size at which the realized per capita population growth rate ($r_{realized}$) will be highest.</mark>
   Student predictions will vary. Once they look at the graph, they will see that r$_{realized}$ is highest at the smallest population size.

9. <mark>*Before* looking at the graph, answer the following questions.</mark>

   a. Predict the population size at which the overall population growth rate (dN/dt) will be highest.
   Student predictions will vary. Once they look at the graph, they will see that dN/dt is highest at an intermediate population size (specifically, when N = K/2).

b. Predict the overall relationship between dN/dt and N, and sketch a graph of your prediction below.
   Student predictions will vary. Once they look at the graph, they will see the relationship shown below.
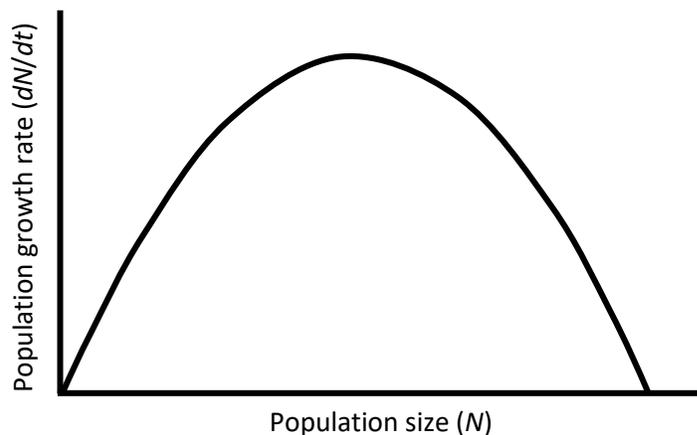
10. <mark>Use the graphs to answer the following questions.</mark>
    a. What is the approximate carrying capacity for this population?
       500 lionfish per 10,000 m²
    b. At what population size (N) is the overall population growth rate (dN/dt) the highest?
       250 lionfish per 10,000 m²
    c. How does your answer to Part B compare to the carrying capacity?
       The answer to Part B (the population size with the highest overall population growth rate) is half the carrying capacity.

11. Over 2004–2006, when the population size is small, the population growth rate (dN/dt) is:
    a. greater than it is over 2008–2010
    b. less than it is over 2008–2010
    c. about the same as it is over 2008–2010

12. Which of the following best explains the low population growth rate (dN/dt) over 2004–2006?
    a. The number of individuals that can reproduce is low.
    b. Food resources are scarce.
    c. Disease and parasitism are common.

13. What could explain the low population growth rate over 2011–2013, when the population size was high? Select all that apply.
    a. The number of individuals that can reproduce is low.
    b. Food resources are scarce.
    c. Disease and parasitism are common.

PART 4: Case Studies

14. At lower densities, paprika pepper plants produce a higher total weight of fruit. In this case, the main factor that limits population growth is:
    a. intraspecific competition
    b. interspecific predation
    c. disease and parasites
    d. social behavior

15. Protozoa at higher densities have lower population growth rates, especially when less food is available. In this case, the main factor that limits population growth is:
    a. intraspecific competition

b. interspecific predation
c. disease and parasites
d. social behavior

16. Fish at high densities have more sea lice, which can injure or kill the fish. In this case, the main factor that limits population growth is:
    a. intraspecific competition
    b. interspecific predation
    c. disease and parasites
    d. social behavior

17. When crab densities are higher, the larger crabs eat more of the smaller crabs. In this case, the main factor that limits population growth is:
    a. intraspecific competition
    b. interspecific predation
    c. disease and parasites
    d. social behavior

18. As the density of mosquito larvae increases, more mosquito larvae are eaten by fish. In this case, the main factor that limits population growth is:
    a. intraspecific competition
    b. interspecific predation
    c. disease and parasites
    d. social behavior

PART 5: Further Study

19. Choose a negative density-dependent factor that you think may affect the lionfish population in the Bahamas. Outline an experiment to test whether this factor is limiting the growth of the lionfish population.
    Student answers will vary and could include any of the factors from the case studies: intraspecific competition, interspecific predation (although this is unlikely because the Click & Learn mentions that lionfish have few predators in the Atlantic), diseases and parasites, and social behavior. Be open to a range of reasonable responses. An example answer is shown below.

    One factor that may affect the lionfish population is competition among lionfish. To test whether competition is limiting the growth of the population, we could group lionfish at different densities, then investigate the growth rates of each group. This type of experiment could be done in a lab or in the field. In the field, we could pick several areas on a reef of the same size with similar conditions (e.g., similar types of prey). We could then put cages around each area and add different numbers of lionfish inside the cages. Over time, we'd measure the growth rate of each group (which would involve monitoring the number of offspring produced and lionfish dying over time). If competition does limit lionfish populations, we'd expect the groups with higher densities to have lower growth rates.

