Educator Supplements to the book,

THE SERENGETI RULES

THE QUEST TO DISCOVER HOW LIFE WORKS AND WHY IT MATTERS

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HOW TEACHERS MIGHT USE *THE SERENGETI RULES* IN THE CLASSROOM

The Serengeti Rules, molecular biologist Sean Carroll takes the reader on a journey through the history of the scientific discovery of many of nature's most important regulatory mechanisms, from molecules to megafauna. In the spirit of Theodisius Dobzhansky, Carroll teaches us in *The Serengeti Rules* that nothing in biology makes sense except in the light of regulation. Thus, at the very center of the book is the big, biological idea of homeostasis. Indeed, a key to understanding how living systems work and the supporting roles played by evolutionary processes is understanding how a relatively stable environment, be it in a cell or in an ecosystem, is maintained and regulated. Throughout the book, Carroll tells the stories of the scientists—and their discoveries—that have given us our current understanding of regulation in nature. But in the stories, Carroll also teaches the reader about the nature of science and scientific reasoning, the importance of modeling, and how scientific discovery is full of determination and success but also frequented with failure.

Through stories of real scientific discovery, *The Serengeti Rules* provides a historical foundation and context for our current understanding of our most fundamental biological topics. Soon after its publication in March of 2016, social media, like the National Association of Biology Teachers Facebook page and the College Board AP Biology online Discussion Board, began buzzing with excitement about the book. Many teachers immediately realized the value of assigning the book as summer reading for students enrolled in their AP and IB Biology courses. Other teachers might consider using the book to drive or supplement the curriculum topics in their biology courses or to pique student curiosity in many of the course topics. However, no materials were available to help teachers integrate the book, its stories, and its overarching theme of regulation (homeostasis) into their current curriculum frameworks. It is thus the goal of Princeton University Press to provide those critical materials and curriculum connections to teachers and their students. The materials available can be used directly in the classroom to supplement what teachers already use to reinforce the big ideas, learning targets, and science practices that frame the biology content. The support materials we have developed are designed to enhance students' biology knowledge and also their scientific skills. Below is a brief summary of *The Serengeti Rules* and descriptions of the materials available and how a teacher might use them in the classroom.

I. SUMMARY OF *THE SERENGETI RULES*

Part I: Everything Is Regulated. One focus in Part I is the work of Walter Cannon, a Harvard University physiologist. In his early years as a scientist, Cannon questioned why fear and stress affect an animal's physiology. Cannon hypothesized that an animal's normal physiological states "remain steady because factors exist that resist change in either direction, positive or negative," but that stress disrupts many highly regulated mechanisms in animals. Cannon's most important test of this hypothesis came while he was assisting in a field hospital in Europe during World War I. Cannon noticed patterns in the wounded soldiers that often led to death, including blood pressures that dropped to levels as low as 50 when blood bicarbonate ion concentration and blood pH also dropped. With regulation in mind, Cannon reasoned that adding bicarbonate ion to the soldiers' blood could raise blood pH and also blood pressure. The method worked and allowed wounded soldiers to be, in the words of Cannon, "snatched from death." After the war, Cannon continued with his physiology and regulation research and eventually described the steady states that the body maintains within a narrow window, like blood pressure and blood pH, with a new term: *homeostasis*.

In Part I we are also introduced to another scientist, Charles Elton. In the 1920s, Elton worked on ecosystem regulatory processes, which are at the other end of the spectrum of biological organization as those studied by Cannon. Elton was a master of abductive reasoning: borrowing ideas from other research and applying them to the systems he was studying. For example, it was Elton, who, from years of field work in hostile arctic ecosystems, abducted the idea of scarce resources from economics and described how the availability of food regulates the sizes of animal populations. Indeed, it is Elton who published the first diagram of a complex food web.

Part II: The Logic of Life. An essential component of the scientific processes that generate new knowledge is modeling. In modeling, we make claims (hypotheses) about the real world and then build theoretical models to test those claims. If a theoretical model is valid, it should fit with what we know about the real world. Thus, when we test our models, the predictions we make should generate data that are evidence that our models work. A well-known example of model building is the original Watson and Crick model for the structure of DNA.

In Part II, Sean Carroll introduces us to some models for regulation that illustrate and simplify the complex interactions from cells to ecosystems that we seek to understand. For example, A indirectly regulates C by regulating B, or the buildup of A inhibits its own synthesis (see Figure 1). We learn that it was through the work of scientists like Jacques

GENERAL RULES OF REGULATION AND THE LOGIC OF LIFE

Positive regulation

A → B	A positively regulates the abundance or activity of B

Negative regulation

A ⊣ B	A negatively regulates the abundance or activity of B

Double-negative logic

A ⊣ B ⊣ C	A negatively regulates B, which negatively regulates C; A increases the abundance of C through double-negative logic

Feedback regulation

A → B → C	The accumulation of C feeds back to negatively regulate A and the production of B and C

Figure 1. The general rules of regulation and the logic of life. Figure is from *The Serengeti Rules*, p. 68.

Monod and François Jacob that we first discovered these negative feedback mechanisms in the context of enzyme function. Among many other great stories in this section, Carroll also recounts how the discovery by Janet Rowley of chromosomal translocations eventually led to the invention of the successful cancer drug Gleevec. Several, if not all, of these significant discoveries may be new to many teachers. The stories can function to put a human face on course content that may be difficult or abstract. The stories can also provide an important historical context to some of our most important scientific discoveries of the past century.

Part III: The Serengeti Rules. "The regulation of populations must be known before we can understand nature and predict its behavior." This quote introduces Part III and comes from a now-classic paper published in 1960 by three ecologists, Nelson Hairston, Fred Smith, and Lawrence Slobodkin. The paper is titled "Community Structure, Population Control, and Competition" but is known by scientists in the field of ecology simply as "Hairston et al., 1960." In the paper, Hairston and his colleagues proposed that "herbivores are held down in numbers by predation below the level at which they damage the vegetation." This statement, along with the other observations presented in the paper, became known as the original Green World Hypothesis. The Green World Hypothesis explains in part why plant-eating animals are not generally and consistently able to grow their populations to sizes that eventually consume all the Earth's plants: the population sizes of herbivores are regulated by the predators who eat them. This idea frames the stories in Part III, where Carroll describes regulation at its largest scales.

The first story Carroll tells is that of Robert Paine. Paine's story is an example of what science textbooks are unable to do because of space constraints and curriculum requirements. Fortunately, a book like *The Serengeti Rules* can bring the material alive for students. In *The Serengeti Rules*, we learn that Paine was a student of Fred Smith's, and in large part through Smith's influence, Paine became well known in the 1960s, 1970s, and 1980s for his kick-it-and-see experimental methods (Paine's early work has now been brought to life in a short film titled *Some Animals Are More Equal than Others: Keystone Species and Trophic Cascades*. The film and its supporting resources are available through the Howard Hughes Medical Institute's Biointeractive website: http://www.hhmi.org/biointeractive/some-animals-are-more-equal-others-keystone-species-and-trophic-cascades).

Early in his career, Paine initiated several large and years-long experiments to test an idea of his called the *Trophic Cascade Hypothesis*. In the 1960s Paine experimented with predator removal along the Pacific Northwest coast. When Paine removed all individuals of the starfish species *Pisaster ochraceus* from their habitat, two species of marine herbivores, goose barnacles and mussels, exploded in number. Paine showed from this experiment that the herbivores in this habitat were indeed being "held down in numbers by predation below the level at which they damage the vegetation." After removal of the starfish, the barnacles and mussels also crowded out many other herbivore species and had almost completely devoured four species of algae, a major component of the "vegetation" of this coastal marine ecosystem. In 1969, after he was convinced of the direction of his results, Paine wrote a letter to the editor of *The American Naturalist* journal, describing his observations and introducing the field of ecology to a new way of thinking about species interactions: the *Keystone Species* concept. In his letter, Paine explained, "These individual populations [of starfish] are the keystone of the community's structure, and the integrity of the community and its unaltered persistence through time, that is, stability, are determined by their activities and abundances." Paine had cleverly abducted the idea of the keystone from its function in stone arches. Figure 2 shows that the stone at the top of the arch, the keystone, keeps the entire arch from falling into itself; and so it goes with keystone species.

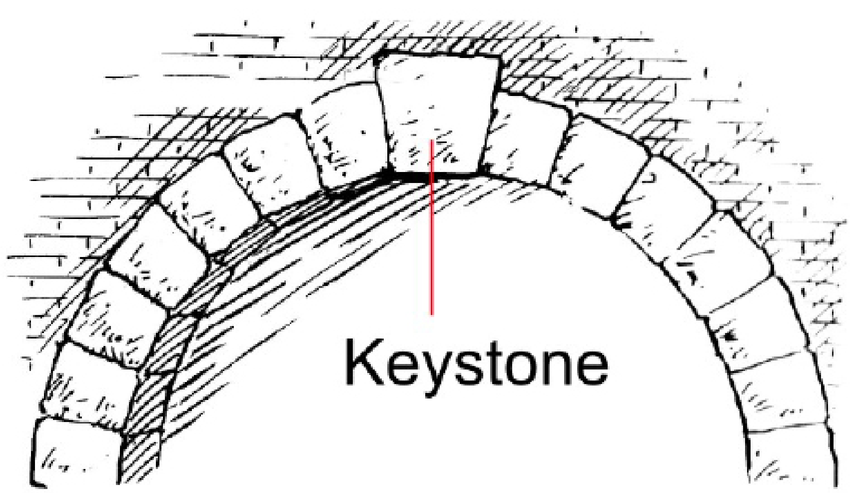

Figure 2. The keystone in a stone arch keeps the entire arch from falling into itself.

Table 1. From Robert Paine's 11-year Mukkaw Bay starfish removal study, published in 1974.

Date	July 1963	April 1973	April 1973	July 1963	August 1966	March 1968	June 1971	April 1973
Type of area	control	control	browsed removal	removal	removal	removal	removal	removal
No. of samples	7	10	8	13	3	4	1	12
Total area sampled in (m^2)	0.14	1.22	0.98	0.26	0.10	0.20	0.34	1.46
Category (% utilization)								
Space	10	14	9	11				trace
Balanus cariosus	10	12	5	13				
B. glandula	{ 30	14	19	{ 33				
Chthamalus fissus		10	6					
Pollicipes polymerus	1	2	<1	1	5	5		
Mytilus californianus	5	2	2	1	95	95	100	100
Endocladia muricata	2	3	6	9				
Corallina vancouveriensis	20	28	33	17				
Lithothamnium sp.	16	5	4	4				
Hedophyllum sessile			3					
Halichondria panacea	5	5	4	5				
Total % recorded	99	95	91	94	100	100	100	100
Other species (numbers)								
Haliclona sp.		trace						
Anthopleura xanthogrammica	3	5	5	3				
Acmaea digitalis, paradigitalis and *pelta*	57	35	30	108				
Thais emarginata		2	1	1				
T. canaliculata		1						
Katharina tunicata	3	4	9	15				
Tonicella lineata	1			1				
Basiliochiton heathii	2			3				
Pisaster ochraceus			2					
Leptasterias hexactis		2						
Strongylocentrotus purpuratus	2							
Ulva sp.			trace	trace				
Porphyra sp.		trace	trace	trace				
Rhodomela larix	trace			trace				
Gigartina papillata	trace		trace					
Callithamnion pikeanum		trace	trace					
Plocamium violaceum		trace	trace					
Polysiphonia spp.		trace	trace					

Robert Paine continued to remove starfish from his experimental plots for several years. By 1973 Paine had monitored his starfish removal experiment for 11 years, and he was ready to publish more than a letter to the editor of a journal. Table 1 comes from Paine's Mukkaw Bay data that he published in the journal *Oecologia* in 1974.

The data in Table 1 show that at the start of Paine's experiment, mussels (*Mytilus californianus*), one of the starfish's main food resources, covered between 1% and 5% of the rock face habitat, and shared the habitat with 17 other species. However, just three years later, on the rock faces without starfish ("removal" in the table), only two species from the rock face community were left and the mussels covered 95% of the rock surface area. By the end of the study in 1973, 100% of the area on the rocks in the removal group were covered with mussels, whereas on the control rock faces ("control" in the table), the total number of species had increased to 20. Thus, removing *Pisaster* starfish allowed mussels to quickly dominate the rock faces, which in turn drove down the species richness (number of species) of the entire ecosystem.

Various illustrations of this keystone species affect revealed by Paine have made their way into the textbooks used in many biology classrooms. Teachers may recognize Figure 3 from *Biology* by Campbell and Reece, or may have a similar figure in their textbooks. Figure 3 summarizes the species richness data described in Table 1. However, the textbooks do not convey the fascinating stories behind discoveries like these. In *The Serengeti Rules*, Sean Carroll makes it clear that stories, especially the ecological ones, are salient, if indeed one of our main goals in teaching is to leave lasting impressions on our students so that they can achieve a deep understanding and respect for how the natural world works.

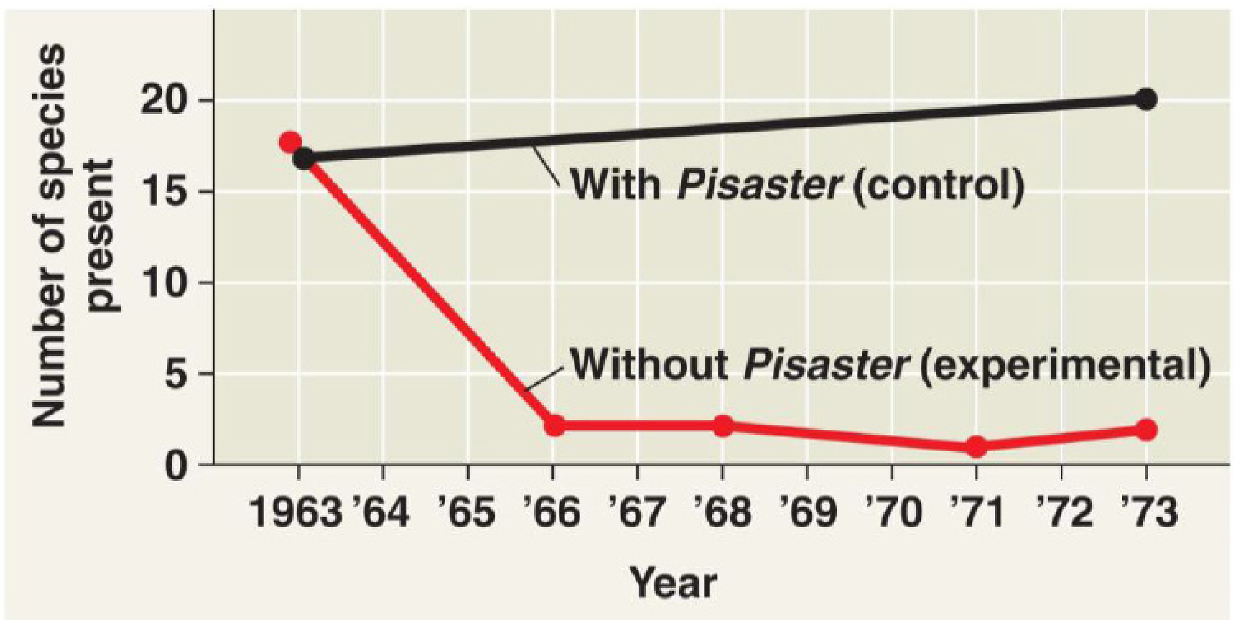

Figure 3. Data from Robert Paine's starfish removal experiment as illustrated in the textbook *Biology*: N. A. Campbell, J. B. Reece, L. A. Urry, M. L. Cain, S. A. Wasserman, P. V. Minorsky, and R. B. Jackson (2008). *Biology*, 8th edition. San Francisco: Pearson Benjamin Cummings. Data are from a 1974 paper by Paine.

In the second half of Part III, Carroll ultimately takes us to the real Serengeti in Africa and explains how these basic rules of regulation, which govern how cells function, also influence the community interactions we observe in vast ecosystems. We are introduced to the interactions among various charismatic species, many of which are already well known to our students, like elephants and lions, but also some not so well-known species, like gazelles and wildebeest. Here Carroll brings in the ideas of competition for resources, body size, population density, and migration as key variables in how the Serengeti system itself is regulated.

Carroll doesn't stop with the Serengeti. The last few chapters of *The Serengeti Rules* are a whirlwind tour of ecosystem processes back and forth between Africa and the United States. We travel from Lake Erie of Ohio to the plains of Ghana to lakes in Wisconsin to Yellowstone National Park and finally back to Africa to Gorongosa National Park in Mozambique. In Gorongosa we learn how a devastating civil war produced an ecosystem that was depleted of most of its large animals. The silver lining to this cloud of human conflict is that ecologists can monitor the results of an unplanned kick-it-and-see experiment on an extremely large scale. Researchers can see in real time how the rules of regulation appear and take hold as the Gorongosa ecosystem surges back to life. The results will likely be as predictable as they are unexpected.

Back in the *Introduction*, Carroll writes, "Diseases … are mostly abnormalities of regulation, where too little or too much of something is made." From molecules to megafauna, regardless of the scale, *The Serengeti Rules* teaches the reader that to understand the disease state of a system, even an ecosystem, one must intimately understand how that system is regulated.

As mentioned above, a teacher may simply assign the book as summer reading to prepare students for a bulk of the content they will be covering in an upper level course like AP Biology, IB Biology, AP Environmental Science, or IB Environmental Systems and Society. Sean Carroll's writing style is engaging enough to keep most any student's attention. And in many places, Carroll avoids delving too deeply into the scientific details. For example, when Carroll begins to explain the regulation of cholesterol synthesis, he is clear in his intention to keep it as simple as possible:

> "[B]ut it was known that the rate of cholesterol synthesis was determined by the activity of the enzyme that acted at the first step of the pathway, whose name is a mouthful: 3-hydroxy-methylglutaryl coenzyme A reductase. I'll just call it 'the reductase,' as it is the one and only enzyme I am going to talk about in this chapter, and what it does exactly is not essential to know here."

As a challenge to students, teachers can encourage them to look for topics in the curriculum that are relevant to the scientific stories in the book—they are everywhere!

II. INTRODUCTION TO QUESTION SETS FOR *THE SERENGETI RULES*

Nearly 100 questions have been written to engage students in the content and concepts presented in *The Serengeti Rules*, as well as to inspire reflection and discussion. Possible assessment questions have also been written to accompany each chapter. Teachers can use the questions directly or can use parts of a question or even rewrite questions to fit student knowledge and ability level. To aid teachers in choosing appropriate questions for their students, each question has been labeled with question level (standard level or higher level) and question type (modeling question, data-based question, or nature of science question). For convenience of curriculum coverage, each question has also been aligned with specific concepts and topics in both the AP Biology curriculum and the IB Biology curriculum.

Engagement Questions

If the book is not assigned as summer reading (some schools may not allow summer reading assignments), teachers can assign chapters or sections of chapters as the school year progresses.

However, before students begin each reading assignment, they can be given engagement questions that get them thinking about what they may already know about a topic or that reveal a misconception they may have. Here is an example from Chapter 6, *Some Animals Are More Equal than Others*, where students are assigned to read the first seven pages of the chapter:

- There seems to be an abundance of plants in many locations on the Earth, especially in those locations where climate supports and promotes plant growth. In other words, the Earth is very green. Propose a hypothesis that tentatively answers this question: With so much plant food available, why don't we see an equally abundant number of animals eating them?
- Describe a method you could design to test your hypothesis.

Discussion Questions

Regardless of the approach teachers use to incorporate student reading of *The Serengeti Rules*, discussion questions are an effective way for students to process and review the stories and the science. Here are two examples of discussion questions that follow Chapter 6, *Some Animals Are More Equal than Others*:

- Robert Paine used a kick-it-and-see approach to understand and reveal the role *Pisaster* starfish play in their tidal zone ecosystem. Paine was able to show that the starfish function as the keystone species in their habitat. Compare Paine's approach to the approach used by Jim Estes and John Palmisano to investigate the role sea otters play in their ecosystem.
- From observations they made in a freshwater stream in Oklahoma, ecologist Mary Power and her colleagues hypothesized that bass acted as a keystone species. Sketch and label a diagram that illustrates the method used by Power and her team to test their hypothesis.