20. Think about the factor you chose in the previous question. Describe what could stop that factor from limiting the lionfish population in the future.
    Student answers will vary depending on their response to the previous question. Below is an example answer that follows the previous response.

    If the lionfish are limited by competition for food in particular, they would be less limited if the food supply increased. This could happen if population sizes of other species that compete for similar food sources decrease due to overfishing.

21. Learn more about another invasive species near you or one that you are personally interested in. Which invasive species did you choose, and what are its impacts?
    Student answers will vary; be open to a range of reasonable responses.

22. What is currently being done to control this invasive species and its impacts?
Student answers will vary; be open to a range of reasonable responses.

23. How might understanding population dynamics help us better manage this invasive species and its impacts?
Student answers will vary; be open to a range of reasonable responses.

CASE STUDY 1: Fruit production in paprika peppers

1. Describe the relationship between plant density and the yield *per plant*.
The greater the plant density, the lower the yield per plant.

2. Predict how the yield per plant (fruit production) might affect the population growth rate.
Lower yield per plant (i.e., lower fruit production) would decrease the population growth rate (assuming that the fruits give rise to seeds that result in new plants, rather than being removed by farmers).

3. What pepper plant density would you recommend to a farmer to maximize the yield *per 10,000 m^2*? Why did you choose that density?
Specific answers will vary but are likely to be from 100,000–200,000 plants per 10,000 m^2. Around this plant density, the overall yield levels off at a maximum, so adding more plants would not benefit the farmer.

CASE STUDY 2: Population growth rates of protozoa

1. Use evidence from the graphs to make a claim about how $r_{realized}$ is affected by the initial population density. In other words, how does $r_{realized}$ differ between populations that start small and those that start big?
In both graphs, populations with a larger initial density have a lower $r_{realized}$. This suggests that increasing the initial population density decreases $r_{realized}$.

2. Use evidence from the graphs to make a claim about how resource availability affects $r_{realized}$.
A population with high resource availability (top graph) has a higher $r_{realized}$ than a population with low resource availability (bottom graph) and the same initial density. This suggests that increasing resource availability increases $r_{realized}$.

CASE STUDY 3: Parasites on fish farms

1. How does density of fish on a farm affect the number of sea lice per fish?
In general, farms with higher densities of fish (higher "local farmed fish biomass density") have more sea lice per fish (higher "sea lice counts").

2. Other research reported a link between sea lice infestation and mortality. If that is the case here, what do you predict will happen to high-density fish populations?
High-density populations have more sea lice per fish. If sea lice are linked to mortality, these fish are more likely to die due to sea lice than are fish in low-density populations.

3. How might the results of Jansen et al. (2012) impact policies about fish farming — in particular, the size of fish farms?
Based on the results in the graph, low-density populations have fewer sea lice per fish. So, fish farms may want to maintain fish at lower densities to limit sea lice infestation and mortality. (You may want to let students know that keeping farmed fish at low densities will also reduce sea lice infections in wild populations that swim nearby, which are not mentioned in the Click & Learn.)

CASE STUDY 4: Cannibalism in shore crabs

1. Describe the pattern shown in the figure.
The number of crabs eaten per cannibal increases with the density of young crabs. The increase is steeper at first, then flattens out at higher densities of young crabs. (Some students may recognize that this relationship is nonlinear.)

2. As density increases, how might changes in the frequency of cannibalism affect the population growth rate?
As density increases, more young crabs will be killed by the cannibals, which will likely reduce the

population growth rate. (You may want to note that this relationship is nonlinear. If the population is already high-density, further increasing density may have less of an effect, since cannibalism appears to slow down at high densities.)

3. Although the cannibal crabs in this study had another food source, they did not eat all of it during the experiment. This result suggests that cannibalism was not a response to starvation. How else might these crabs benefit from cannibalism?

   Student answers will vary. They may suggest that the cannibals get more nutrition from other crabs or catch other crabs more easily, compared to other food sources. Cannibalism may also reduce intraspecific competition for food and space and therefore increase the cannibals' survival rate.

CASE STUDY 5: Predation of mosquito larvae

1. How did the number of mosquito larvae killed by predators change as the density of larvae increased?

   As the density of larvae increased, more larvae were killed by predators. The increase is steeper at first, then flattens out at higher densities of larvae. (Some students may recognize that the relationship is nonlinear.)

2. Based on your answer to the previous question, how might the mosquito population growth rate change as the density of mosquito larvae increases?

   As the density of mosquito larvae increases, more larvae will be killed by predators, which will likely reduce the mosquito population growth rate. (You may want to note that this relationship is nonlinear. If the population is already high-density, further increasing density may have less of an effect, since predation appears to slow down at high densities.)

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