Assessment Questions

No matter how teachers choose to use *The Serengeti Rules* to supplement their curricula, we have provided one or two assessment questions that relate to or extend from the concepts presented in each chapter. Thus the assessment questions are not intended to simply check student recall of the content of each chapter; instead they challenge students to pool their knowledge and science literacy skills to make claims and arrive at conclusions. Indeed, many of these questions simulate the kinds of thought-provoking, data-based questions students might encounter on their AP and IB end-of-program exams. Here is an example of an assessment question for Chapter 8, *Another Kind of Cancer*:

1. Study the four graphs in Figure 4. The data in the graphs come from an experimental forest in North Carolina. Part of the forest was exposed to CO_2 levels meant to simulate the atmosphere predicted for the year 2050: 580 parts per million (ppm). Another part of the forest was left alone to experience the ambient CO_2 levels of 1996, when experiments on the forest began: 380 ppm. Researchers sampled four different types of arthropods in the two parts of the forest to get an idea of what effect higher CO_2 levels might have on forest ecosystem food webs. Wasps and spiders are carnivores and prey on caterpillars and mites, which are herbivores. Before the study was conducted, researchers had

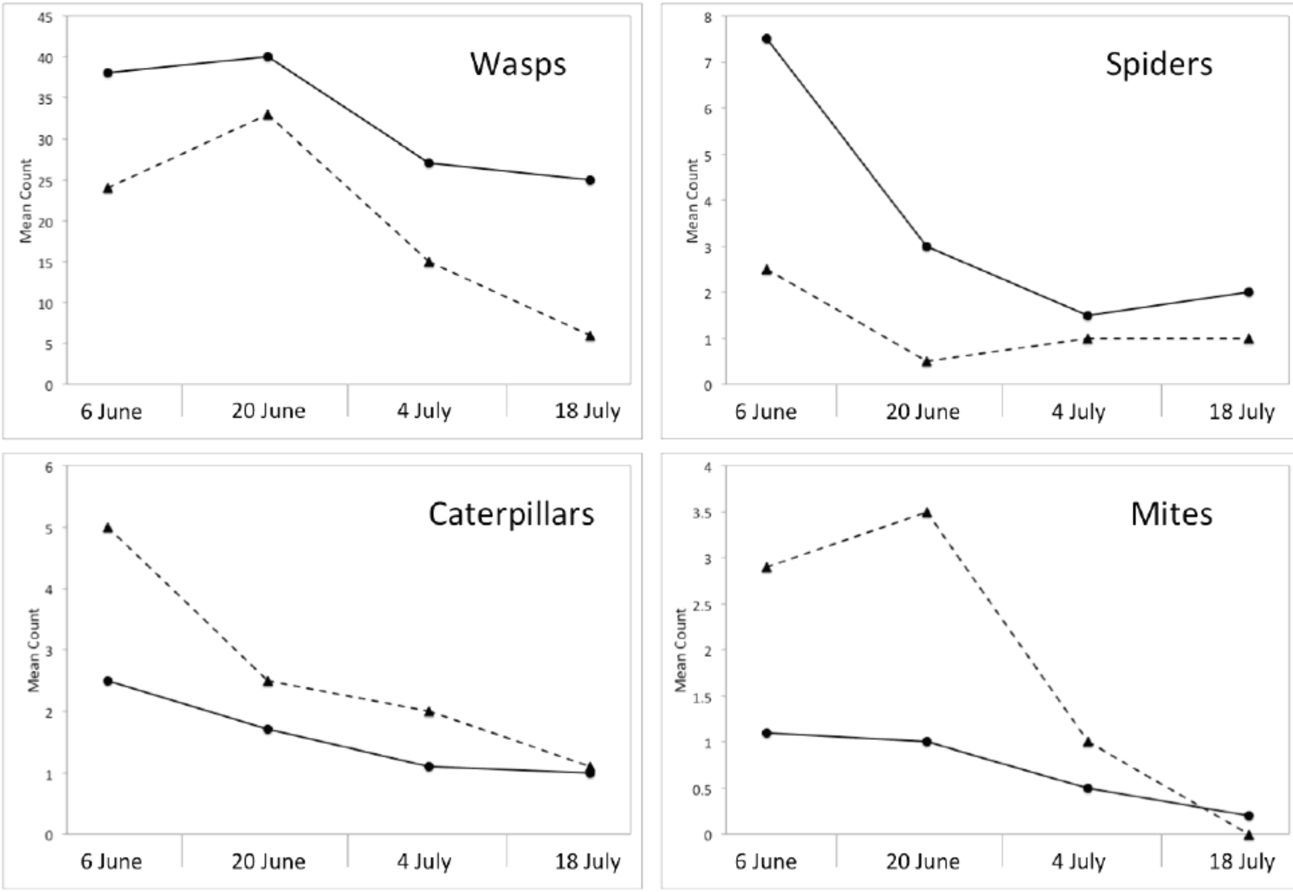

Figure 4. Population sizes of four different groups of arthropods sampled in habitats under two different atmospheric conditions: ambient (1996) CO_2 levels (380 ppm; dashed line with triangles) and future (2050) CO_2 levels (580 ppm; solid line with circles). The data in the graphs are from J. Hamilton, A. R. Zangerl, M. R. Berenbaum, J. P. Sparks, L. Elich, A. Eisenstein, and E. H. DeLucia (2012). "Elevated Atmospheric CO_2 Alters the Arthropod Community in a Forest Understory." *Acta Oecologica*, 43, 80–85.

already discovered that plants grow faster in elevated CO_2 conditions, but this faster growth makes the plants' leaves less nutritious. The less nutritious leaves require herbivores to eat more plant material and spend more time eating plants to get the same nutrition as they do from plants that grow more slowly under lower CO_2 conditions.

a. Identify what you see in each of the graphs.
b. Based on the graphs, interpret what effect you think higher CO_2 levels have on forest ecosystem food webs.
c. Propose a hypothesis to explain the effect you described in part (b).

Course Curriculum Alignments

Teachers at the secondary level like to see how a new resource aligns with the curriculum they are following. The three main curriculum frameworks to which teachers look for alignment are the AP Biology Course Description, the IB Biology Guide, and the Next Generation Science Standards (NGSS). For example, the AP Biology Course Description includes four Big Ideas. The following is an alignment example:

CHAPTER 3: GENERAL RULES OF REGULATION

Historical context: Jacques Monod and François Jacob discover feedback mechanisms in bacteria metabolism and reveal several general rules of regulation.

From the AP Biology Course Description:

1. Big Idea #2: Biological systems utilize free energy and molecular building blocks to grow, to reproduce, and to maintain dynamic homeostasis.

2. Enduring Understanding 2.C: Organisms use feedback mechanisms to regulate growth and reproduction, and to maintain dynamic homeostasis.
3. Essential knowledge 2.C.1: Organisms use feedback mechanisms to maintain their internal environments and respond to external environmental changes.
4. Learning Objective LO 2.18: The student can make predictions about how organisms use negative feedback mechanisms to maintain their internal environments.

Example Course Outline

At the end of this document there is also an example curriculum map for a first-year Advanced Biology course with ideas for how *The Serengeti Rules* might fit into the course content.

NOTE ABOUT SYMBOLS

At the end of each question are two sets of symbols. One set identifies the question type. The other set identifies general connections to the Advanced Placement (the Science Practices and Enduring Understandings) and International Baccalaureate Biology curricula. Use the following key as a guide for question type:

SL	Standard level (General HS Biology) Question
HL	Higher level (AP, IB, Intro College) Question
DBQ	Data Based Questions
MQ	Modeling Questions
NOS	Nature of Science Questions

III. ENGAGEMENT QUESTIONS

Introduction: Miracles and Wonder

1. The growth rate of the cells that make up a human embryo right after conception is exponential: one cell becomes two cells, which become four cells, then eight cells, 16 cells, and so on. This rate of cell population growth begins to slow down after about 20 days, but from 50 days to birth the mass of a human fetus continues to increase from about 1 gram to 3.5 kg as even more cells are added. By the time we reach adulthood, we have about 30 trillion cells, and we more or less stay that way for the rest of our lives. What ideas do you have for how all of this growth is regulated? What processes are responsible for the rapid growth of the number of cells followed by a slowdown and ultimate balancing act at a relatively unchanging number of cells? (SL) (AP: SP 2, 2.B–E; IB: 1.6)

2. Figure 5 shows the actual growth curves of two populations. Both curves have time on the *x*-axis. Which curve do you think is for the global human population in billions of people from 1800 to the present, and which curve is for a microbe called *Lactobacillus plantarum* on a log scale grown at 35° C? Explain the reasoning you used to make your claim. (HL, DBQ, NOS) (AP: SP 1–2, 2.A,C,D; IB: C.5)

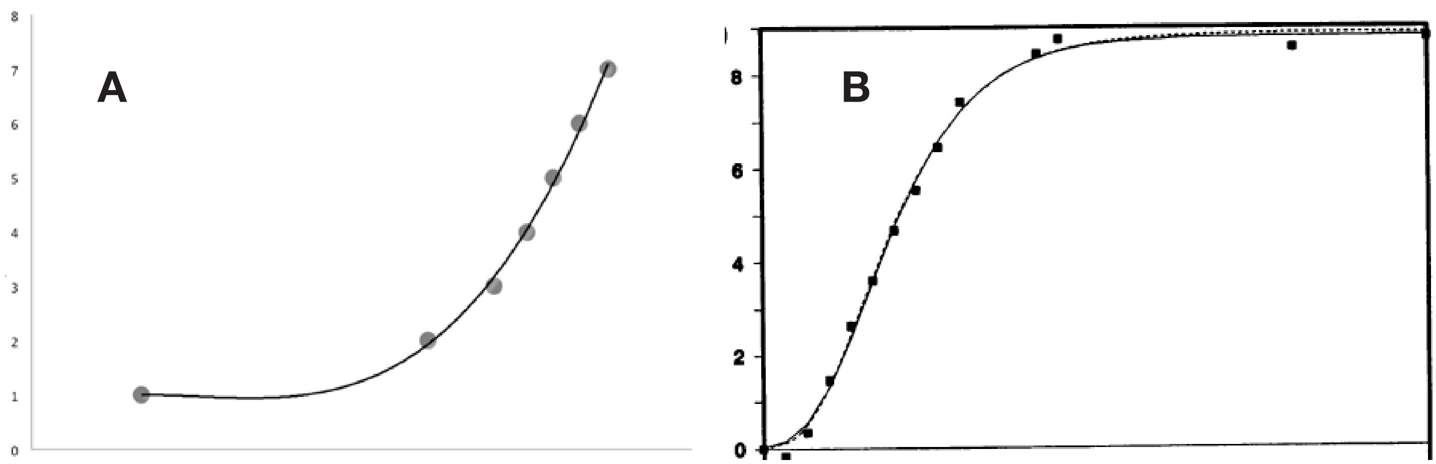

Figure 5. Two growth curves of real populations. Sources: M. H. Zwietering, I. Jongenburger, F. M. Rombouts, and K. Van't Riet (1990). "Modeling of the Bacterial Growth Curve." *Applied and Environmental Microbiology*, 56(6), 1875–1881, and Wikipedia (https://en.wikipedia.org/wiki/File:Human_population_growth_from_1800_to_2000.png).

3. Determine whether the following statement is true or false and explain your reasoning for your choice: Diseases are mostly abnormalities of regulation, where too little or too much of something is made. (SL) (AP: 2.A–2.E; IB: 6.1–6.6, 11.1, 11.3, D.1–D.6)

Part I: Everything Is Regulated

CHAPTER 1: THE WISDOM OF THE BODY

1. Think of a time when you were preparing to perform in some way in front of an audience (give a speech, play a solo in a concert, run a race, etc.). In small groups, discuss with your classmates how your body reacts (i.e., how did you physically feel) as the moment of a performance approaches. Come up with a list of those reactions, and propose some ideas to explain these physiological reactions. (SL) (AP: D.2; IB: 6.1, 6.4, A.3, D.2, D.4)

2. The body can largely take of itself. So what is the function doctors? (SL) (AP: 2.A–2.E; IB: 6.1–6.6, 11.1, 11.3, D.1–D.6)

3. When your body gets cold, you shiver. When your body gets hot, you sweat. Why do you think your body resists these changes in temperature? What other changes are resisted by your body? (SL) (AP: 2.C, 4.A; IB: 2.5, A.3)

CHAPTER 2: THE ECONOMY OF NATURE

1. List and describe as many factors in nature that can keep populations from growing out of control. (SL) (AP: 2.C; IB: C.5)

Part II: The Logic of Life

CHAPTER 3: GENERAL RULES OF REGULATION

1. Enzyme A regulates (promotes and suppresses) the function of enzyme B, and enzyme B regulates the function of Enzyme C. What is the relationship between enzyme A and enzyme C? (SL) (AP: 2.C; IB: 2.5)
2. Study Figure 6. (SL, MQ) (AP: SP 1, 2.C; IB: 4.1, 8.1, 11.3, A.3, C.5)
   a. Use arrows and descriptions to explain how the firing of the rubber band is regulated (suppressed and also promoted) by the firing mechanism.
   b. The way that the firing mechanism in Figure 6 works is by using a system called double-negative feedback. Identify a system in nature that you think might also be regulated by a double-negative feedback mechanism and is analogous to the rubber band firing mechanism. What part of the system plays the part of the pulley in the middle? The rubber band? The trigger arm?

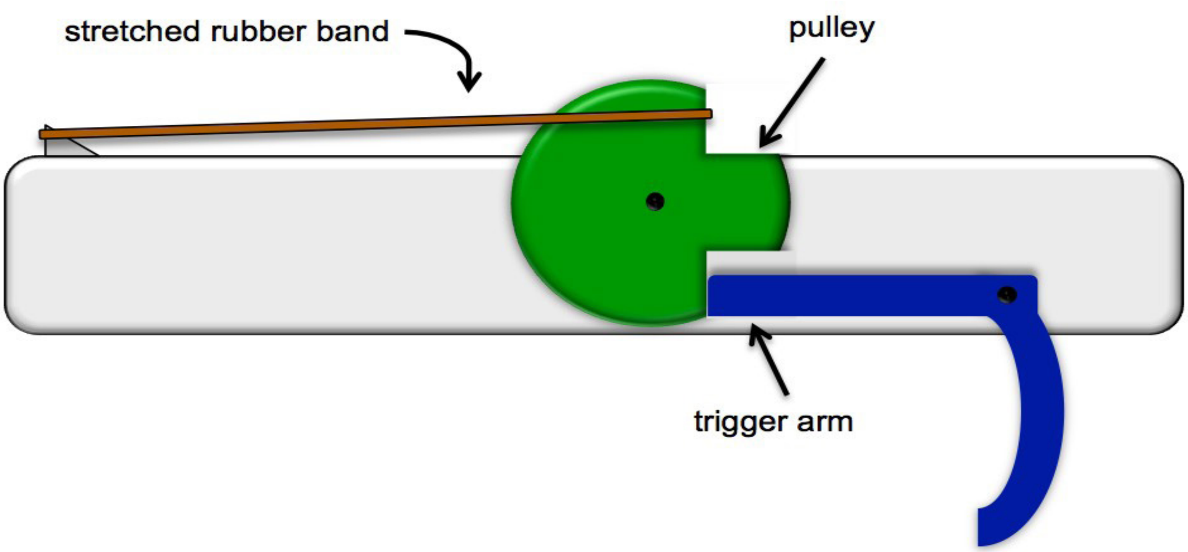

Figure 6. A possible simple firing mechanism for a rubber band.

3. Chapter 3 recounts how two biologists, Jacques Monod and François Jacob, discovered the general rules of enzyme regulation in a microbe called E. coli. In 1961, long after their discoveries, Monod and Jacob famously claimed that it was a "well- known axiom that anything found to be true of E. coli must be true of Elephants." What do you think is true about nature's regulatory mechanisms that allowed Monod and Jacob to make this claim? (HL) (AP: SP 7, 1.B; IB: C.5)

1. Consider the following claim: The cholesterol molecule is vital for life. Is this claim true or false? Explain why you think so. (HL) (AP: 2.B, 4.A; IB: 1.3, 2.3, 6.2, D.1, D.3)

2. In the middle of the past century, physiologist Ancel Keys discovered that firemen in Naples, Italy, who lived on diets high in fresh produce had low blood cholesterol and few heart attacks. He also found low blood cholesterol and few heart attack rates in poor people in Spain who had diets low in expensive foods like meats. Keys compared these findings to the high blood cholesterol of American businessmen and concluded that wealthier people had diets rich in fats, which was causing them to have more heart attacks than other groups. Keys medical colleagues were skeptical. (HL, NOS) (AP: 2.B, 4.A; IB: 1.3, 2.3, 6.2, D.1, D.3, D.4)

   a. Using your knowledge of how science works, comment on why you think that Ancel Keys's colleagues were skeptical of his claim.

   b. If you were Ancel Keys, what kind of a study would you conduct to answer the skeptical questions from your colleagues?

3. What does it mean for a person to be *homozygous* for a trait? *Heterozygous*? Is one better than the other? Explain your answer. (SL) (AP: 3.A, 3.B; IB: 3.1, 3.3, 3.4, 10.1)

4. Figure 7 shows the biosynthetic pathway of cholesterol. If you were to try to regulate this series of reactions, even shut them down completely, where do you think would be a good place to intervene? Why? (SL) (AP: SP 1, 2.C; IB: 2.1, 2.3, 2.5)

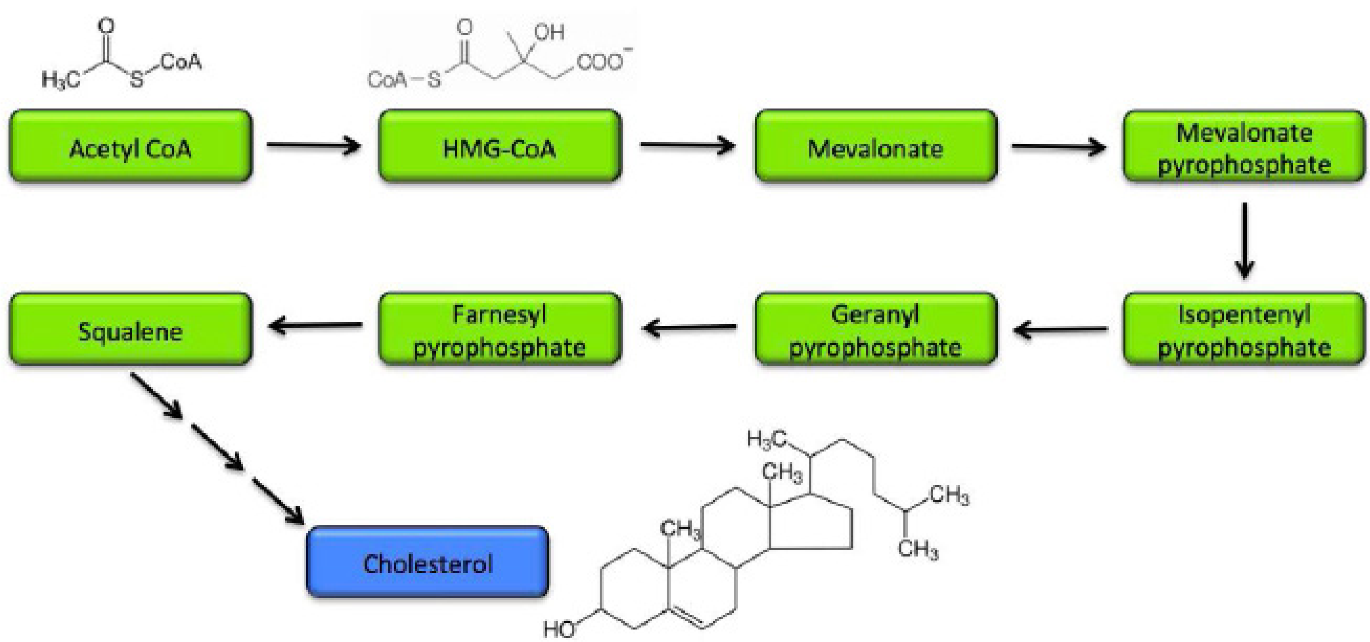

Figure 7. A simplified version of the cholesterol biosynthesis pathway—the process actually requires more than 30 enzymes. The first two structures that begin the pathway are shown for reference, as is the structure of the final product, cholesterol. The arrows represent the enzymes that catalyze each reaction as well as the order of the structures as they are synthesized.

1. Karyograms are photos of the chromosomes found in the nucleus of an organism's cells. A karyogram shows both sets of chromosomes an individual received from its two parents as they appear during Prophase of the cell cycle. Study the human chromosome karyograms in Figure 8. (SL) (AP: 3.A; IB: 3.2)
   a. Which karyograms show a biologically female karyotype? Which show a biologically male karyotype? How do you know?
   b. Which karyograms show chromosomal abnormalities? How do you know there is an abnormality?
   c. Extension: Do some additional research to identify each chromosomal abnormality and describe its symptoms.

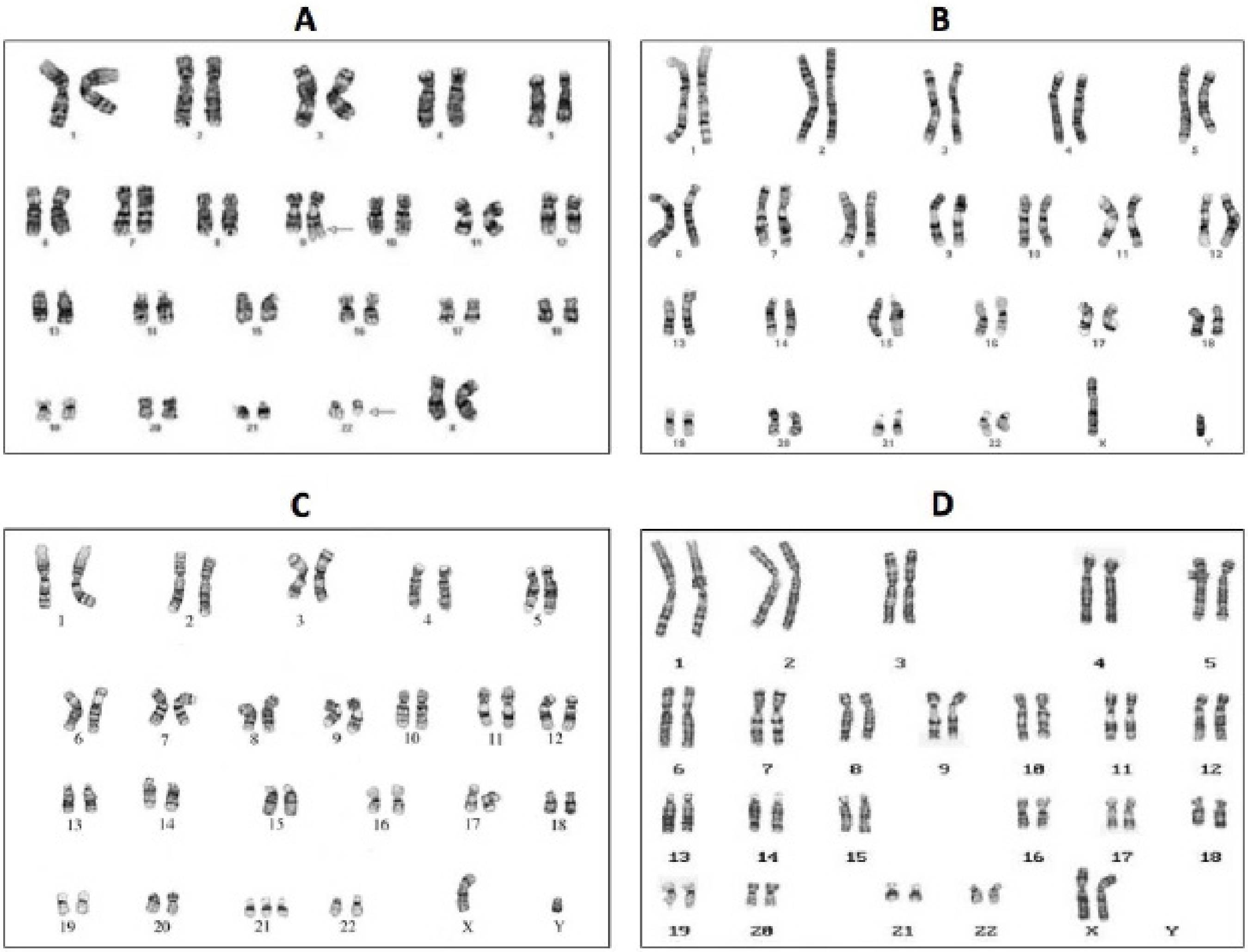

Figure 8. Four different human chromosome karyograms.

2. Which factors from the list below are possible causes of cancer? (SL) (AP: 2.E, 3.C; IB: 1.6, 3.4, 6.4)

I. Viruses
II. Radiation
III. Chromosomal abnormalities
IV. Genetic mutations
V. Smoking
VI. Some chemicals

   a. II and V only
   b. II, IV, and V only
   c. II, III, IV, and V only
   d. All of the factors listed can cause cancer

CHAPTER 6: SOME ANIMALS ARE MORE EQUAL THAN OTHERS

1. Herbivores eat plants. Plants cover the landscape across most areas of the Earth. Explain why the herbivores do not eat up all the plants. (SL, MQ) (AP: AP 1, 2.A, 2.E; IB: C.1, C.4, C.5)
2. Study the food chain pyramids shown in Figure 9. (SL, MQ) (AP: AP 1, 2.A, 2.E; IB: 4.1, 4.2, C.1, C.4, C.5)
    a. For each of the Grass → Prairie Dog → Coyote pyramids, explain why they are shaped the way they are.
    b. For each of the Phytoplankton → Zooplankton → Squid → Penguin pyramids, explain why they are shaped the way they are.
    c. Imagine that squid are the primary consumers of zooplankton and are also the primary food for penguins. Describe what might happen to the pyramid of numbers if the squid began disappearing from this marine ecosystem.
    d. Often trophic pyramids like these are drawn as triangles with smooth sides. Why might blocks like the ones shown in Figure 9 be more representative of the actual relationships between trophic levels?

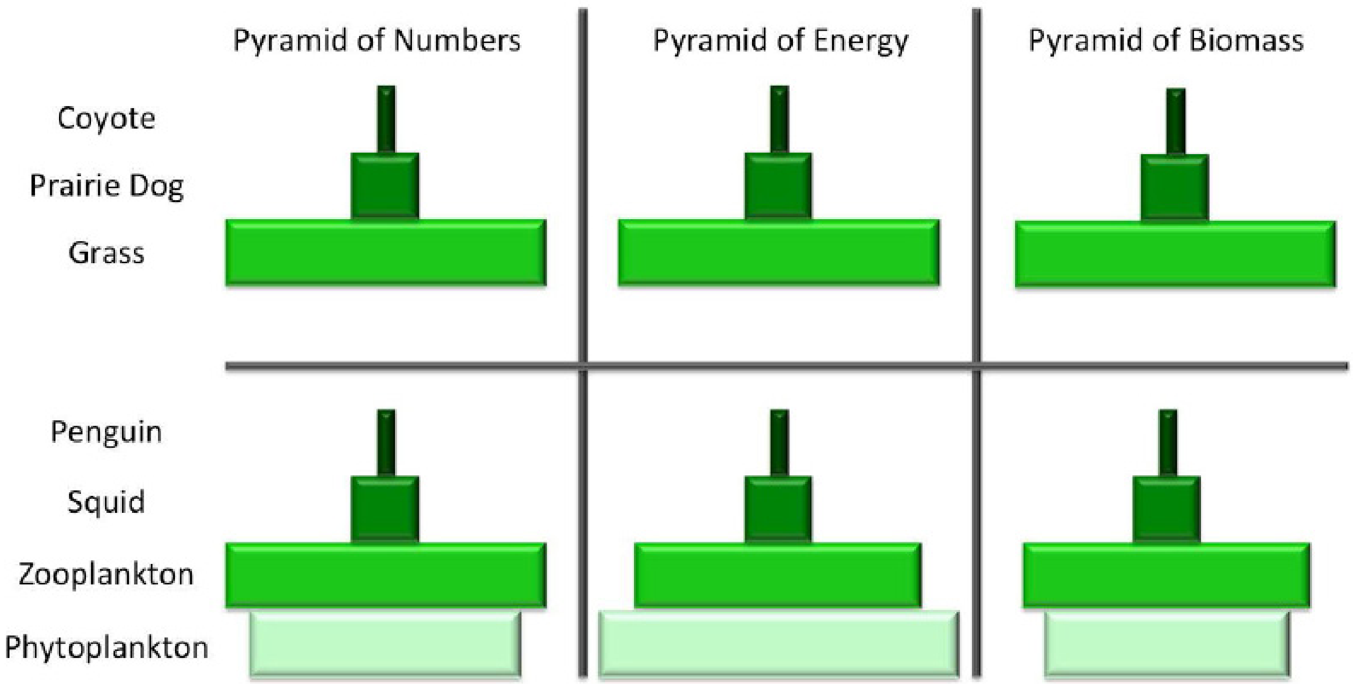

Figure 9. The three basic trophic pyramids found in food chains.

CHAPTER 7: SERENGETI LOGIC

1. When an ecosystem ecologist looks at landscape full of interacting plants and animals, all kinds of questions about how ecosystems function come to mind, and they are not that easy to answer. For example, in an African savanna, the following observations can be made: Gazelles, zebras, and wildebeest eat grass, but wildebeest eat a lot of grass; giraffes eat the leaves of acacia trees; lions and cheetahs eat zebras, gazelles, and wildebeest; more lightning-caused fires burn when there is more grass; more acacia trees grow when there are fewer fires. Predict how this savanna ecosystem might change if the cheetah and lion populations decline due to a feline (cat) virus. (SL, MQ) (AP: SP 3, SP 4, SP 6, 2.A, 2.D, 2.E, 4.A, 4.B, 4.C; IB: 4.1, 4.2, 4.4, 5.3, 9.3, 9.4, C.1–C.6)
2. True or False: Disturbances/perturbations to ecosystems—like fires, disease, or floods—can often shed light on how an ecosystem works. Explain your answer. (SL) (AP: 2.E, 4.A, 4.B; IB: 4.1–4.4, C.1–C.6)

1. Study Figure 10. Imagine that this food web exists in a California coastal range canyon. Indicate with up and down arrows what might happen to the populations of each species if roads and homes were built up into the canyon and the coyotes were pushed out of the canyon. (SL, MQ) (AP: SP 1, 4.A, 4.C; IB: 4.1, C.1–C.5)

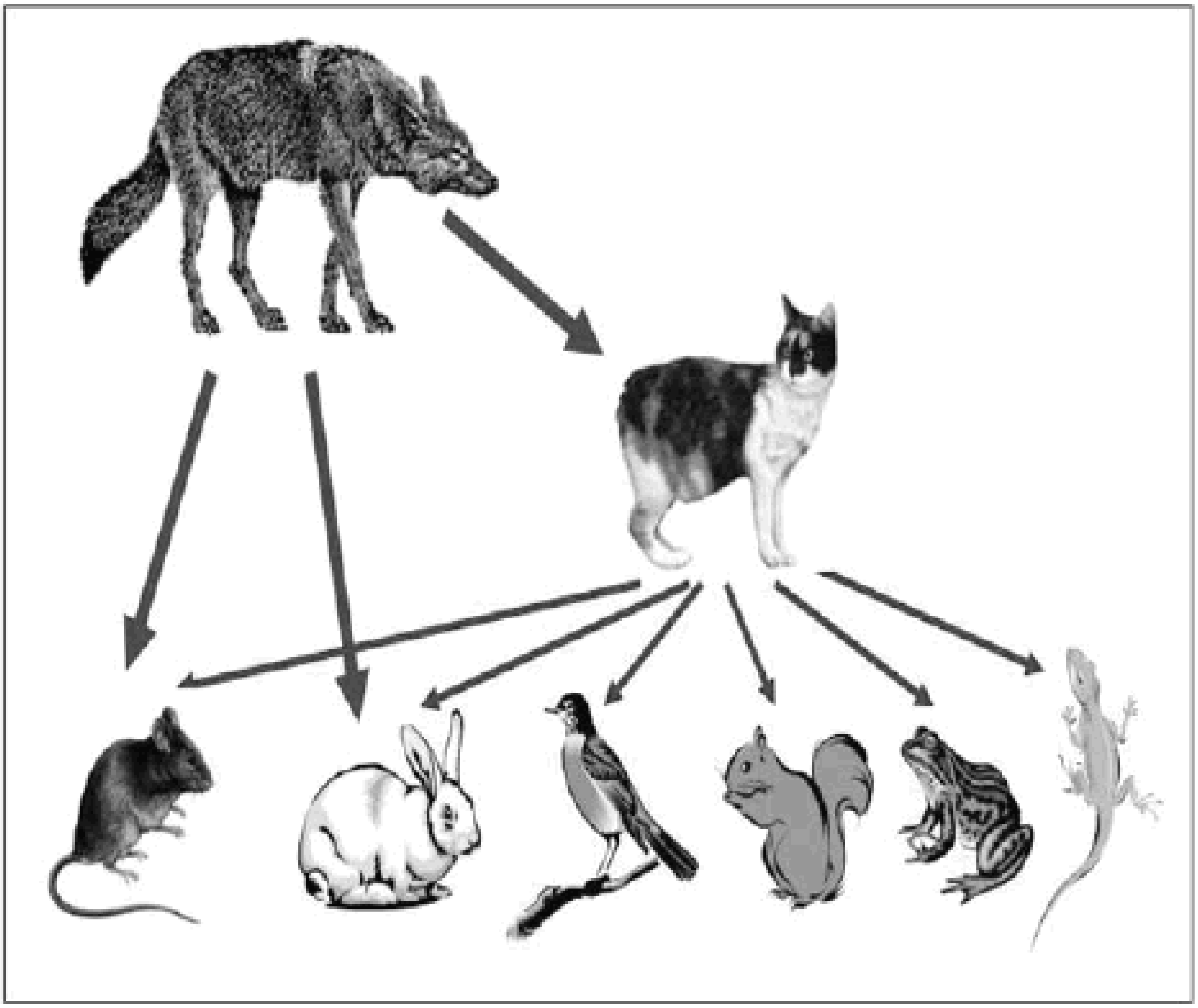

Figure 10. Example of a mesopredator interaction involving coyotes, domestic cats, and small vertebrates. Figure is from J. S. Brashares, L. R. Prugh, C. J. Stoner, and C. W. Epps (2010). "Ecological and Conservation Implications of Mesopredator Release." In J. Terborgh and J. A. Estes (eds.), *Trophic Cascades: Predators, Prey, and the Changing Dynamics of Nature*. Washington, DC: Island Press, 221–240. Copyright © 2010 Island Press. Reproduced by permission of Island Press, Washington, DC.

2. True or False: Algae are photosynthetic, so they produce oxygen as a by-product of photosynthesis. When an aquatic ecosystem is over-fertilized by excess nutrients, the nutrients cause an excess of photosynthesis and a surge in the production of oxygen. The increase in oxygen in the water makes it easier for aerobic organisms like fish to survive and thrive. Explain your answer. (HL, MQ) (AP: 4.A; IB: C.3, C.6)

3. Why do you think many insects and weeds have developed resistance to the pesticides we have invented to control them? *Hint: The answer lies in Evolutionary Theory*. (SL) (AP: 1.A, 1.C; IB: 5.2, 10.3)

4. Study Figure 11. In this experiment, ecologist, Henry Wilbur, at Duke University, tested the ***generalizing hypothesis*** that high population densities produce toads with lower body masses by the time they finish metamorphosis (when the tadpole tails disappear). He reared tadpoles in 0.9 m^2 enclosures in a pond and adjusted how many tadpoles were living in each enclosure: 20, 40, 80, 160, and 320 tadpoles, respectively. (HL, DBQ, NOS) (AP: SP 1–3, SP 5–7, 2.C; IB: C.5)

a. Write the prediction Wilbur likely made given the experimental methods he used to test his hypothesis. Hint: A prediction describes what data you should be able to measure as the result of an experiment given the methods you used.
b. Why do you think it was important for Wilbur to replicate his experiment four times?
c. Identify what you see in the graph.
d. From what you see in the graph, interpret the effect you think higher tadpole densities have on their final body masses.
e. Propose an explanatory hypothesis for the results Wilbur observed in his experiment. Hint: Think about factors that put more pressure on individuals in populations as population density increases.

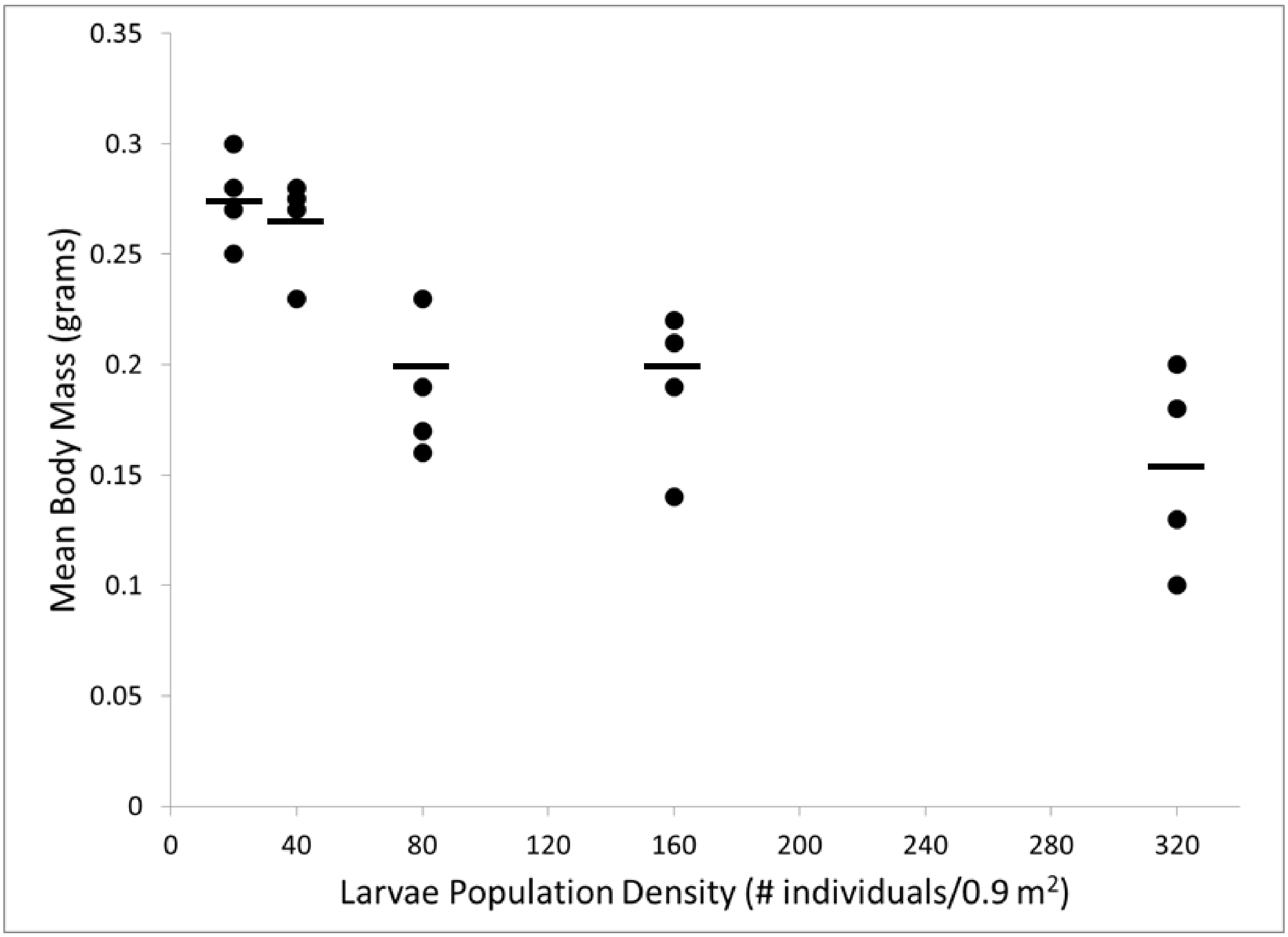

Figure 11. Mean body mass at the end of metamorphosis for American toad (*Bufo americanus*) larvae (tadpoles). Circles are the means for each of the four replicates in each population density. Horizontal lines are the overall means of the replicates at each population density. Figure adapted from H. M. Wilbur (1977). "Density-Dependent Aspects of Growth and Metamorphosis in *Bufo americanus*." *Ecology*, 58(1), 196–200.

Table 2. Number of dung flies (Sepsis cynipsea) alive as a function of time (days) after inoculation with parasitic mites (Pediculoides mesembrinae). Data are from O. Y. Martin and D. J.Hosken (2009). "Longevity and Developmental Stability in the Dung Fly Sepsis cynipsea, as Affected by the Ectoparasitic Mite, Pediculoides mesembrinae." *Journal of Insect Science*, 9(1), 66.

No mites	Day	0	10	11	12	17	28	34	37	38	39	42	43	44
	# of flies alive	20	18	16	14	13	12	8	6	5	4	3	2	0
Mites	Day	0	5	7	9	10	11	12	14	18	19	28	—	—
	# of flies alive	20	17	15	13	11	9	4	3	2	1	0	—	—

5. Two Swiss ecologists, Oliver Martin and David Hosken, were interested in the relationship between parasites and their hosts. They chose dung flies (*Sepsis cynipsea)* and parasitic mites (*Pediculoides mesembrinae*) that use the flies as hosts to test the hypothesis that parasites compete directly with their hosts for resources and can reduce their ability to survive (i.e., reduce their longevity). The researchers randomly selected 10 male and 10 female flies that had been infected with mites and the same number of flies that had no mites. The experimental flies were placed singly in vials with ample sugar and water and checked daily for death. The longevity for the flies was recorded in days. The researchers' data are recorded in Table 2. (HL, DBQ, NOS) (AP: SP 1, SP 3, SP 5–7, 4.A, 4.B; IB: C.5)

a. Graph the data from Table 2 in a way that you think illustrates how the presence of mites affects the longevity of the flies.

b. Summarize the results of this experiment, and compare the results in light of the researchers' hypothesis.

c. What do the results suggest about the effect of parasites on their hosts? In other words, what hypothesis might explain these results?

CHAPTER 9: TAKE 60 MILLION WALLEYE AND CALL US IN TEN YEARS

1. True or False: In a food chain there are three trophic levels: producers, herbivores, and carnivores. Explain your answer. (SL) (AP: 2.A; IB: 4.2)

2. In Lake Ontario, the native lake trout (*Salvelinus namaycush*) began declining during the first half of the past century. By 1950 the lake trout population of Lake Ontario had gone extinct. In the 1960s, fish biologists began adding lake trout fry (little fish) from fisheries to Lake Ontario to restore the population. These initial efforts were unsuccessful, because the small fish that were stocked were being eaten by invasive sea lampreys (*Petromyzon marinus*). Control of the lampreys began in 1971, and lake trout stocking efforts restarted in 1973. Lake trout stocking increased from 66,000 fish in 1973 to 1.9 million fish in 1985 and was maintained above 2 million fish annually until 1992. By 1993 the lake trout began reproducing naturally. Information from: E. L. Mills, J. M. Casselman, R. Dermott, J. D. Fitzsimons, G. Gal, K. T. Holeck, and E. S. Millard (2003). "Lake Ontario: Food Web Dynamics in a Changing Ecosystem (1970–2000)." *Canadian Journal of Fisheries and Aquatic Sciences*, 60(4), 471–490. (SL) (AP: 2.A; IB: 4.1, 4.2)

a. Why do you think it was necessary to add so many fish to Lake Ontario every year?

b. Why were fish biologists from the United States and Canada so interested in restoring the Lake Ontario lake trout population?

1. When countries go to war, humans are not the only species that are affected. What effects do you think the Vietnam War had on the ecosystems of Vietnam? What effects do you think the Iraq War had on the ecosystems of Iraq? How might the effects of the two wars have been similar? How might they have been different? (SL) (AP: SP 7, 4.C; IB: 4.2, C.3, C.4)

2. Consider an ecosystem that has lost most of its large animal species. If you were in charge of restoring the ecosystem and its functions, which types of animal species (i.e., herbivores, predators) would you bring back first? Second? Explain your reasoning. (SL) (AP: SP 1, SP 7, 2.A; IB: 4.2, C.3, C.4)

3. Other than helping bring animals and plants back to a damaged ecosystem, discuss what roles humans can play in restoring and conserving large natural areas. (HL) (AP: SP 7; IB: C.4)

4. Coffee is the second most-consumed drink in the world; water is the first. To grow enough coffee to supply global demand, expansive landscapes have been converted from natural habitat to coffee plantations. However, some methods for growing coffee might be less destructive, and might even be beneficial to ecosystem function. Table 3 shows the results of a study that compared the species richness (number of species) of beetles, bats, and frogs between tropical montane cloud forest ecosystems and shaded coffee plantations (SCPs) that are grown in the same habitat as tropical forest trees—called an agroecosystem. The researchers chose to study the three groups of species because their presence is an indicator of a healthy and functioning ecosystem. The researchers argue that the shaded coffee plantation/forest tree combination produces a matrix of habitat across the landscape that surrounds and connects tropical montane cloud forest fragments and reduces the environmental impact of coffee plantations in general. (HL, DBQ, NOS) (AP: SP 1, SP 4, SP 5, SP 7, 4.A, 4.C; IB: C.4, C.5)

a. Summarize in words what you see in Table 3.

b. In the journal article the researchers published about the study, they claim that their results "demonstrate the importance of agroecosystems such as SCP for the conservation of biodiversity in this type of landscape."

i. What is the evidence for this claim?

ii. What more data would you like to see to further test this claim?

Table 3. The number of species (species richness) of beetles, bats, and frogs counted in tropical montane cloud forests, shaded coffee plantations, and in both types of habitats combined. Data are from E. Pineda, C. Moreno, F. Escobar, and G. Halffter (2005). "Frog, Bat, and Dung Beetle Diversity in the Cloud Forest and Coffee Agroecosystems of Veracruz, Mexico." *Conservation Biology*, 19(2), 400–410.

Species	*Cloud forest*	*Shaded coffee plantation*	*Both habitats*
Beetles	8	16	17
Bats	10	10	11
Frogs	16	13	21

1. Figure 12 shows the estimated human population in Europe from 1000 to 1700. (SL, DBQ) (AP: SP 1, SP 7, 2.D, 4.B; IB: 4.1)

a. What regulatory factors do you think were responsible for the pattern you see in the graph?
b. What lessons can humans learn from studying the European populations from 1000 to 1700?

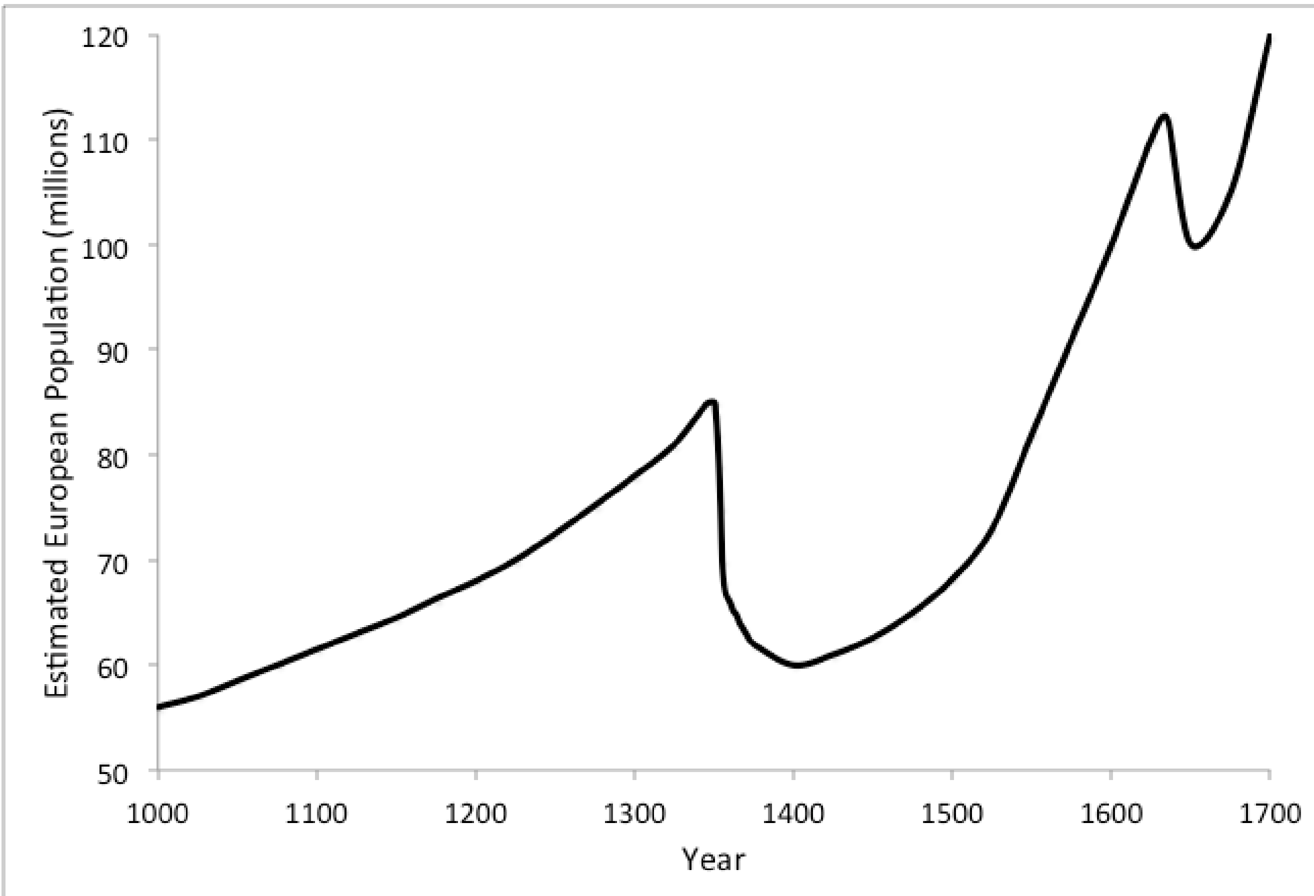

Figure 12. Estimated European human population from 1000 to 1700. Figure adapted from W. L. Langer (1964). "The Black Death." *Scientific American*, 210, 114–121.

2. Make a list of what you think are the biggest ecological/environmental challenges facing humans today. List them in order of importance/urgency. Next, list the challenges in order of easiest to solve to most difficult to solve. As you study your two lists, make an argument for the conservation strategy you propose we should take as we meet these challenges and attempt to solve them. (HL) (AP: SP 1, SP 7, 4.A–4.C; IB: 4.1, C.3, C.4)

IV. DISCUSSION QUESTIONS

Introduction: Miracles and Wonder

1. Sean Carroll states, "Diseases, it turns out, are mostly abnormalities of regulation, where too little or too much of something is made." He then gives three examples: diabetes, atherosclerosis, and cancer. Identify and describe another human disease that results from an abnormality of regulation. For this disease, how has medical technology attempted to help reset its regulation? (SL)

2. Describe how advances in medicine and food production have affected the natural regulation of the global human population. (SL)

3. Describe how growth in the global human population has affected the natural regulation of a nonhuman population. (SL)

Part I: Everything Is Regulated

CHAPTER 1: THE WISDOM OF THE BODY

1. Walter Cannon worked near the front line in a medical hospital in northern France during World War I. Cannon was able to use the knowledge of physiology he gained earlier while experimenting on animals to save hundreds of soldiers from certain death from the symptoms of shock. In the years that have followed, doctors have been able to use Cannon's techniques to reverse the symptoms of shock for countless numbers of people. How do you feel about the roles animals have played—and the prices they have paid—in advancing medical treatments for humans? (SL) (AP: SP 7, 2.D; IB: 6.1, 6.2)

2. Near the end of Chapter 1, Sean Carroll writes, "Combined with his knowledge of the control of digestion, respiration, heart rate, and the responses to stress in animals, Cannon was provoked to think about the body's ability to react to disturbances and yet to maintain critical functions within fairly narrow ranges." (SL, NOS) (AP: SP 7, 2.D; IB: 6.1, 6.2)
   a. Describe one of Cannon's discoveries that helped lead him to conclude that the body is able to "maintain critical functions within fairly narrow ranges."
   b. What term was coined by Walter Cannon to "describe the steady states maintained in the body"?

CHAPTER 2: THE ECONOMY OF NATURE

1. On pages 38 and 39 of *The Serengeti Rules*, Sean Carroll describes the arctic food chain illustrated by Charles Elton (Figure 2.3) that ends with the arctic fox. (SL, MQ) (AP: SP 1, 2.A; IB: 4.1, 4.2)
   a. Sketch this food chain, and connect each member of the chain with an arrow that indicates the direction of energy flow.
   b. Explain the origin of the energy that allows this food chain to exist.

2. In Charles Elton's 1926 book, *Animal Ecology*, he wrote, "It is clear that animals are organized into a complex society, as complex and as fascinating to study as human society," and "subject to economic laws." Here Elton cleverly stole an idea from economics and used it as an analogy for the interactions he observed in animal communities; a reasoning strategy called abduction. Identify the characteristics of human economic systems that Elton argued were analogous to animal communities. What do you think of Elton's analogy? (HL, NOS) (AP: SP 1, SP 2, 2.A; IB: C.1, C.2, C.5)

3. Study Figure 2.4 on page 42 of *The Serengeti Rules*. This figure shows the number of rabbit and lynx furs (pelts) sold by trappers to the Hudson Bay Trading Company of Canada. Now go to Google Images and search "lynx hare population cycle." The graphs that you will see are from textbooks used in biology courses. Compare these graphs to the original Charles Elton graph. (HL, DBQ, NOS) (AP: SP 5; IB: C.1, C.5)
   a. Comment on how well the patterns in the textbook graphs match the original graph.
   b. How do you explain the differences you see?
   c. What was Charles Elton trying to infer from the lynx-hare data? What are the limitations of the inference?

4. In 1997, ecologist Nils Stenseth and his colleagues published a study on the Canadian lynx and rabbit population cycles first made famous by Charles Elton in 1924. The researchers expanded on Elton's lynx-rabbit food chain relationship by including dozens more interactions at play in the lynx-rabbit ecosystem. Study Figure 13. (HL, DBQ, NOS) (AP: SP 1, SP 7, 2.A; IB: 4.2, C.1, C.2, C.5)

a. Explain how these food web models build on the population cycles of the lynx and rabbits (snowshoe hares) revealed by the Hudson Bay Trading Company data.

b. Using the links in the graphs, sketch the food web for the wolf that includes the animals that it eats (excluding the lynx) and their food sources. When do you think the wolves will seek out the lynx as prey?

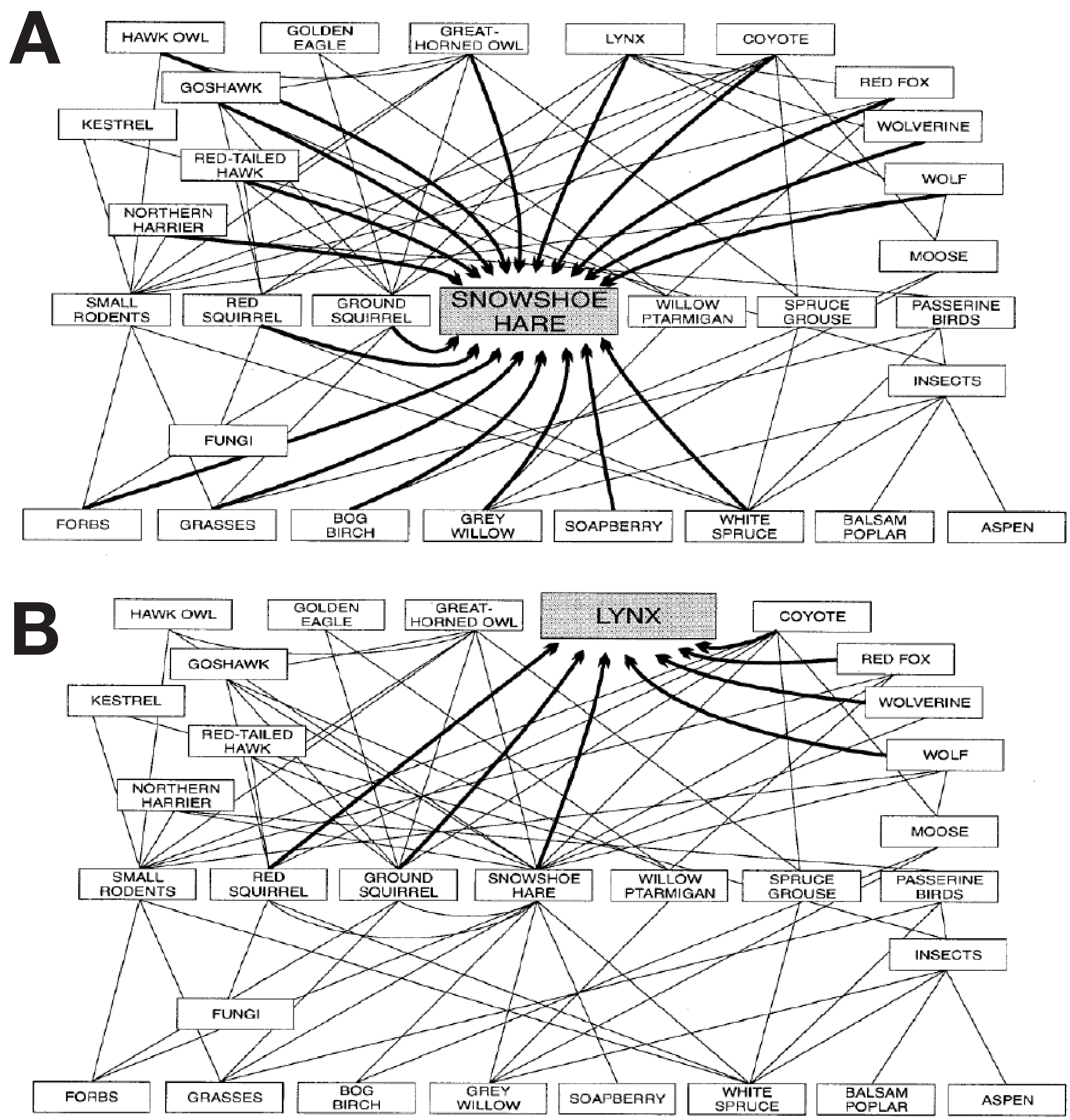

Figure 13. Arrows indicate the food web links that directly influence the snowshoe hare and lynx populations. In these graphs, the directions in which the arrows point are not be interpreted as the direction of energy flow. Figure is from N. C. Stenseth, W. Falck, O. N. Bjornstad, and C. J. Krebs (1997). "Population Regulation in Snowshoe Hare and Canadian Lynx: Asymmetric Food Web Configurations between Hare and Lynx." *Proceedings of the National Academy of Sciences*, 94, 5147–5152.

CHAPTER 3: GENERAL RULES OF REGULATION

1. Study Figure 3.2 on page 56 of *The Serengeti Rules*. In the figure caption, Sean Carroll writes, "That pause and second growth curve became the basis of Monod's thesis and eventual Nobel Prize." Here Carroll refers to the 1965 Nobel Prize in Physiology or Medicine awarded to Jacques Monod and François Jacob. How did this one discovery by Monod lay the foundation for a Nobel Prize 25 years later? (HL) (AP: SP 7; IB: B.1)
2. Turn to pages 56 and 57 of *The Serengeti Rules*. Here Sean Carroll describes a critical Nature of Science moment in the career of Jacques Monod. (SL, NOS) (AP: SP 1, SP 4, SP 6; IB: 2.5)
   a. Describe the observation Monod made as a result of his experiment, which is illustrated by Figure 3.2.
   b. Write the hypothesis Monod proposed to explain his observation.
   c. Briefly outline the method Monod designed to test his hypothesis.
   d. Write the prediction Monod made for what he expected to see if his hypothesis was supported.

CHAPTER 4: FAT, FEEDBACK, AND A MIRACLE FUNGUS

1. On pages 79 and 80 of *The Serengeti Rules*, Dr. Carroll describes several experiments that allowed Joe Goldstein and Mike Brown to understand how blood cholesterol is regulated. Choose one of the experiments and outline its components: (HL, NOS) (AP: SP 1, SP 4, SP 6, C.2; IB: 1.3, 2.5, 6.2, D.3)
   a. Describe an ***observation*** about cholesterol regulation Goldstein and Brown made as a result of their research.
   b. Write a potential ***research question*** inspired by the above observation.
   c. Write the ***hypothesis*** Goldstein and Brown proposed to answer their research question.
   d. Briefly outline the ***method*** Goldstein and Brown designed to test their hypothesis.
   e. Write the ***prediction*** Goldstein and Brown made for what they expected to see if their hypothesis was supported.
2. Figure 14 shows the molecular structures of cholesterol and ergosterol. These two molecules are found in the cell membranes of fungi (ergosterol) and animals (cholesterol) and are essential for proper membrane function in both groups of organisms. (HL) (AP: SP 7, 1.B, 2.C, 3.D; IB: 1.3, 2.3, 5.4, 8.1)
   a. Identify the class of biological molecules that contains ergosterol and cholesterol: proteins, lipids, carbohydrates, or nucleic acids. How do you know?
   b. Why do you think these two molecules are essential for membrane function in fungi ***and*** in animals?
   c. Explain why Akira Endo studied 6,000 different species of fungi in an attempt to discover an enzyme that might inhibit the synthesis of cholesterol in humans.
   d. What do the similarities between the two molecules suggest about the evolutionary relationship between fungi and animals?

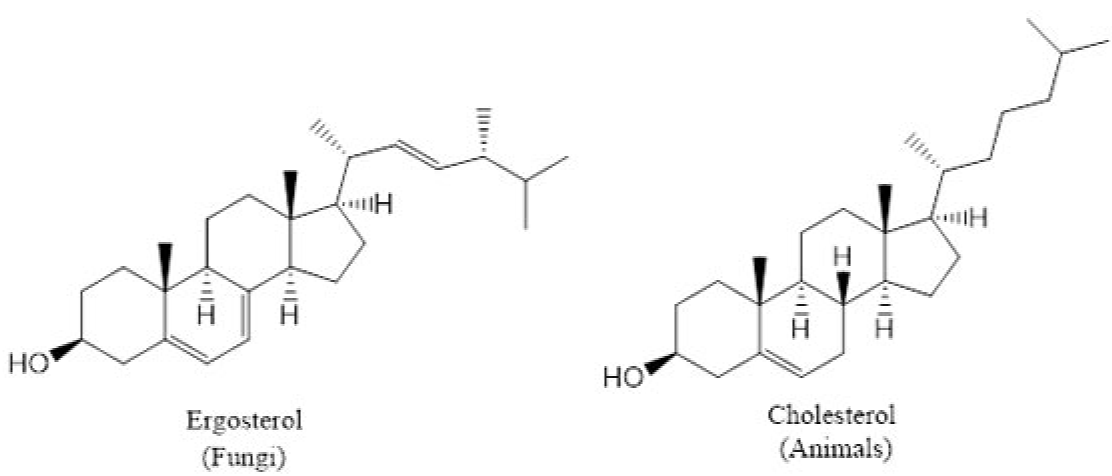

Figure 14. The molecular structures of the membrane sterols ergosterol and cholesterol.

3. A recent study by Tufts University and published in the *Journal of Health Economics* estimates that the average cost of developing a new drug and bringing it to market exceeds $2.5 billion. The probability that a new drug makes it through all phases of testing and is approved for medical use is less than 10%. These high costs tend to keep most drug development in the hands of for-profit companies like Merck, the company that developed the first statin drugs for lowering blood cholesterol levels. Discuss the medical and individual costs and benefits of this drug development model. Data mentioned are from J. A. DiMasi, H. G. Grabowski, and R. W. Hansen (2016). "Innovation in the Pharmaceutical Industry: New Estimates of R&D Costs." *Journal of Health Economics*, 47, 20-33. (HL, NOS) (AP: SP 7; IB: 2.1, 6.2, B.4)

CHAPTER 5: STUCK ACCELERATORS AND BROKEN BRAKES

1. Explain how Janet Rowley's work on chromosome abnormalities laid the foundation for the understanding that cancer is a genetic disease. (SL) (AP: 3.A, 3.C; IB: 1.6, 3.2)

2. Why are many types of cancer described as diseases of cell cycle regulation? (SL) (AP: 3.A, 3.C; IB: 1.6, 3.2)

3. Sean Carroll explains that two common events in the genesis of cancer are stuck "accelerators" and broken "brakes." For many of a person's genes there are two copies, one inherited from a person's father, and one from a person's mother. For types of cancer that involve broken brakes and stuck accelerators, which case requires both genes to be malfunctioning? Which requires just one malfunctioning gene? Explain. (SL) (AP: 3.A, 3.B, 3.C; IB: 1.6, 3.2)

4. On pages 102–104, Sean Carroll describes the development of a drug called Gleevec. The Howard Hughes Medical Institute provides an online narrated animation of how Gleevec works at http://www.hhmi.org/biointeractive/gleevec. Watch the animation, and then sketch and annotate a model of Gleevec's mode of action. (SL, MQ) (AP: 3.A, 3.B, 3.C; IB: 1.6, 3.2, B.4)

5. On page 105, Sean Carroll states, "Mistakes get made in the copying of DNA. Most of these mutations are harmless, but some create the potential for disaster." Explain the positive role that some of these DNA copying mistakes can play in evolution. (SL) (AP: SP 1, 1.A, 3.C; IB: 2.7, 10.3)

Part III. The Serengeti Rules

CHAPTER 6: SOME ANIMALS ARE MORE EQUAL THAN OTHERS

1. Robert Paine used a kick-it-and-see approach to understand and reveal the role *Pisaster* starfish play in their tidal zone ecosystem. Paine was able to show that the starfish function as the keystone species in their habitat. Compare Paine's approach to the approach used by Jim Estes and John Palmisano to investigate the role sea otters play in their ecosystem. (SL, NOS) (AP: SP 1, SP 7, 4.B, 4.C; IB: 4.1, 4.2)

2. Consider the results Robert Paine's *Pisaster* starfish experiment. Compare the results of his starfish removal experiment to how many cancers work. (HL, MQ) (AP: SP 7, 3.A, 3.B, 3.C, 4.B, 4.C; IB: 1.6, 4.1, 4.2)

3. In a 1980 lecture and associated paper in the *Journal of Animal Ecology*, Robert Paine introduced the field of ecology to the idea of the trophic cascade. That same year, a group of ecologists led by Peter Price at the University of Illinois published a paper in the *Annual Review of Ecology and Systematics*, titled "Interactions among Three Trophic Levels: Influence of Plants on Interactions between Insect Herbivores and Natural Enemies." Without any mention of Paine's trophic cascade hypothesis (indeed, Price and his colleagues may have not had the chance to read Paine's paper), the ecologists made the following statements: "Consideration of the third trophic level is indispensable to an understanding of any part of the system. We cannot understand the plant-herbivore interaction without understanding the role of enemies. We cannot understand predator-prey relationships without understanding the role of plants. Enemies [of insect herbivores] should be considered as mutualists with plants and part of plant defense." (HL, NOS) (AP: SP 7, 4.B, 4.C; IB: 4.1, 4.2)

   a. How does Jim Estes's sea otter trophic system relate to these statements?
   b. "The enemy of my enemy is my friend" is an ancient proverb that dates back to the 4th century BCE and has been used as a guiding principle during wartime and in other international affairs. How does this proverb relate to Paine's trophic cascade hypothesis and the above claim by Price and his colleagues?

4. From observations they made in a freshwater stream in Oklahoma, ecologist Mary Power and her colleagues hypothesized that bass act as a keystone species and regulate the populations in their food web. Sketch and label a diagram that illustrates the method used by Power and her team to test their hypothesis. (SL, MQ) (AP: SP 1, SP 4, 4.B, 4.C; IB: 4.1, 4.2)

5. On pages 125–126, Sean Carroll describes and illustrates several different trophic cascades. Choose a three-level food chain and a different four-level food chain not mentioned here and illustrate the cascades that exist in these two systems. (SL, MQ) (AP: SP 1, SP 4, 4.B, 4.C; IB: 4.1, 4.2)

CHAPTER 7: SERENGETI LOGIC

1. Hairston et al. (1960) introduced their fellow ecologists to the Green World Hypothesis when then famously said, "Herbivores are held down in numbers by predators below the level at which they damage the vegetation." Describe what other factors are missing from this statement that also regulate population sizes. (SL) (AP: 4.B, 4.C; IB: 4.1, 4.2)

2. Figure 15 shows the trophic level occupied by a terrestrial animal species as a function of its mean body mass. (SL, DBQ) (AP: SP 5, SP 6, 4.B, 4.C; IB: 4.1, 4.2)

   a. Which species are herbivores and which are carnivores? How do you know?
   b. Taking these terrestrial animals as an entire group, describe the relationship between mean species body mass and its trophic level, and propose an explanation for this relationship.

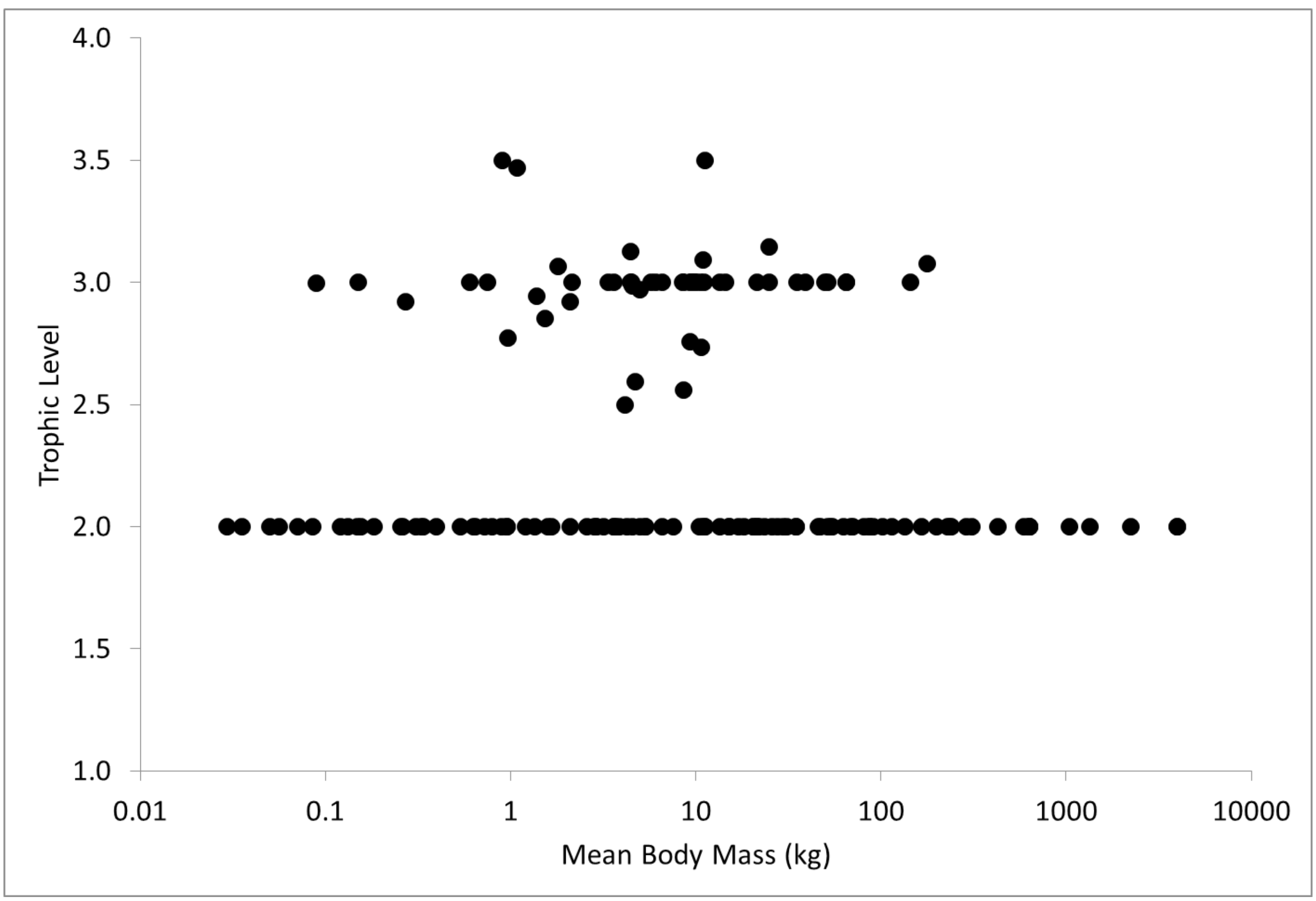

Figure 15. Trophic level as a function of species body mass compared for species occupying terrestrial environments. Each datum represents a species mean value (n = 107 species). Data are from M. A. Tucker and T. L. Rogers (2014). "Examining Predator-Prey Body Size, Trophic Level and Body Mass across Marine and Terrestrial Mammals." *Proceedings of the Royal Society of London B: Biological Sciences*, 281(1797), 2014–2103.

3. If the herbivores that live in the Serengeti are too large to be preyed on by carnivores, what factor most regulates their population sizes? Compare this factor to the regulation systems discovered in enzyme production by Jacques Monod. (SH, MQ) (AP: SP 7, 4.B; IB: 4.1, 4.2)

4. Explain why Jacques Monod was able to answer his questions about regulation rather quickly (in a few years), while it took ecologist Tony Sinclair decades to answer his questions about regulation. (SL, NOS) (AP: SP 4, SP 7; IB: 2.5, 4.1, 4.2)

5. Construct a table that combines the rules of regulation followed by enzymes with the General Rules of Regulation and the Serengeti Rules shown on page 153. How are the rules similar? How are they different? (SL, MQ) (AP: SP 1, 4.B; IB: 2.5, 4.1, 4.2)

CHAPTER 8: ANOTHER KIND OF CANCER

1. Cancer is a disease of cell cycle regulation. In Chapter 8, Sean Carroll describes how a surge in phosphorus in Lake Erie has catalyzed massive algal blooms, a stuck accelerator perhaps. Choose either the nitrogen cycle or the carbon cycle and describe a situation—local, regional, or global—where the environment may be suffering from cancer-like symptoms. (SL) (AP: SP 7, 3.A, 3.B; IB: 1.6, 3.4, 4.3, C.6)

2. Sean Carroll closes Chapter 8 with the claim that "the ultimate causes of these cancers are not the missing predators, they are a matter of humans doing too much." Indeed, for human societies to exist, we must grow food, lots of it, and keep insects, fungi, and herbivores from eating the food we grow and predators from eating the animals we raise. What recommendation(s) do you have that could bring natural regulation back to the ecological systems on which we depend? (SL) (AP: SP 1, SP 7; IB: 4.3, C.6)

CHAPTER 9: TAKE 60 MILLION WALLEYE AND CALL US IN TEN YEARS

1. On pages 171–172, Sean Carroll describes an experiment conducted on some Wisconsin lakes by aquatic ecologists Stephan Carpenter and James Kitchell. Reread these two pages, and outline the ecologists' experiment using the guidance below. (HL, NOS) (AP: SP 3, SP 4, SP 6, 4.B; IB: C.2–C.4)

   a. Write a potential ***research question*** that guided Carpenter and Kitchell in their research on lake trophic cascades.
   b. Write the ***hypothesis*** Carpenter and Kitchell proposed to answer their research question.
   c. Briefly outline the ***method*** Carpenter and Kitchell designed to test their hypothesis.
   d. Write the ***prediction*** Carpenter and Kitchell made for what they expected to see if their hypothesis was supported.
   e. Describe the ***results*** of their experiment. How well did their results support their hypothesis?

2. Study the diagram on page 173. Bass were added to the Tuesday Lake, Wisconsin, food web. Compare this diagram to Figure 16, which was published in 1998 by Jim Estes and his colleagues in the journal Science. How are the two trophic cascades, one freshwater and the other marine, similar? How are they different, given the regulation of the health of their aquatic ecosystems? (SL, MQ, DBQ) (AP: SP 7, 4.B, 4.C; IB: 4.1, 4.2)

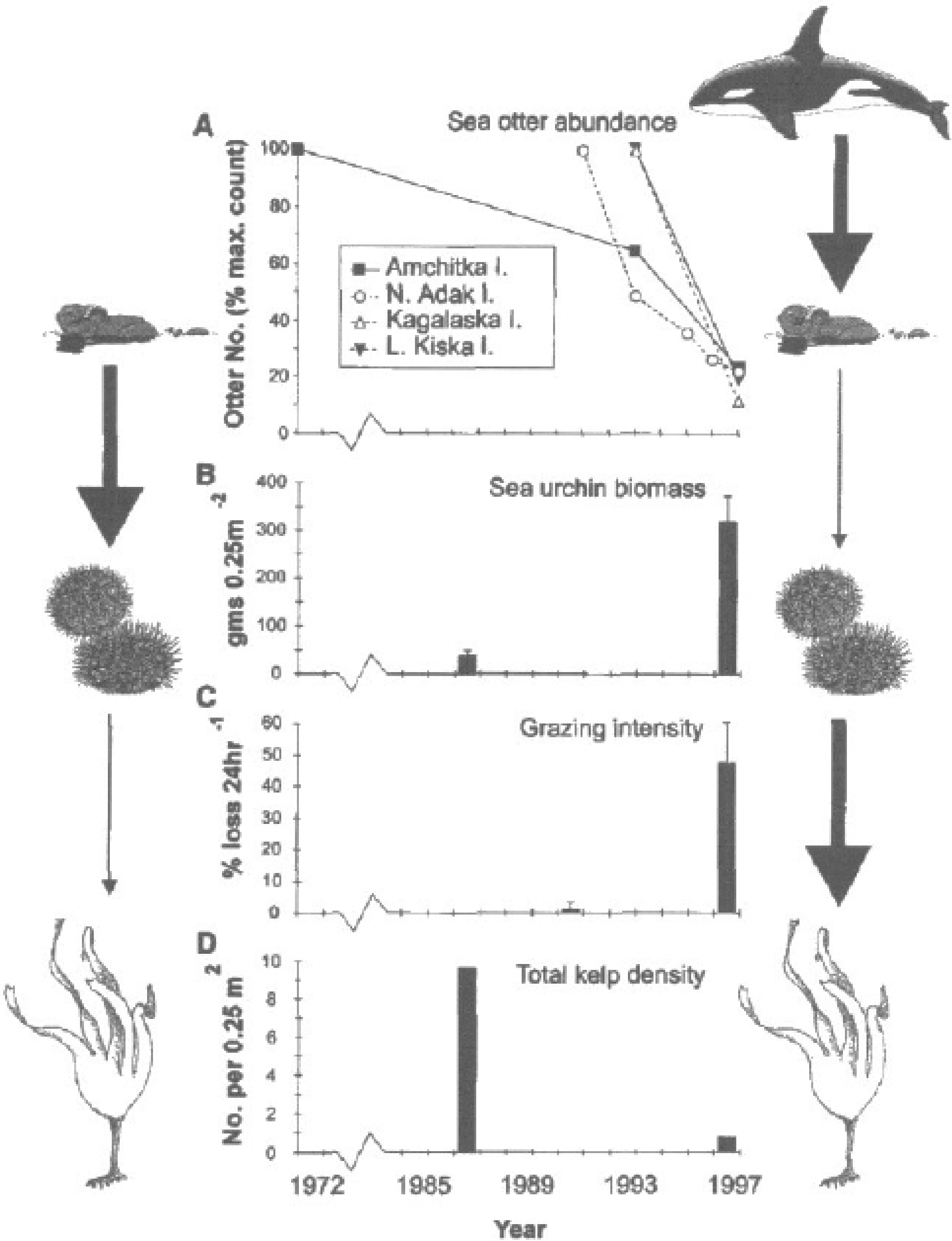

Figure 16. Changes in sea otter abundance over time at several islands in the Aleutian archipelago with concurrent changes. Panel A shows sea otter abundance around four different islands from 1972 to 1997. Panel B shows the amount of sea urchins (i.e., sea urchin biomass) in 1987 and 1997. Panel C shows the amount of kelp that sea urchins eat over a 24-hour period (i.e., grazing intensity) in 1987 and in 1997. Panel D shows the number of kelp plants in a specific area (i.e., density of kelp) in 1987 and 1997. The thickness of the arrows illustrate the strength of the effect one species has on the species below it in the food web. Figure is from J. A. Estes, M. T. Tinker, T. M. Williams, and D. F. Doak (1998). "Killer Whale Predation on Sea Otters Linking Oceanic and Nearshore Ecosystems." *Science*, 282, 473–476. Reprinted with permission from AAAS.

3. On pages 177–182, Sean Carroll describes the reintroduction of wolves to Yellowstone National Park in the United States. From Carroll's description of the Yellowstone ecosystem, diagram the Yellowstone food web with respect to the following animals: elk, bison, beavers, coyotes, pronghorn antelope, cottonwood, aspen, willow, deer, bighorn sheep, and mountain goats. Indicate with up arrows (increase in population) and down arrows what effect (if any) the wolf reintroduction had on the Yellowstone populations of these organisms. (SL, MQ) (AP: SP 1, 4.B, 4.C; IB: 4.1, 4.2)

4. Skepticism is an essential component of how science works. Describe the skepticism of many ecologists about the trophic cascade hypothesis even after Robert Paine had shown experimental support for it. (SL, NOS) (AP: SP 5, SP 6, 4.B, 4.C; IB: 4.1, 4.2)

CHAPTER 10: RESURRECTION

1. Yellowstone National Park covers roughly a 9,000 km^2 area in the northwest corner of Wyoming. In contrast, Gorongosa National Park covers about 4,000 km^2 in the middle of Mozambique. Yellowstone has been protected as a national park since 1872, while Gorongosa and its animals have suffered through 15 years of destruction (1977–1992) from civil war. Describe a few things we can learn from Yellowstone that will help us restore and conserve Gorongosa. What are some things we can learn from Gorongosa that will help us understand how Yellowstone functions as an ecosystem? (SL, NOS) (AP: SP 7; IB: 4.1)

2. Analyze the data in Table 4. Summarize the recovery trends for the animals listed in the table. Propose some reasons for why some animals have recovered well, while others have not. (SL, DBQ) (AP: SP 5, SP 6; IB: C.3)

Table 4. Historical and recovery population estimates for nine of the largest animals of Gorongosa National Park. Data are from M. Stalmans, M. Peel, and T. Massad (2014). "Aerial Wildlife Count of the Parque Nacional Da Gorongosa, Mozambique, October 2014." Parque Nacional Da Gorongosa. Available at http://www.biofund.org.mz/wp- content/uploads/2015/03/GorongosaAerialWildlifeCount2014-GeneralReport-December2014- compress.pdf.

Species	*1972 Estimate*	*2000 Estimate*	*Estimated loss 1972–2000 (%)*	*2014 Counts*	*Current recovery as a percentage of historical levels*
Buffalo	14,000	<100	>99	>650	<5
Elephant	2,500	<200	>92	>500	>20
Hippo	3,500	<100	>97	>430	>15
Waterbuck	3,500	<300	>91	>34,000	>100
Zebra	3,500	<20	>99	<40	<2
Blue wildebeest	6,500	<20	>99	>350	<7
Sable antelope	700	<100	>86	>750	>100
Lichtenstein hartebeest	800	<100	>88	>600	>75
Lion	200	?	?	>50	>25

3. As Greg Carr and his scientific team planned the restoration strategy for Gorongosa, why did they decide to restore large herbivores like buffalo, zebra, and elephants instead of large carnivores like lions? (SL) (AP: SP 1, 4.C; IB: C.2–C.5)

4. The constant presence of tourists at national parks like Yellowstone inevitably has an effect on the animals that live there and their behaviors. A plan for the restoration and conservation of Gorongosa includes tourism. Discuss the costs and benefits of allowing tourism in natural places like Gorongosa and Yellowstone. (SL) (AP: SP 7; IB: C.2–C.5)

Afterword: Rules to Live By

1. In the Afterword of *The Serengeti Rules*, Sean Carroll states, "One coalition that I would like to see emerge is the entire biological community standing together to support ecological priorities. This means the molecular tribe, a very numerous and influential group, must get on board and use that influence to support ecological research and education." How might an acknowledgment and understanding of the thesis of this book—*everything is regulated*—by both groups function to see Carroll's hope through? (HL) (AP: SP 7)

2. Sean Carroll makes three points about the ecological challenges before us: (i) nothing gets conquered everywhere at once, (ii) important challenges can't wait until everyone gets on board, and (iii) individuals' choices matter. For each of these three points, chose a story of inquiry and discovery from *The Serengeti Rules* and explain how that story exemplifies the point. (HL, NOS) (AP: SP 7)

3. In a 1973 essay with the same name, geneticist Theodosius Dobzhansky made famous the idea that *nothing in biology makes sense except in the light of evolution*. From a careful reading of *The Serengeti Rules*, one could also argue that *nothing in biology makes sense except in the light of* ***regulation***. Do you agree or disagree with this claim? Why or why not? (SL) (AP: 2.A–2.E)

V. ASSESSMENT QUESTIONS

Introduction: Miracles and Wonder

1. Recall that osmosis is the movement of water across a selectively permeable membrane (e.g., a cell or tissue membrane), usually in response to different concentrations of solutes (dissolved minerals) on the two sides of the membrane. Osmoregulation is thus how organisms maintain an internal balance between water and dissolved minerals (solutes). Different ways to regulate water and solutes have evolved in different groups of animals. However, each of the unique systems involve similar structures: tubes! Insects have tubes called Malphigian tubules, earthworms have tubes called nephridia, and vertebrates have tubes in their kidneys called nephrons. (SL) (AP: 2.B; IB: 1.3, 11.3)
   a. Why do you think tubes have evolved as a way to perform osmoregulation?
   b, What do you think the role of surface area to volume ratio is in osmoregulation with tubes?
   c. What role do you think natural selection has played in the evolution of osmoregulation strategies in animals?
   d. Why is the regulation of water and minerals important for the survival of all types of organisms?

2. Use the data in Table 5 to construct a graph of the global human population as a function of time. Label the x-axis and the y-axis. (SL, DBQ) (AP: SP 1, SP 2, SP 5; IB: 4.1)
   a. Identify what you see in your graph.
   b. Interpret what you see in your graph: Considering all the information in your graph, what do you think it means for the Earth and its ability to support the global human population over the next several decades?
   c. Use the data in your graph to predict when the global human population might reach 14 billion. Explain the logic you used to make this prediction.
   d. What do you think the information in your graph means for the Earth's plant populations and the other species of animals (humans are animals too!) that also use the Earth's resources?
   e. As an extension, find and sketch a graph of the global human population that begins 12,000 years ago—around 10,000 BCE (before the common era). Circle the part of the 12,000-year-long graph that includes the data from Table 5.

Table 5. Global human population in billions every other year, 1961–2015. Data are from the World Bank (http://data.worldbank.org/indicator/SP.POP.TOTL?end=2015&start=1960&view=chart).

Year	*Population*	*Year*	*Population*	*Year*	*Population*	*Year*	*Population*
1961	3.07	1975	4.07	1989	5.19	2003	6.35
1963	3.19	1977	4.21	1991	5.37	2005	6.51
1965	3.33	1979	4.36	1993	5.54	2007	6.68
1967	3.46	1981	4.51	1995	5.71	2009	6.84
1969	3.61	1983	4.68	1997	5.87	2011	7.01
1971	3.76	1985	4.84	1999	6.03	2013	7.18
1973	3.91	1987	5.01	2001	6.20	2015	7.35

CHAPTER 1: THE WISDOM OF THE BODY

1. On page 19 of *The Serengeti Rules*, Dr. Carroll writes, "To figure out what stopped the activity of the stomach and intestines under emotional stress, Cannon and his students conducted a series of simple but fundamental studies." Choose one of Cannon's experiments that Carroll then describes and outline his methodology using the guidance below. (SL, NOS) (AP: SP 1, SP 3-SP 6; IB: 6.1)
    a. What was Walter Cannon's research question?
    b. What hypothesis (observed pattern or explanation) was he testing?
    c. List briefly the method Cannon took to test the hypothesis.
    d. Given the methods he designed, describe the data Cannon predicted he would record if his hypothesis was correct.
    e. Construct a labeled graph that models what Cannon should be able to produce from this experiment.

CHAPTER 2: THE ECONOMY OF NATURE

1. In his book *On the Origin of Species*, Charles Darwin tried to estimate what uncontrolled elephant population growth might look like. He wrote, "The elephant is reckoned the slowest breeder of all known animals, and I have taken some pains to estimate its probable minimum rate of natural increase; it will be safest to assume that it begins breeding when thirty years old, and goes on breeding till ninety years old, bringing forth six young in the interval, and surviving till one hundred years old." For ease in calculations, assume that every 100 years, each female elephant produces three additional females and three additional males.
    a. Starting with one female (and a male, of course), graph a simple population growth model for female elephants over a 1,000 year period.
    b. The African bush elephant (Loxodonta africana) has an average mass of around 6,000 kg (13,200 lbs). The mass of the Earth is around 6 X 1024 kg. How many years would unchecked growth take for African bush elephants to equal or exceed the mass of the Earth?
    c. How would you describe your 1,000 year population growth model in words to another person without showing the person your graph?
    d. What factors present in a real ecosystem will most likely keep the elephant population in the model from growing out of control?
2. Table 6 shows a sample of data on Canada lynx furs and snowshoe hare pelts sold to the Hudson Bay Trading Company of Canada by fur trappers in the 1800s. Construct a line graph of the rabbit pelt and lynx fur data, with both animals on the same graph. (SL, DBQ) (AP: SP 1, SP 5, SP 6, 4.A, 4.B; IB: 4.1, 4.2, C.2, C.5)

a. Identify what you see in your graph.
b. Interpret what it might mean.

Table 6. Snowshoe hare and lynx data from the Hudson Bay Trading Company of Canada from 1860 to 1889. Estimated from C. S. Elton (1924). "Periodic Fluctuations in the Numbers of Animals: Their Causes and Effects." British Journal of Experimental Biology, 2, 119–163.

Year	*Snowshoe hare pelts*	*Canada lynx furs*	*Year*	*Snowshoe hare pelts*	*Canada lynx furs*
1860	2,000	25,000	1875	5,000	15,000
1861	1,000	20,000	1876	5,000	20,000
1862	1,500	15,000	1877	10,000	30,000
1863	4,000	5,000	1878	9,000	40,000
1864	100	2,000	1879	7,000	30,000
1865	15,000	10,000	1880	1,500	20,000
1866	14,000	15,000	1881	1,000	15,000
1867	11,000	35,000	1882	1,500	10,000
1868	8,000	70,000	1883	1,000	10,000
1869	3,500	80,000	1884	2,000	20,000
1870	500	40,000	1885	5,000	40,000
1871	500	10,500	1886	13,000	70,000
1872	1,000	8,000	1887	14,000	80,000
1873	100	2,000	1888	13,500	60,000
1874	6,000	10,000	1889	9,000	25,000

Part II: The Logic of Life

CHAPTER 3: GENERAL RULES OF REGULATION

1. Many bacteria must be able to synthesize the tryptophan amino acid for survival. In 1953, Jacques Monod showed how tryptophan synthesis is regulated in bacteria when he discovered the tryptophan operon. The tryptophan operon is composed of the genetic sequence that codes for an enzyme called tryptophan synthetase. Tryptophan synthetase catalyzes the final two steps of the pathway responsible for tryptophan synthesis. Upstream of this tryptophan operon is the gene that codes for a protein that represses the tryptophan operon and its ability to catalyze tryptophan. However, the repressor is unable to function unless it has the amino acid tryptophan bound to it! (HL, MQ) (AP: SP 1, 2.C, 3.B; IB: 2.2, 2.7, 3.1)
   a. Using a model similar to those found on page 68 of *The Serengeti Rules*, show how the tryptophan operon regulatory system works.
   b. Using Figure 3.6 on page 70 for inspiration, construct a model for how tryptophan regulates its own synthesis.

2. Evolution Extension: Hypothesize why the evolution of regulatory mechanisms like the ones discovered by Jacques Monod and François Jacob have not always produced systems as simple as A promotes the function of B or A suppresses the function of B. (HL) (AP: 1.A, 1.C; IB: 5.2, 10.3)

CHAPTER 4: FAT, FEEDBACK, AND A MIRACLE FUNGUS

1. There are two types of hypotheses tested by science: generalizing hypotheses and explanatory hypotheses. A ***generalizing hypothesis*** is a description of a pattern in nature (e.g., exercise increases heart rate), while an ***explanatory hypothesis*** is an explanation for an observation made in nature (e.g., exercise produces excess CO_2, which lowers blood pH, which stimulates the heart to beat faster and get rid of the CO_2, bringing the blood pH back to normal). (HL, NOS) (AP: SP 3–SP 7)
   a. What is the relationship between a **hypothesis** and a **prediction**?
   b. Explain how you might set up an experiment to test the generalizing hypothesis that *exercise increases heart rate*.
   c. Describe the prediction you should be able to make from your planned test. In other words, what measurements do you think you should be able to record as a result of your experiment that will support your hypothesis?

2. Table 7 shows data from an experiment conducted by medical researchers Michael Brown, Suzanna Dana, and Joseph Goldstein from the University of Texas in the early 1970s. The three scientists were trying to home in on a substance in the blood that controls the synthesis of cholesterol and ***hypothesized*** that lipoproteins—proteins in the blood that transport cholesterol—may play a role in regulating an enzyme called reductase that is involved in the synthesis of cholesterol. (HL, DBQ, NOS) (AP: SP 1, SP 5, SP 6, 3.D, 3.E; IB: 2.3–2.5, 6.2)
   a. Graph all the data in Table 7 in one figure. What is/are the independent variable(s)? What is/are the dependent variable(s)?
   b. Describe what you see in your graph.
   c. Explain what you think the graph means in light of the researchers' hypothesis.

Table 7. Data from an experiment by Brown, Dana, and Goldstein performed on cells called fibroblasts. Serum refers to blood serum taken from unborn calves that have been adjusted to have different fractions (levels) of lipoprotein. Data are from M. S. Brown, S. E. Dana, and J. L. Goldstein (1973). "Regulation of 3-Hydroxy-3-Methylglutaryl Coenzyme A Reductase Activity in Human Fibroblasts by Lipoproteins." *Proceedings of the National Academy of Sciences*, 70(7), 2162–2166. (— means that no data were taken at this serum fraction.)

Serum fraction (volume %)	*Reductase activity (pmol/minute per mg of lipoprotein)*		
	Whole blood serum	*Blood serum with only lipoproteins*	*Blood serum with no lipoproteins*
0	30.0	30.0	30.0
8	10.5	—	—
10	9.0	20.0	29.0
30	7.0	10.0	23.0

CHAPTER 5: STUCK ACCELERATORS AND BROKEN BRAKES

1. Cancer is often described as a disease of cell cycle regulation, in which cell division is unregulated and is speeding out of control. Imagine, as a model for cancer, a car with two brakes and two gas pedals (accelerators), one each on the floor of each of the two front seats. The car is speeding out of control. The hypotheses to explain the speeding car could be either broken brakes or stuck accelerators. (SL, MQ) (AP: SP 1, SP 6, 2.C, 2.D; IB: 1.6, 3.4, 10.1)
   a. If the brakes are the reason that the car is unstoppable, does one or both of the brakes need to be broken? Explain your reasoning.
   b. Given your answer to part (a), is a "broken brake" mutation a dominant or a recessive mutation? Explain your reasoning.
   c. If the accelerators are the reason the car is speeding out of control, does one or both of the accelerators need to be stuck? Explain your reasoning.

d. Given your answer to part (c) above, is a "stuck accelerator" mutation a dominant or a recessive mutation? Explain your reasoning.

e. How do you think the brakes and accelerators analogy above relates to the fact that we have two copies of each of the genes that are involved in regulating the cell cycle?

Part III: The Serengeti Rules

CHAPTER 6: SOME ANIMALS ARE MORE EQUAL THAN OTHERS

1. In the 1990s, ecologists Deborah Letourneau and Lee Dyer studied a tropical forest shrub called the piper plant and the various insect species that live on and near the shrub. A species of ant uses the piper plant as a home by hollowing out some of its branches and building colonies inside the hollow branch cores. The ants do not eat the plant's leaves. Instead, the leaves are consumed mostly by caterpillars. When the ants encounter caterpillars or caterpillar eggs on the plant's leaves, they either eat them or kick them off. Figure 17 is the result of one of Letourneau's and Dyer's experiments in which they compared control plots of piper plants, which contain ants and are shown as the round

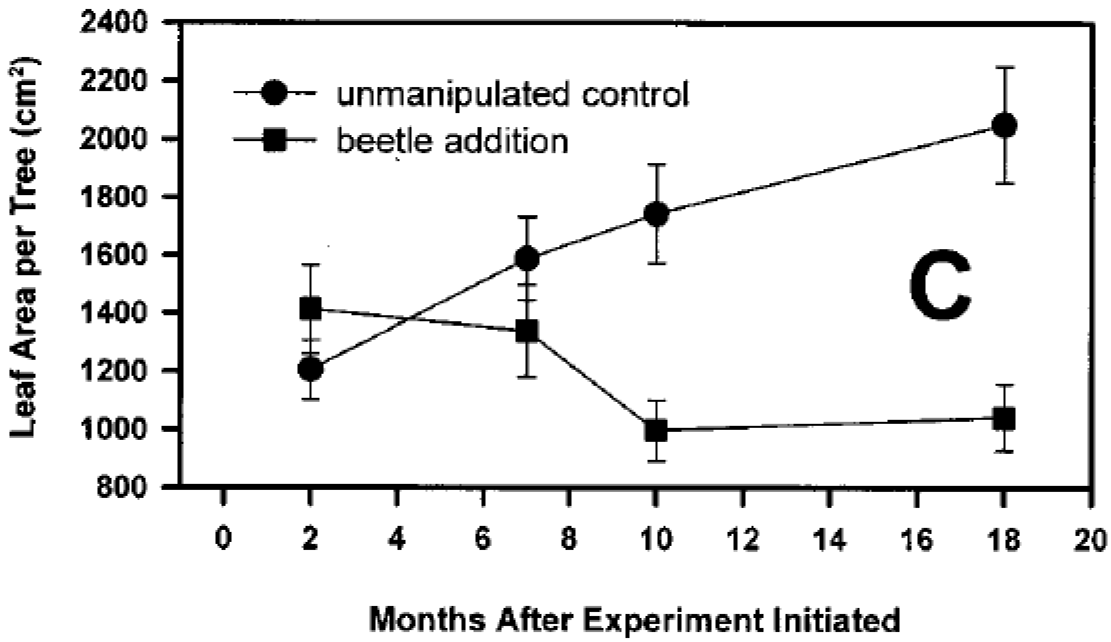

Figure 17. Mean leaf area per tree. Initial measurements were taken before (0 to 2 months) and after (7–18 months) beetles were added to 40 of 80 plants. The round symbols represent measurements taken of the control plants, to which beetles were not added. The square symbols represent measurements taken of the experimental plants to which beetles were added. Measurements were made on all leaves to calculate the mean leaf area per plant. Error bars represent standard error of the mean. Figure is from D. K. Letourneau and L. A. Dyer (1998). "Experimental Test in Lowland Tropical Forest Shows Top-Down Effects through Four Trophic Levels." *Ecology*, 79, 1678–1687.

symbols on the graph, to experimental plots to which they had added beetles that eat ants, which are shown as the squares. (HL, DBQ, MQ) (AP: SP 1, SP 5, 4.A, 4.B; IB: 4.1, C.1, C.2, C.5)

a. Compare the trends in mean tree leaf area per plot for both the plants with the beetle added and the control plants over the 18 months of the experiment.
b. Create a model that shows the expected interactions among the species for both the experimental and control plots. Include interactions between predatory beetles (if present), ants, herbivores of the piper plants, and the piper plants.

CHAPTER 7: SERENGETI LOGIC

1. Table 8 displays descriptive statistics on the size (body mass in kg) of terrestrial herbivores and carnivores. (HL, DBQ, NOS) (AP: SP 1, SP 2, SP 5, SP 6, 4.A, 4.B; IB: 4.1, C.5)

a. Sketch and label a bar graph of the means for these two groups of animals. Include SEM as error bars.
b. Compare the statistics of these two groups and propose some hypotheses for why the statistics are different for the two groups of animals.

Table 8. Descriptive statistics on body mass (kg) for terrestrial herbivores and carnivores. Data are from M. A. Tucker and T. L. Rogers (2014). "Examining Predator-Prey Body Size, Trophic Level and Body Mass across Marine and Terrestrial Mammals." *Proceedings of the Royal Society of London B: Biological Sciences*, 281(1797), 2014–2103.

	Terrestrial herbivores	*Terrestrial carnivores*
Count	98	50
Mean (kg)	192	18
Variance	394,487	1,115
Standard deviation	628	33
Standard error of the mean (SEM)	63	5
Minimum (kg)	0.03	0.09
Maximum (kg)	3,981	177
Range (kg)	3,981	177
Sum (kg)	18,782	877

2. Study Figure 18. The black dashed lines are the routes walked by a field ecologist, and the lighter dotted lines indicate how far on either side of the transect that the ecologist could detect individuals. Individuals are indicated by

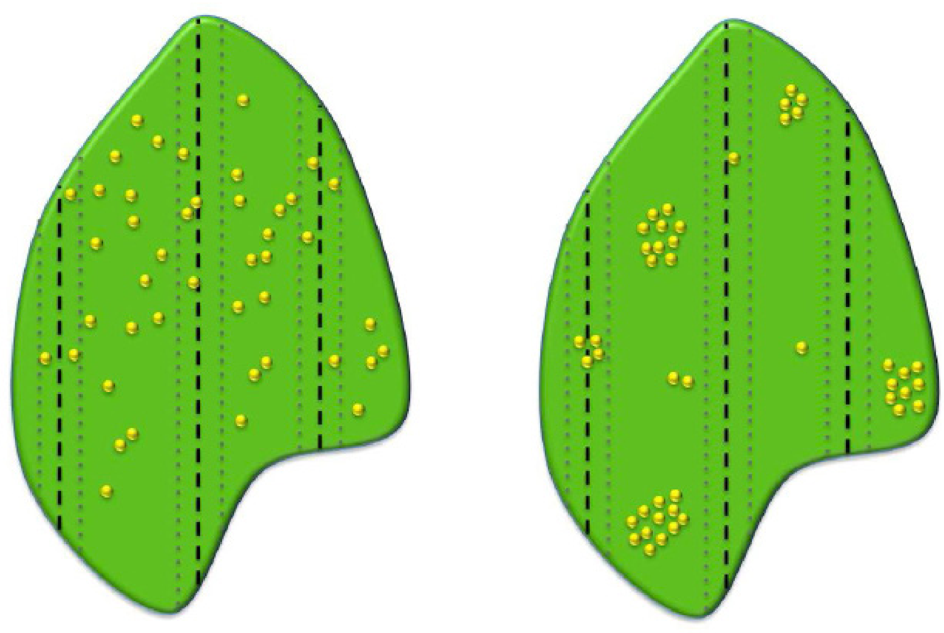

Figure 18. Two hypothetical landscapes where two species with different patterns of dispersion have been sampled using transects.

yellow dots. The total area of the habitat is 100 hectares (ha), and the area sampled with transects totals 20 ha. (HL, DBQ) (AP: SP 1, SP 7, 4.A; IB: C.5)

a. What is the estimated density (number of individuals/ha) of the species that are being sampled in habitat A? Habitat B? What is your percentage error for each estimate?
b. Does the sampling technique of using transects work better for the pattern of dispersion of the species in habitat A or in habitat B? Explain your answer.
c. Describe a different way to sample the individuals in each habitat that might yield a better estimate of the population size.

CHAPTER 8: ANOTHER KIND OF CANCER

1. Study the four graphs in Figure 19. The data in the graphs come from an experimental forest in North Carolina. Part of the forest was exposed to CO_2 levels meant to simulate the atmosphere predicted for the year 2050: 580 parts per million (ppm). Another part of the forest was left alone to experience the ambient CO_2 levels of 1996, when experiments on the forest began: 380 ppm. Researchers sampled four different types of arthropods in the two parts of the

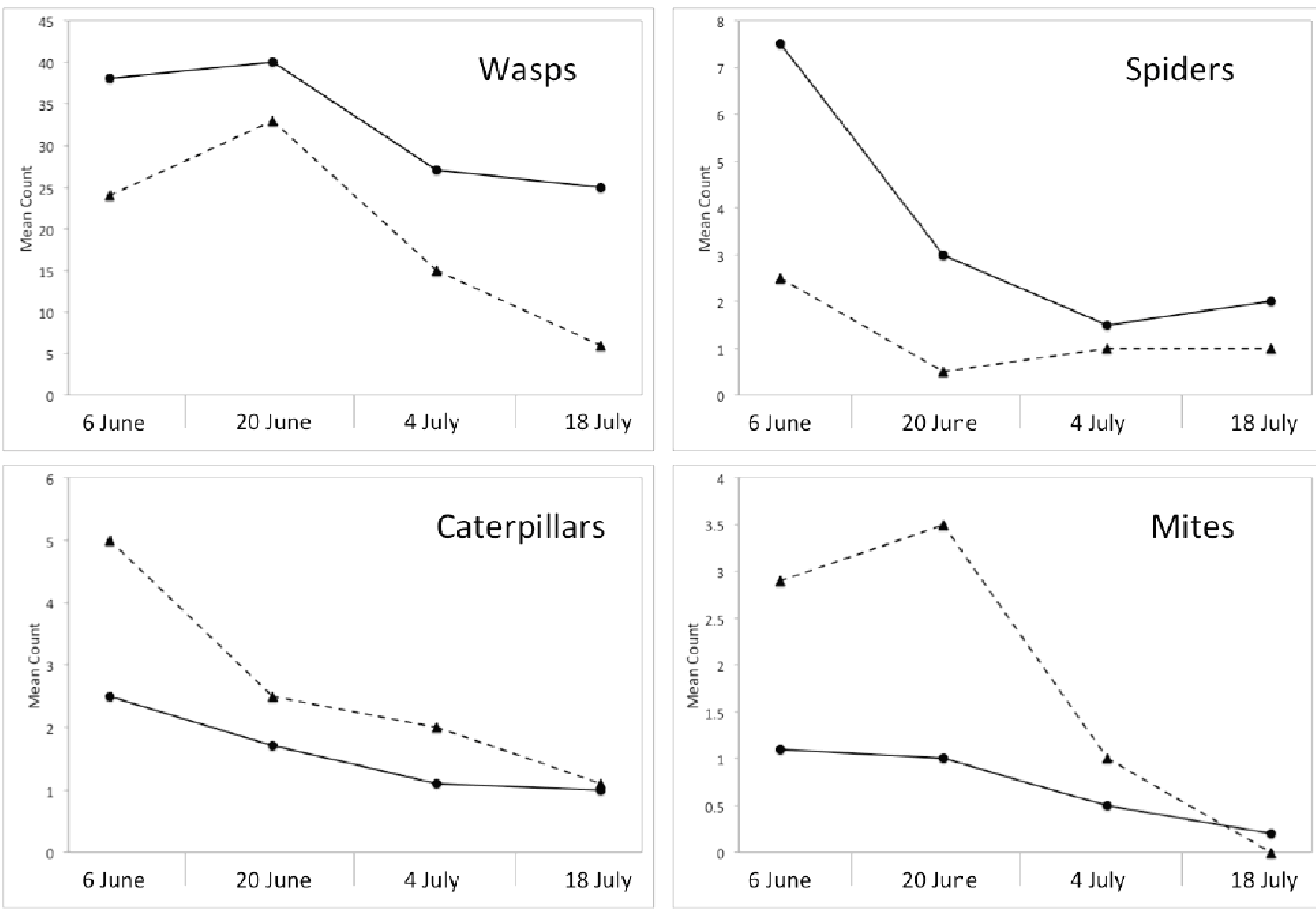

Figure 19. Population sizes of four different groups of arthropods sampled in habitats under two different atmospheric conditions: ambient (1996) CO_2 levels (380 ppm; dashed line with triangles) and future (2050) CO_2 levels (580 ppm; solid line with circles). Data are from J. Hamilton, A. R. Zangerl, M. R. Berenbaum, J. P. Sparks, L. Elich, A. Eisenstein, and E. H. DeLucia (2012). "Elevated Atmospheric CO2 Alters the Arthropod Community in a Forest Understory." *Acta Oecologica*, 43, 80–85.

forest to get an idea of what effect higher CO_2 levels might have on forest ecosystem food webs. Wasps and spiders are carnivores and prey on caterpillars and mites, which are herbivores. Before the study was conducted, researchers had already discovered that plants grow faster in elevated CO_2 conditions, but this faster growth makes the plants' leaves less nutritious. The less nutritious leaves require herbivores to eat more plant material and spend more time eating plants to get the same nutrition as they do from plants that grow more slowly in lower CO_2 conditions. (HL, DBQ) (AP: SP 1, SP 5, SP 6, SP 7, 4.A–4.C; IB: 4.1–4.4, C.1–C.5)

a. Identify what you see in each of the graphs.
b. Based on the graphs, interpret what effect you think higher CO_2 levels have on forest ecosystem food webs.

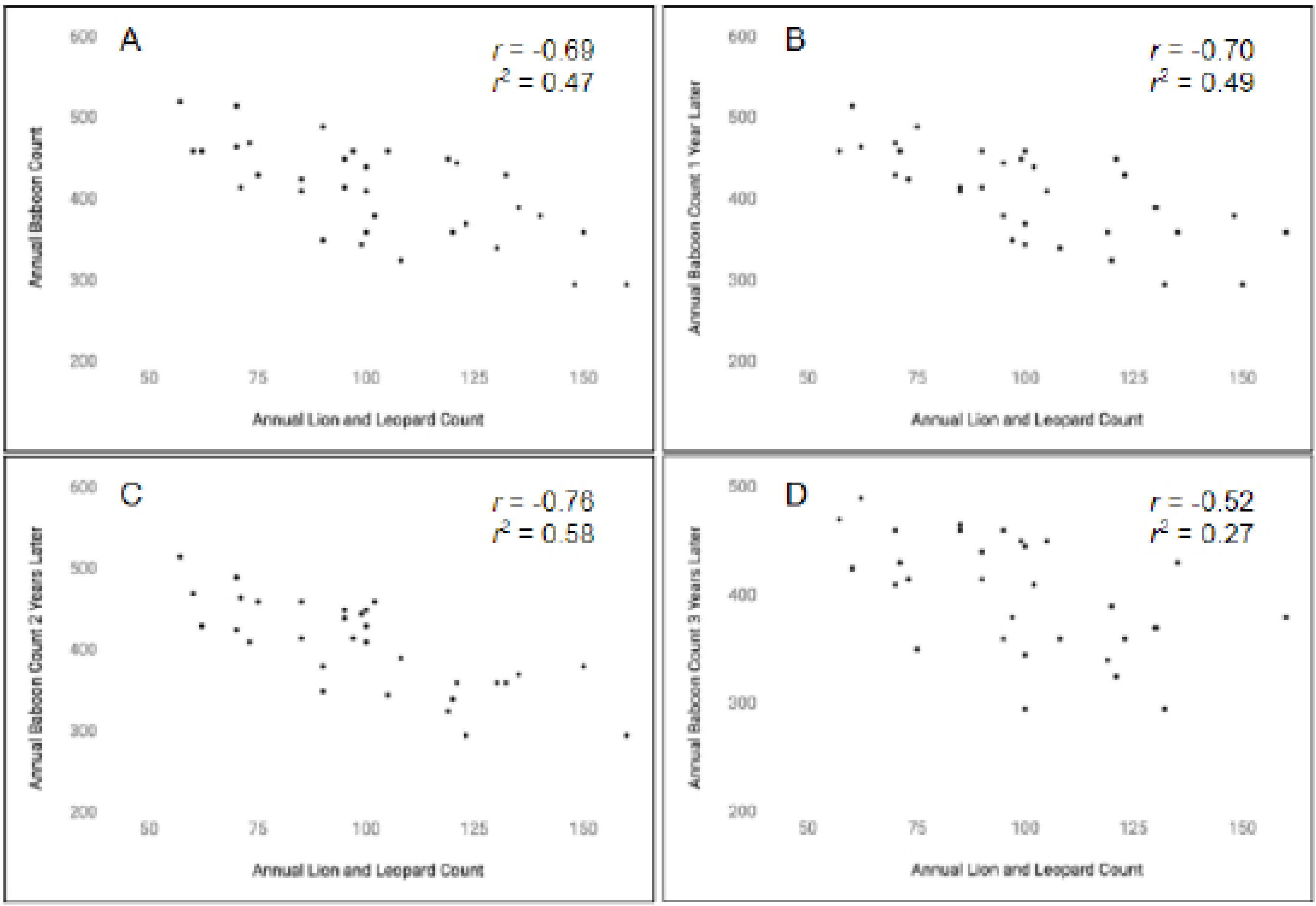

Figure 20. Annual lion and leopard count and baboon counts in Ghana's six savanna parks from 1971 to 2003. Panel A compares the counts in the same year. Panel B compares the baboon count a year after the lion and leopard count was made. Panel C compares the baboon count two years after the lion and leopard count was made. Panel D compares the baboon count three years after the lion and leopard count was made. The count data are estimated from J. S. Brashares, L. R. Prugh, C. J. Stoner, and C. W. Epps (2010). "Ecological and Conservation Implications of Mesopredator Release." In J. Terborgh and J. A. Estes (eds.), *Trophic Cascades: Predators, Prey, and the Changing Dynamics of Nature*. Washington, DC: Island Press: 221–240.

c. Propose a hypothesis to explain the effect you described in part (b).

2. Analyze the four graphs in Figure 20. These data were recorded in Ghana's six savanna parks from 1971 to 2003. (HL, DBQ) (AP: SP 1, SP 5, SP 6, SP 7, 4.A–4.C; IB: 4.1, C.1–C.5)

a. Describe the overall relationship between the number of apex predators in Ghana's savanna parks and the number of baboons.

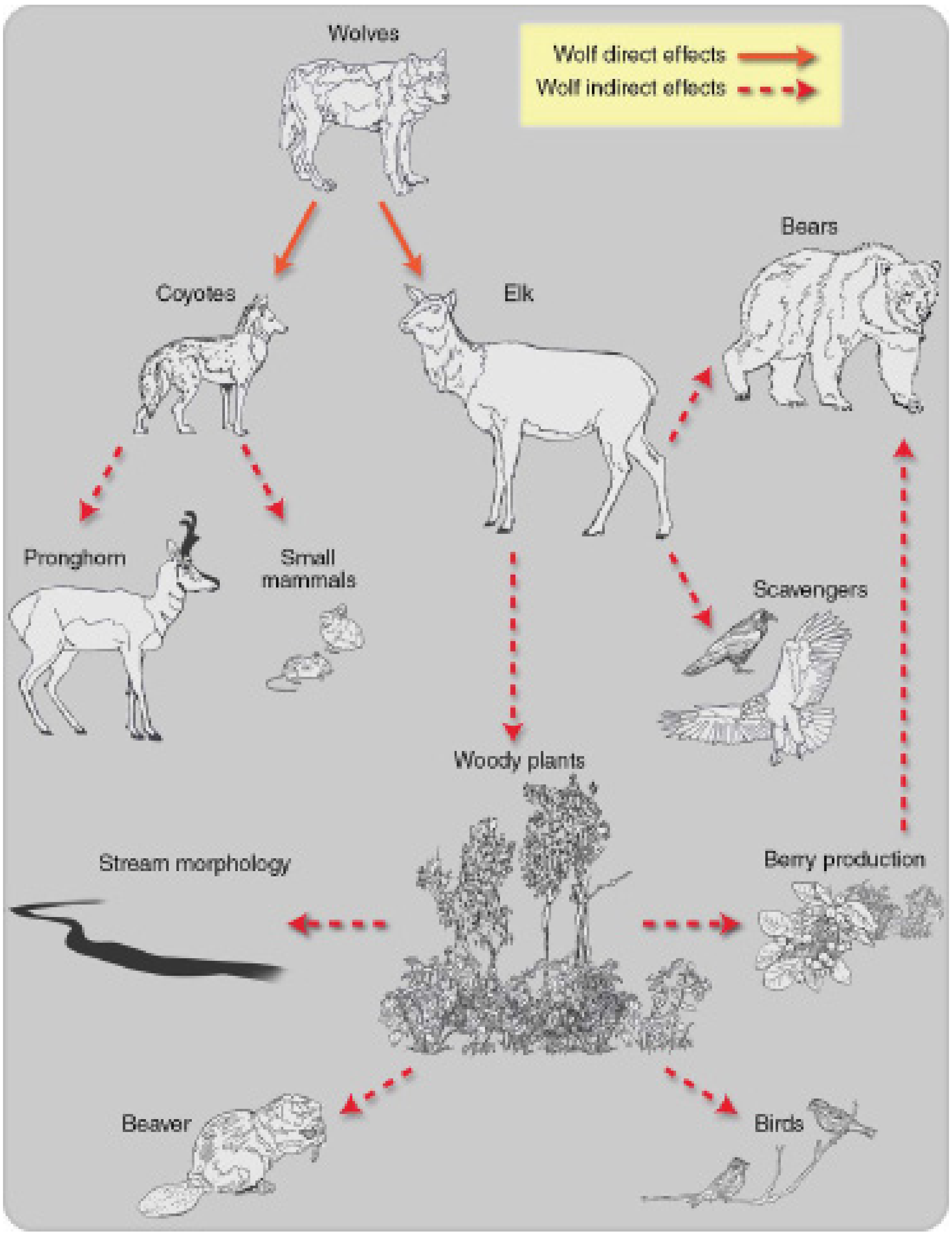

Figure 21. Diagram showing the effects of wolves on the Yellowstone National Park ecosystem. Solid arrows indicate direct effects of wolves on the ecosystem, and dashed arrows indicate indirect effects. Note: Direction of arrows does not indicate direction of energy flow as in most food webs. Figure is from W. J. Ripple, J. A. Estes, R. L. Beschta, C. C. Wilmers, E. G. Ritchie, M. Hebblewhite, et al. (2014). "Status and Ecological Effects of the World's Largest Carnivores." *Science*, 343, 1241484. Reprinted with permission from AAAS.

b. Given the r and r2 statistics in the graphs, which relationship is the strongest: the counts in the same year (A), the counts that compare the baboon numbers the next year (B), two years later (C), or three years later (D)? How do you know?
c. Explain why one of the relationships is stronger than the others.

CHAPTER 9: TAKE 60 MILLION WALLEYE AND CALL US IN TEN YEARS

1. Study Figure 21. Describe the effects you think wolves in Yellowstone have on (SL, MQ) (AP: SP 1, 4.A–4.C; IB: 4.1, 4.2)
   a. Birds
   b. Beavers
   c. Bears
   d. Rivers

CHAPTER 10: RESURRECTION

1. Create a time series graph of the data in Table 9. (SL, DBQ) (AP: SP 1, SP 5–SP 7, 4.A–4.C; IB: 4.1)
   a. Identify what you see in your graph.
   b. Interpret the trends that your graph reveals, and propose some hypotheses to explain these trends.
   c. A pie chart is another way to illustrate data like these. Construct a pie chart for the 1970 data and a pie chart for the 2014 data. In which year was the Gorongosa ecosystem more diverse? How do you know?

Table 9. Estimated percentage of biomass for the six most abundant species at Gorongosa National Park. Data are from M. Stalmans, M. Peel, and T. Massad (2014). "Aerial Wildlife Count of the Parque Nacional Da Gorongosa, Mozambique, October 2014." Parque Nacional Da Gorongosa. Available at http://www.biofund.org.mz/wp-content/uploads/2015/03/GorongosaAerialWildlifeCount2014-GeneralReport-December2014-compress.pdf.

	Year of survey				
Species	*1970*	*2007*	*2010*	*2012*	*2014*
Buffalo	33.4	0.7	8.2	4.1	3.0
Hippo	20.4	8.2	2.5	0.7	4.8
Waterbuck	3.3	35.0	49.8	57.5	62.5
Reedbuck	1.5	9.7	7.3	6.0	6.0
Warthog	1.2	6.1	5.1	5.5	4.1
Elephant	26.5	29.2	16.5	19.4	10.8
Other	13.7	11.1	10.6	6.6	8.8

VI. COURSE CURRICULUM ALIGNMENTS: AP BIOLOGY, IB BIOLOGY, NGSS

Chapter Content Summaries

Introduction: Miracles and Wonder

Introduction to the Serengeti ecosystem, brief discussion of human evolution, human disease, and food production. Introduction to the rules and regulations that govern nature and an argument for understanding those rules.

Chapter 1: The Wisdom of the Body

The story of Walter Cannon's research on animal and human physiology, discovery of the blood buffer system, and inception of the concept of homeostasis; historical discussion of the role of doctors in managing human disease.

Nature of Science: experimental method, controlling variables, hypothesis generation and testing, abductive reasoning.

Chapter 2: The Economy of Nature

The history of Charles Elton's discovery of the economy of nature through food chains, food webs, energy flow, and population dynamics in ecosystems.

Nature of Science: science discovery, model building, data analysis and interpretation, abductive reasoning.

Chapter 3: General Rules of Regulation

The history of Jacques Monod's and François Jacob's discovery of metabolic enzyme regulation in bacteria, including inducers, repressors, operons, double-negative feedback, and allosteric regulation.

Nature of Science: science discovery, model building, data analysis and interpretation, experimental method, controlling variables, hypothesis generation and testing, abductive reasoning.

Chapter 4: Fat, Feedback, and a Miracle Fungus

The history of the epidemiological studies by Ancel Keys on the role of cholesterol in heart disease. History of Joe Goldstein's and Mike Brown's research on blood cholesterol regulation, including the role of genetics in disease, and protein function (transport proteins, membrane receptor proteins, and enzymes). The story of Akira Endo's discovery of an inhibitor of cholesterol metabolism and the trial and error of drug development and testing by pharmaceutical companies.

Nature of Science: science discovery, correlation and causation, sample size, hypothesis generation, model building, experimental method, controlling variables, hypothesis testing, abductive reasoning.

Chapter 5: Stuck Accelerators and Broken Brakes

Janet Rowley's story of her discovery of the link between chromosomal abnormalities, human disease syndromes, and cancer. The role of viruses and genetic mutations in cancer and the discovery of cancer as a disease of cell cycle regulation. The development of the drug Gleevec as a suppressor of the growth of specific cancers.

Nature of Science: role of peer-reviewed publishing in science communication and scientific progress, hypothesis generation and testing, model building, designing and implementing clinical studies for drug testing.

Chapter 6: Some Animals Are More Equal than Others

The story of Robert Paine's discovery of trophic cascades and keystone species as negative-feedback regulatory mechanisms of coastal ecosystem food webs and community structure. Jim Estes and Joe Palmisano's discovery of sea otters as a keystone species in marine food webs, and Mary Power's controlled experiments on trophic cascades in freshwater streams.

Serengeti Rule 1—Keystones: Not all species are equal.

Serengeti Rule 2—Some species mediate strong indirect effects through trophic cascades.

Nature of Science: observational science, model building, experimental method, controlling variables, hypothesis generation and testing, abductive reasoning.

Chapter 7: Serengeti Logic

The story of Tony Sinclair's decades-long research on the population dynamics of Serengeti National Park and discovery of large-scale and landscape-scale negative feedback regulatory mechanisms.

Applying the general rules of regulation of functions at the molecular level to functions at the level of food webs and entire ecosystems.

Serengeti Rule 3—Competition: Some species compete for common resources.

Serengeti Rule 4—Body size affects the mode of regulation.

Serengeti Rule 5—Density: The regulation of some species depends on their density.

Serengeti Rule 6—Migration increases animal numbers.

Nature of Science: observational science, model building, data analysis and interpretation, experimental method, controlling variables, hypothesis generation and testing, abductive reasoning, using scientific knowledge to make decisions.

Chapter 8: Another Kind of Cancer

Discovering the role of human activity in creating disease-like symptoms in food web and ecosystem function: Lake Erie algal blooms, rice paddy plant hopper control, Ghanaian baboon population control, and collapse of coastal fisheries.

Nature of Science: observational science, model building, data analysis and interpretation, using scientific knowledge to make decisions.

Chapter 9: Take 60 Million Walleye and Call Us in Ten Years

Using the results of trophic cascade restoration experiments on freshwater ponds to guide the restoration of top-down trophic functioning in Lake Mendota in Wisconsin. Bringing top-down predator regulation back to Yellowstone National Park with the reintroduction of wolves. How cultural, social, and political issues drive and shape large-scale ecosystem restoration decisions and efforts.

Nature of Science: observational science; model building; data analysis and interpretation; experimental method; controlling variables; hypothesis generation and testing; abductive reasoning; science, politics, and society; using scientific knowledge to make decisions.

Chapter 10: Resurrection

The ecological and political history of Gorongosa National Park in Mozambique. How we are using funding from Greg Carr's foundation and our knowledge of ecosystem function and regulation to begin restoring the park. Educating local landowners and residents about Gorongosa National Park's ecological services and value to their own livelihoods and involving the public in the restoration and conservation of the park. How cultural, social, and political issues drive and shape large-scale ecosystem restoration decisions and efforts.

Nature of Science: observational science; model building; data analysis and interpretation; experimental method; controlling variables; hypothesis generation and testing; abductive reasoning, science, politics, and society; using scientific knowledge to make decisions.

Afterword: Rules to Live By

How we can use our knowledge of feedback control, small- and large-scale regulatory mechanisms, and the role of science in society to guide our decision making for the future in light of human and ecosystem health.

Nature of Science: Using scientific knowledge to make decisions.

The Serengeti Rules AP Biology Curriculum Alignment	Introduction: *Miracles and Wonder*	CH 1: *The Wisdom of the Body*	CH 2: *The Economy of Nature*	CH 3: *General Rules of Regulation*	CH4: *Fat, Feedback, and a Miracle Fungus*	CH 5: *Stuck Accelerators and Broken Brakes*	CH 6: *Some Animals Are More Equal than Others*	CH 7: *Serengeti Logic*	CH 8: *Another Kind of Cancer*	CH 9: *Take 60 Million Walleye and Call Us in Ten Years*	CH 10: *Resurrection*	Afterword: *Rules to Live By*
*__Science Practice 1__: The student can use representations and models to communicate scientific phenomena and solve scientific problems.		X	X	X	X	X	X	X	X	X	X	
*__Science Practice 2__: The student can use mathematics appropriately.	X		X	X				X	X			
*__Science Practice 3__: The student can engage in scientific questioning to extend thinking or to guide investigations in the context of the AP course.												
*__Science Practice 4__: The student can plan and implement data-collection strategies appropriate to a particular scientific question.												
*__Science Practice 5__: The student can perform data analysis and evaluation of evidence.	X		X	X				X	X			
*__Science practice 6__: The student can work with scientific explanations and theories.	X	X	X	X	X	X	X	X	X	X	X	X
*__Science Practice 7__: The student is able to connect and relate knowledge across various scales, concepts, and representations in and across domains.	X	X	X	X	X	X	X	X	X	X	X	X
*All of the Science Practices are also emphasized in the Engagement and Discussion Questions that accompany *The Serengeti Rules*												
Big Idea 1: The process of evolution drives the diversity and unity of life.												
Enduring Understanding 1.A: Change in the genetic makeup of a population over time is evolution.						X						
Enduring Understanding 1.B: Organisms are linked by lines of descent from common ancestry.						X						
Enduring Understanding 1.C: Life continues to evolve within a changing environment.												
Enduring Understanding 1.D: The origin of living systems is explained by natural processes.												
Big Idea 2: Biological systems utilize free energy and molecular building blocks to grow, to reproduce, and to maintain dynamic homeostasis.												
Enduring Understanding 2.A: Growth, reproduction, and maintenance of the organization of living systems require free energy and matter.			X	X								

	Introduction	CH 1	CH 2	CH 3	CH4	CH 5	CH 6	CH 7	CH 8	CH 9	CH 10	Afterword
Enduring Understanding 2.B: Growth, reproduction, and dynamic homeostasis require that cells create and maintain internal environments that are different from their external environments.				X	X	X						
Enduring Understanding 2.C: Organisms use feedback mechanisms to regulate growth and reproduction, and to maintain dynamic homeostasis.		X	X	X	X	X						
Enduring Understanding 2.D: Growth and dynamic homeostasis of a biological system are influenced by changes in the system's environment.							X	X	X	X	X	
Enduring Understanding 2.E: Many biological processes involved in growth, reproduction, and dynamic homeostasis include temporal regulation and coordination.		X	X	X	X	X	X	X	X	X	X	
Big Idea 3: Living systems store, retrieve, transmit, and respond to information essential to life processes.												
Enduring Understanding 3.A: Heritable information provides for continuity of life.					X	X						
Enduring Understanding 3.B: Expression of genetic information involves cellular and molecular mechanisms.					X	X						
Enduring Understanding 3.C: The processing of genetic information is imperfect and is a source of genetic variation.					X	X						
Enduring Understanding 3.D: Cells communicate by generating, transmitting, and receiving chemical signals.				X	X	X						
Enduring Understanding 3.E: Transmission of information results in changes within and between biological systems.		X	X	X	X	X	X	X	X	X	X	
Big Idea 4: Biological systems interact, and these systems and their interactions possess complex properties.												
Enduring Understanding 4.A: Interactions within biological systems lead to complex properties.		X	X	X	X	X	X	X	X	X	X	
Enduring Understanding 4.B: Competition and cooperation are important aspects of biological systems.			X	X	X		X	X	X	X	X	
Enduring Understanding 4.C: Naturally occurring diversity among and between components within biological systems affects interactions with the environment.			X	X	X	X	X	X	X	X	X	

The Serengeti Rules IB Biology Curriculum Alignment	Introduction: *Miracles and Wonder*	CH 1: *The Wisdom of the Body*	CH 2: *The Economy of Nature*	CH 3: *General Rules of Regulation*	CH4: *Fat, Feedback, and a Miracle Fungus*	CH 5: *Stuck Accelerators and Broken Brakes*	CH 6: *Some Animals Are More Equal than Others*	CH 7: *Serengeti Logic*	CH 8: *Another Kind of Cancer*	CH 9: *Take 60 Million Walleye and Call Us in Ten Years*	CH 10: *Resurrection*	Afterword: *Rules to Live By*
Topics 1–6: Standard Level (SL) Material												
Topic 1: Cell Biology												
1.1 Introduction to cells: The evolution of multicellular organisms allowed cell specialization and cell replacement.												
1.2 Ultrastructure of cells: Eukaryotes have a much more complex cell structure than prokaryotes.												
1.3 Membrane structure: The structure of biological membranes makes them fluid and dynamic.					X							
1.4 Membrane transport: Membranes control the composition of cells by active and passive transport.					X							
1.5 The origin of cells: There is an unbroken chain of life from the first cells on Earth to all cells in organisms alive today.												
1.6 Cell division: Cell division is essential but must be controlled.						X						
Topic 2: Molecular Biology												
2.1 Molecules to metabolism: Living organisms control their composition by a complex web of chemical reactions.				X	X	X						
2.2 Water: Water is the medium of life.												
2.3 Carbohydrates and lipids: Compounds of carbon, hydrogen, and oxygen are used to supply and store energy.				X								
2.4 Proteins: Proteins have a very wide range of functions in living organisms.				X	X	X						
2.5 Enzymes: Enzymes control the metabolism of the cell.				X	X	X						
2.6 Structure of DNA and RNA: The structure of DNA allows efficient storage of genetic information.						X						
2.7 DNA replication, transcription, and translation: Genetic information in DNA can be accurately copied and can be translated to make the proteins needed by the cell.						X						
2.8 Cell respiration: Cell respiration supplies energy for the functions of life.				X								

	Introduction	CH 1	CH 2	CH 3	CH4	CH 5	CH 6	CH 7	CH 8	CH 9	CH 10	Afterword
2.9 Photosynthesis: Photosynthesis uses the energy in sunlight to produce the chemical energy needed for life.												
Topic 3: Genetics												
3.1 Genes: Every living organism inherits a blueprint for life from its parents.					X	X						
3.2 Chromosomes: Chromosomes carry genes in a linear sequence that is shared by members of a species.						X						
3.3 Meiosis: Alleles segregate during meiosis, allowing new combinations to be formed by the fusion of gametes.												
3.4 Inheritance: The inheritance of genes follows patterns.					X							
3.5 Genetic modification and biotechnology: Biologists have developed techniques for artificial manipulation of DNA, cells, and organisms.												
Topic 4: Ecology												
4.1 Species, communities, and ecosystems: The continued survival of living organisms, including humans, depends on sustainable communities.									X		X	X
4.2 Energy flow: Ecosystems require a continuous supply of energy to fuel life processes and to replace energy lost as heat.			X				X	X				
4.3 Carbon cycling: Continued availability of carbon in ecosystems depends on carbon cycling.			X									
4.4 Climate change: Concentrations of gases in the atmosphere affect climates experienced at the Earth's surface.												X
Topic 5: Evolution and Biodiversity												
5.1 Evidence for evolution: There is overwhelming evidence for the evolution of life on Earth.												
5.2 Natural selection: The diversity of life has evolved and continues to evolve by natural selection.			X									
5.3 Classification of biodiversity: Species are named and classified using an internationally agreed-on system.												
5.4 Cladistics: The ancestry of groups of species can be deduced by comparing their base or amino acid sequences.												

	Introduction	CH 1	CH 2	CH 3	CH4	CH 5	CH 6	CH 7	CH 8	CH 9	CH 10	Afterword
Topic 6: Human Physiology												
6.1 Digestion and absorption: The structure of the wall of the small intestine allows it to move, digest, and absorb food.												
6.2 The blood system: The blood system continuously transports substances to cells and simultaneously collects waste products.		X			X							
6.3 Defence against infectious disease: The human body has structures and processes that resist the continuous threat of invasion by pathogens.						X						
6.4 Gas exchange: The lungs are actively ventilated to ensure that gas exchange can occur passively.												
6.5 Neurons and synapses: Neurons transmit the message, synapses modulate the message.	X	X										
6.6 Hormones, homeostasis, and reproduction: Hormones are used when signals need to be widely distributed.		X										
Topics 7–11: Additional Higher Level (AHL) Material												
Topic 7: Nucleic Acids												
7.1 DNA structure and replication: The structure of DNA is ideally suited to its function.												
7.2 Transcription and gene expression: Information stored as a code in DNA is copied onto mRNA.												
7.3 Translation: Information transferred from DNA to mRNA is translated into an amino acid sequence.												
Topic 8: Metabolism, Cell Respiration, and Photosynthesis												
8.1 Metabolism: Metabolic reactions are regulated in response to the cell's needs.				X								
8.2 Cell respiration: Energy is converted to a usable form in cell respiration.												
8.3 Photosynthesis: Light energy is converted into chemical energy.												
Topic 9: Plant Biology												
9.1 Transport in the xylem of plants: Structure relates to function in the xylem of plants.												
9.2 Transport in the phloem of plants: Structure relates to function in the phloem of plants.												

	Introduction	CH 1	CH 2	CH 3	CH4	CH 5	CH 6	CH 7	CH 8	CH 9	CH 10	Afterword
9.3 Growth in plants: Plants adapt their growth to environmental conditions.												
9.4 Reproduction in plants: Reproduction in flowering plants is influenced by the biotic and abiotic environments.												
Topic 10: Genetics and Evolution												
10.1 Meiosis: Meiosis leads to independent assortment of chromosomes and unique composition of alleles in daughter cells.												
10.2 Inheritance: Genes may be linked or unlinked and are inherited accordingly.												
10.3 Gene pools and speciation: Gene pools change over time.												
Topic 11: Animal Physiology												
11.1 Antibody production and vaccination: Immunity is based on recognition of self and destruction of foreign material.												
11.2 Movement: The roles of the musculoskeletal system are movement, support, and protection.		X										
11.3 The kidney and osmoregulation: All animals excrete nitrogenous waste products, and some animals also balance water and solute concentrations.												
11.4 Sexual reproduction: Sexual reproduction involves the development and fusion of haploid gametes.												
Options												
A. Neurobiology and Behavior												
A.1 Neural development: Modification of neurons starts in the earliest stages of embryogenesis and continues to the final years of life.												
A.2 The human brain: The parts of the brain specialize in different functions.												
A.3 Perceptions of stimuli: Living organisms are able to detect changes in the environment.		X										
A.4 Innate and learned behavior: Behavioral patterns can be inherited or learned.												
A.5 Neuropharmacology: Communication between neurons can be altered through the manipulation of the release and reception of chemical messengers.		X										

	Introduction	CH 1	CH 2	CH 3	CH4	CH 5	CH 6	CH 7	CH 8	CH 9	CH 10	Afterword
A.6 Ethology: Natural selection favors specific types of behavior.												
B. Biotechnology and Bioinformatics												
B.1 Microbiology (organisms in industry): Microorganisms can be used and modified to perform industrial processes.												
B.2 Biotechnology in agriculture: Crops can be modified to increase yields and to obtain novel products.												
B.3 Environmental protection: Biotechnology can be used in the prevention and mitigation of contamination from industrial, agricultural, and municipal wastes.												
B.4 Medicine: Biotechnology can be used in the diagnosis and treatment of disease.												
B.5 Bioinformatics: Bioinformatics is the use of computers to analyze sequence data in biological research.												
C. Ecology and Conservation												
C.1 Species and communities: Community structure is an emergent property of an ecosystem.			X				X	X	X	X	X	
C.2 Communities and ecosystems: Changes in community structure affect and are affected by organisms.			X				X	X	X	X	X	
C.3 Impacts of humans on ecosystems: Human activities impact ecosystem function.							X	X	X	X	X	X
C.4 Conservation of biodiversity: Entire communities need to be conserved to preserve biodiversity.							X	X	X	X	X	X
C.5 Population ecology: Dynamic biological processes impact population density and population growth.			X				X	X	X	X	X	
C.6 Nitrogen and phosphorus cycles: Soil cycles are subject to disruption.									X			
D. Human Physiology												
D.1 Human nutrition: A balanced diet is essential to human health.												
D.2 Digestion: Digestion is controlled by nervous and hormonal mechanisms.		X										
D.3 Functions of the liver: The chemical composition of the blood is regulated by the liver.		X										

	Introduction	CH 1	CH 2	CH 3	CH4	CH 5	CH 6	CH 7	CH 8	CH 9	CH 10	Afterword
D.4 The heart: Internal and external factors influence heart function.												
D.5 Hormones and metabolism: Hormones are not secreted at a uniform rate and exert their effect at low concentrations.												
D.6 Transport of respiratory gases: Red blood cells are vital in the transport of respiratory gases.												

The Next Generation Science Standards for the High School Life Sciences

Students in high school develop an understanding of key concepts that will help them make sense of the life sciences. The ideas are built on students' scientific understanding of disciplinary core ideas, science and engineering practices, and crosscutting concepts from earlier grades. There are four life science disciplinary core ideas in high school: 1) From Molecules to Organisms: Structures and Processes; 2) Ecosystems: Interactions, Energy, and Dynamics; 3) Heredity: Inheritance and Variation of Traits; and 4) Biological Evolution: Unity and Diversity. The performance expectations for high school life sciences blend core ideas with scientific and engineering practices and crosscutting concepts to help students develop usable knowledge that can be applied across the science disciplines. While the performance expectations in high school life sciences couple particular practices with specific disciplinary core ideas, instructional decisions should include use of many practices underlying the performance expectations.

The performance expectations in **LS1: From Molecules to Organisms: Structures and Processes** help students answer the question, "How do organisms live and grow?" The LS1 Disciplinary Core Idea from the NRC Framework is presented as three sub-ideas: Structure and Function, Growth and Development of Organisms, and Organization for Matter and Energy Flow in Organisms. In these performance expectations, students demonstrate that they can use investigations and gather evidence to support explanations of cell function and reproduction. They understand the role of proteins as essential to the work of the cell and living systems. Students can use models to explain photosynthesis, respiration, and the cycling of matter and flow of energy in living organisms. The cellular processes can be used as a model for understanding the hierarchical organization of organisms. Crosscutting concepts of matter and energy, structure and function, and systems and system models provide students with insights into the structures and processes of organisms.

The performance expectations in **LS2: Ecosystems: Interactions, Energy, and Dynamics** help students answer the question, "How and why do organisms interact with their environment, and what are the effects of these interactions?" The LS2 Disciplinary Core Idea includes four sub-ideas: Interdependent Relationships in Ecosystems; Cycles of Matter and Energy Transfer in Ecosystems; Ecosystem Dynamics, Functioning, and Resilience; and Social Interactions and Group Behavior. High school students can use mathematical reasoning to demonstrate understanding of fundamental concepts of carrying capacity, factors affecting biodiversity and populations, and the cycling of matter and flow of energy among organisms in an ecosystem. These mathematical models provide support of students' conceptual understanding of systems and their ability to develop design solutions for reducing the impact of human activities on the environment and maintaining biodiversity. Crosscutting concepts of systems and system models play a central role in students' understanding of science and engineering practices and the core ideas of ecosystems.

The performance expectations in **LS3: Heredity: Inheritance and Variation of Traits** help students answer the questions: "How are characteristics of one generation passed to the next? How can individuals of the same species and even siblings have different characteristics?" The LS3 Disciplinary Core Idea from the NRC Framework includes two sub-ideas: Inheritance of Traits and Variation of Traits. Students are able to ask questions, make and defend a claim, and use concepts of probability to explain the genetic variation in a population. Students demonstrate understanding of why individuals of the same species vary in how they look, function, and behave. Students can explain the mechanisms of genetic inheritance and describe the environmental and genetic causes of gene mutation and the alteration of gene expression. Crosscutting concepts of patterns and cause and effect are called out as organizing concepts for these core ideas.

The performance expectations in **LS4: Biological Evolution: Unity and Diversity** help students answer the question, "What evidence shows that different species are related?" The LS4 Disciplinary Core Idea involves four sub-ideas: Evidence of Common Ancestry and Diversity, Natural Selection, Adaptation, and Biodiversity and Humans. Students can construct explanations for the processes of natural selection and evolution and communicate how multiple lines of evidence support these explanations. Students can evaluate evidence of the conditions that may result in new species and understand the role of genetic variation in natural selection. Additionally, students can apply concepts of probability to explain trends in populations as those trends relate to advantageous heritable traits in a specific environment. The crosscutting concepts of cause and effect and systems and system models play an important role in students' understanding of the evolution of life on Earth.

The Serengeti Rules NGSS Curriculum Alignment	Introduction: *Miracles and Wonder*	CH 1: *The Wisdom of the Body*	CH 2: *The Economy of Nature*	CH 3: *General Rules of Regulation*	CH4: *Fat, Feedback, and a Miracle Fungus*	CH 5: *Stuck Accelerators and Broken Brakes*	CH 6: *Some Animals Are More Equal than Others*	CH 7: *Serengeti Logic*	CH 8: *Another Kind of Cancer*	CH 9: *Take 60 Million Walleye and Call Us in Ten Years*	CH 10: *Resurrection*	Afterword: *Rules to Live By*
Science and Engineering Practices												
Asking questions and defining problems	X	X	X	X	X	X	X	X	X	X	X	X
Developing and using models		X	X	X	X	X	X	X				
Planning and carrying out investigations		X	X	X	X	X	X	X	X	X		
Using mathematics and computational thinking	X											
Analyzing and interpreting data			X	X		X		X	X			
Constructing explanations and designing solutions		X	X	X	X	X	X	X	X	X	X	X
Scientific investigations use a variety of methods		X	X	X	X	X	X	X	X	X	X	
Engaging in argument from evidence		X	X	X	X	X	X	X	X	X	X	X
Obtaining, evaluating, and communicating information		X	X	X	X	X	X	X	X	X	X	X
Scientific knowledge is open to revision in light of new evidence		X	X	X	X	X	X	X	X	X	X	X
Science models, laws, mechanisms, and theories explain natural phenomena		X	X	X	X	X	X	X	X	X	X	X
Disciplinary Core Ideas												
HS-LS1 From Molecules to Organisms: Structures and Processes												
LS1.A: Structure and function		X		X	X	X						
LS1.B: Growth and development of organisms				X		X						
LS1.C: Organization for matter and energy flow in organisms			X	X			X	X	X			
HS-LS2 Ecosystems: Interactions, Energy, and Dynamics												
LS2.A: Interdependent relationships in ecosystems			X				X	X	X	X	X	
LS2.B: Cycles of matter and energy transfer in ecosystems							X	X	X	X	X	
LS2.C: Ecosystem dynamics, functioning, and resilience							X	X	X	X	X	
LS2.D: Social interactions and group behavior								X				
LS4.D: Biodiversity and humans										X	X	X
PS3.D: Energy in chemical processes												
ETS1.B: Developing possible solutions					X	X			X	X	X	X

	Introduction	CH 1	CH 2	CH 3	CH4	CH 5	CH 6	CH 7	CH 8	CH 9	CH 10	Afterword
HS-LS3 Heredity: Inheritance and Variation of Traits												
LS1.A: Structure and function												
LS3.A: Inheritance of traits												
LS3.B: Variation of traits												
HS-LS4 Biological Evolution: Unity and Diversity												
LS4.A: Evidence of common ancestry and diversity												
LS4.B: Natural selection												
LS4.C: Adaptation			X									
LS4.D: Biodiversity and humans										X		
ETS1.B: Developing possible solutions					X	X			X	X	X	X

VII. EXAMPLE ADVANCED BIOLOGY CURRICULUM MAP FOR *THE SERENGETI RULES*

This example curriculum outline has been produced for a first year Advanced Biology course. This particular course is taught with Evolutionary Theory and homeostasis (regulation) as two main unifying themes. This curriculum outline includes content descriptions for each unit, possible connections to *The Serengeti Rules*, and some ideas for lab activities.

"Nothing in biology makes sense except in the light of evolution [and regulation!]." – Theodosius Dobzhansky, 1973

<table>
<tr><td colspan="2">BIOLOGY COURSE CURRICULUM: SEMESTER ONE</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td colspan="2">Unit One: How Science Works</td></tr>
<tr><td>Content Topics</td><td>Example Lab Activities</td></tr>
<tr><td>What is biology? How (mechanistic) and Why (evolutionary) questions in biology.
Levels of organization and characteristics of life</td><td>Nature walk and scavenger hunt for examples of the characteristics of life</td></tr>
<tr><td>Scientific methodology
Hypotheses vs predictions
Data and error analysis: variance, standard deviation, standard error, and 95% confidence intervals
Analyzing data with the t-test</td><td>Using toothpicks to test the hypothesis that dominant hands are better at fine motor movements than non-dominant hands
*Written Methods and Results Section</td></tr>
<tr><td colspan="2">The Serengeti Rules
• Introduction
human evolution, human disease, food production, and the rules of nature
• Chapter 1: The Wisdom of the Body
homeostasis and human disease</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td colspan="2">Unit Two: Principles of Ecology and Evolution</td></tr>
<tr><td>Content Topics</td><td>Example Lab Activities</td></tr>
<tr><td>Ecosystem ecology</td><td></td></tr>
<tr><td>Population ecology and the evolution of populations</td><td>Microbe growth rate in nutrient broth using spectrophotometry

Evolution of antibiotic resistance in E. coli K12.</td></tr>
<tr><td>Community ecology and the evolution of species Interactions
Analyzing data with the t-test</td><td>Testing the effect of the presence or absence of simulated aquatic macrophytes on water flea predation by goldfish
*Written Methods and Results Section</td></tr>
<tr><td>Human impacts on ecosystems
Analyzing data with regression analysis</td><td>Testing the effect of nitrogen and phosphorus on algae growth

Using HHMI Biointeractive Earth Viewer data to investigate the relationship between atmospheric CO_2 concentration and global temperatures</td></tr>
<tr><td colspan="2">The Serengeti Rules
• Chapter 2: The Economy of Nature
Charles Elton's discovery of the economy of nature through food chains, food webs, energy flow, and population dynamics in ecosystems
• Chapter 3: General Rules of Regulation
Regulation of population growth in bacteria by enzymes
• Chapter 6: Some Animals Are More Equal than Others
Trophic cascades and keystone species
• Chapter 7: Serengeti Logic
Population dynamics of Serengeti National Park
• Chapter 9: Take 60 Million Walleye and Call Us in Ten Years
Using the science of trophic cascades to guide the restoration of ecosystems and their functions</td></tr>
</table>

Unit Three: Water and Life's Adaptations for Osmoregulation and Temperature Regulation	
Content Topics	***Example Lab Activities***
Emergent properties of water Water and plant structural adaptations Water and adaptations in animals for temperature regulation	The effect of wind on transpiration rate in bean plants
Acids, bases, and buffers	The acid-base buffering capacity of various substances: potato, liver, pond water, tap water *Written Methods and Results Section
Blood chemistry regulation	
Osmoregulation and animal adaptations	
The vertebrate excretory system	Kidney dissection Urinalysis
The Serengeti Rules • Revisit Chapter 1 and the blood buffer system	

Unit Four: Molecules of Life, Metabolic Adaptations, and Human Nutrition	
Content Topics	***Example Lab Activities***
Biological molecules carbohydrates lipids proteins nucleic acids	Organic molecule building kits: Build models of glucose, fructose, sucrose, glycine, alanine, valine, saturated fatty acid, unsaturated fatty acid, triglyceride DNA molecule model building kit
Human nutrition and metabolism	Effect of temperature and pH on catalase enzyme activity Effect of lactase enzyme on lactose sugar in milk
The Serengeti Rules • Chapter 4: *Fat, Feedback, and a Miracle Fungu*s Cholesterol metabolism and cell membrane structure and function	

Unit Five: Cell Structure, Function, and Their Unique Adaptations	
Content Topics	***Example Lab Activities***
Cell theory	Comparative cell structure
Evolution of bacteria, archaea, and eukarya Cell diversity and structure	Surface area to volume ratio in phenolphthalein agar cubes
Cell organelles and their functions Evolution and the endosymbiotic theory	
Cell membrane structure and function	
Diffusion and osmosis Statistics: 95% confidence intervals, the t-test, ANOVA, and regression analysis	Estimating potato cell molarity with sucrose solutions *Written Introduction, Methods, Results, and Evaluation/Discussion
The Serengeti Rules • Chapter 4: Fat, Feedback, and a Miracle Fungus Cholesterol metabolism and cell membrane structure and function	

BIOLOGY COURSE CURRICULUM: SEMESTER TWO	
Unit Six: Evolution and Mechanisms of Photosynthesis and Aerobic Respiration	
Content Topics	***Example Lab Activities***
Review of endosymbiotic theory Evolution of photosynthesis	
Mechanism of photosynthesis Statistics: 95% confidence intervals and the t-test	Effects of abiotic factors on photosynthesis in algae balls
Mechanism of aerobic respiration Statistics: 95% confidence intervals and the t-test	Effects of abiotic factors on respiration in yeast balls Effects of temperature on pea seed germination using bromo-thymol blue and spectrophotometry
Photosynthesis-respiration evolutionary connections	
Carbon cycle and human impacts	
	*Written Methods and Results Section on one of the three lab activities
Unit Seven: The Cell Cycle, the Evolution of Cancer, and Introduction to Biotechnology	
Content Topics	***Example Lab Activities***
DNA structure, replication, and the RNA world hypothesis	Modeling DNA replication
Stages of the cell cycle Statistics: the chi-square test	Allium root tip mitosis and the mitotic index of root meristem
Evolution of cancer	
Restriction enzymes and biotechnology	Lambda DNA digestion and gel electrophoresis
The Serengeti Rules • Chapter 5: *Stuck Accelerators and Broken Brakes* Chromosomal abnormalities, human disease syndromes, and cancer • Chapter 8: *Another Kind of Cancer* When humans create disease-like symptoms in ecosystems	
Unit Eight: The Evolution of Sexual Reproduction, Meiosis, and Mendelian Genetics	
Content Topics	***Example Lab Activities***
PBS Evolution Series Film: Why Sex?	
Meiosis	Modeling meiosis with popbeads
Meiosis as an evolutionary offshoot of mitosis	
Mendel's and Morgan's experiments	
Monohybrid crosses and inheritance patterns Statistics: the chi-square test	Human traits that appear Mendelian: adaptive or not? *Written Methods and Results Section
Genetic and Chromosomal Disorders	
The Serengeti Rules • Chapter 5: *Stuck Accelerators and Broken Brakes* Chromosomal abnormalities, human disease syndromes, and cancer	
Unit Nine: Microevolution	
Content Topics	***Example Lab Activities***
How errors in DNA replication make evolution possible	Modeling DNA replication and protein folding
Evolution of the three-spined stickleback Statistics: the chi-square test	Testing inheritance hypotheses in fish
Genetic drift and gene flow	Modeling microevolution with A/a cards

<table>
<tr><th colspan="2">Unit Ten: Macroevolution and the Evolution of Humans</th></tr>
<tr><th>Content Topics</th><th>Example Lab Activities</th></tr>
<tr><td>Natural selection and micro vs macroevolution
Statistics: chi-square test and regression analysis</td><td>Modeling the evolution of camouflage</td></tr>
<tr><td>Cladistics and tree thinking</td><td>Canary Island lizards phylogeny

Building evolutionary trees from morphological data</td></tr>
<tr><td>Primate evolution and the evolution of Homo
Statistics: regression analysis and the t-test</td><td>Comparative skull and skeleton analysis
*Written Introduction, Methods, Results, and Evaluation/Discussion</td></tr>
<tr><td colspan="2">Year’s End Recap with The Serengeti Rules
• Chapter 10: Resurrection
How cultural, social, and political issues drive and shape large-scale ecosystem restoration decisions and efforts.
• Afterword: Rules to Live By
How we can use our knowledge of feedback control, small- and large-scale regulatory mechanisms, and the role of science in society to guide our decision-making for the future in light of human and ecosystem health.</td></tr>
</table>