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Center for Biodiversity and Conservation
Network of Conservation Educators and Practitioners

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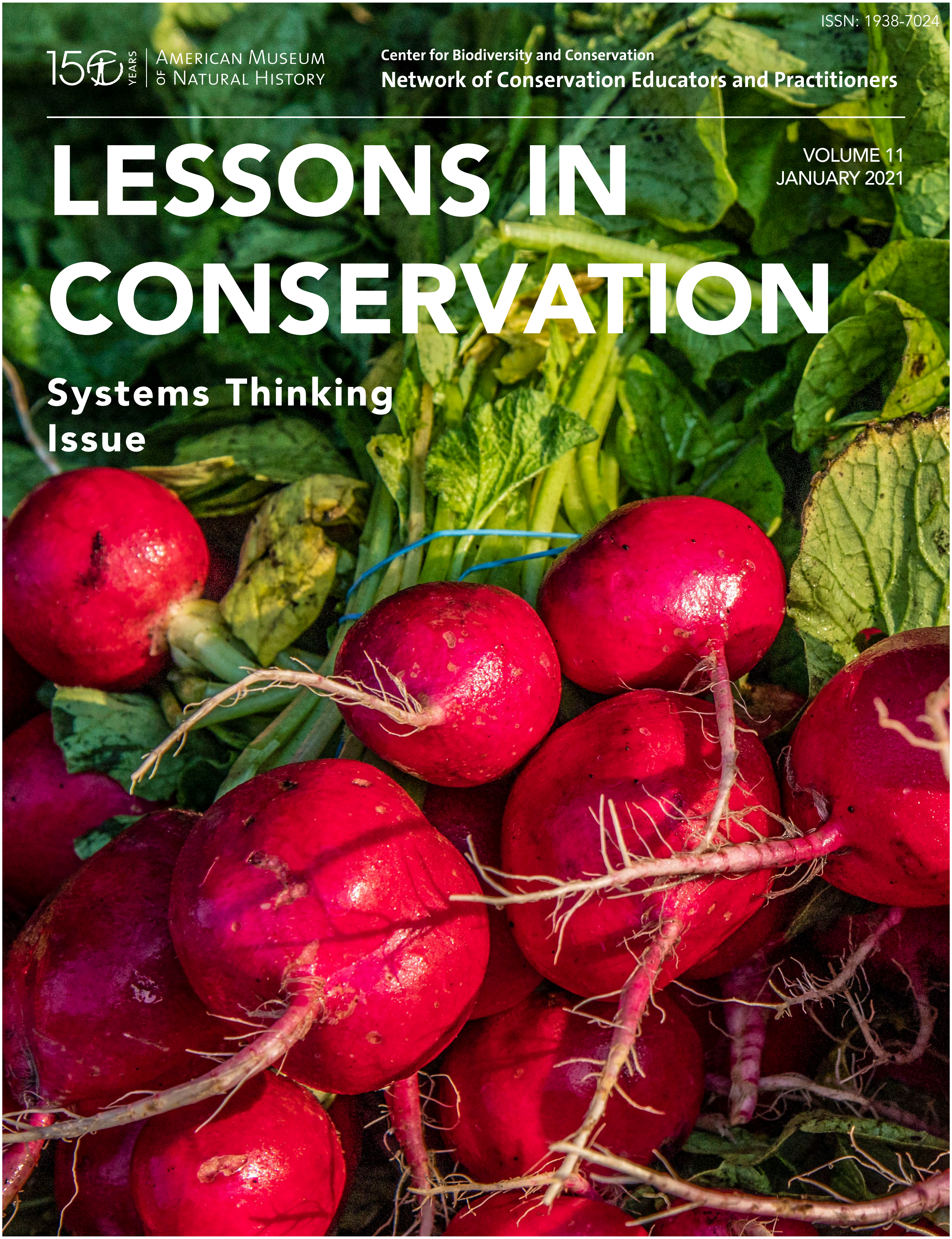
Systems Thinking Issue



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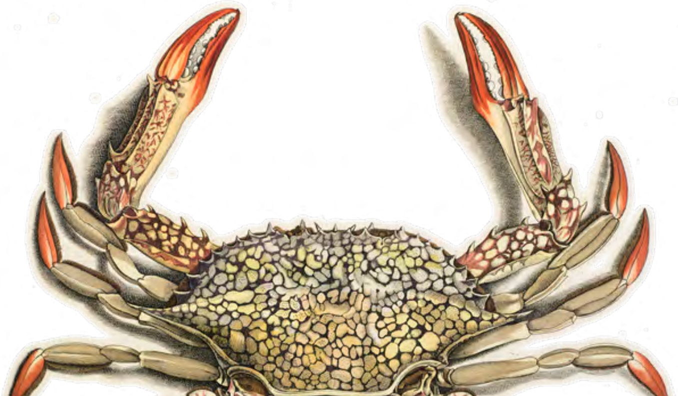

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LETTER FROM THE EDITORS

Dear Reader,

Welcome to Lessons in Conservation, the official journal of the Network of Conservation Educators and Practitioners (NCEP), a collaborative project of the Center for Biodiversity and Conservation at the American Museum of Natural History. This journal aims to introduce NCEP teaching and learning resources, or modules, to a broad audience. Our modules are designed to support undergraduate and professional level education on a variety of conservation topics, and are available for free download at our website (ncep.amnh.org).

For this issue, we present a suite of materials designed to foster systems thinking in students. The materials provide a valuable introduction to systems thinking, both as a way of seeing the world, and a specific set of tools, with illustrative examples. Through exercises, the materials in this issue also promote engagement with the complexity of biodiversity conservation problems, as students are asked to apply different systems thinking tools, both qualitative and quantitative, to understand the connections between our food systems and biodiversity.

More details on how the materials have been developed and what they encompass can be found in the editorial article included in this issue, titled The Value of Systems Thinking in a Rapidly Changing World.

We hope you enjoy this issue of Lessons in Conservation! We are grateful to many people who collaborate with NCEP and the Center for Biodiversity and Conservation for their contributions. Please see the back cover for a full acknowledgment of those who have made this issue possible.

We invite you to visit our website to start using NCEP resources in your classroom, and we welcome your feedback. If you are interested in being further involved in the Network, we hope to hear from you!

Erin Betley Eleanor J. Sterling Ana L. Porzecanski

Visit us at: ncep.amnh.org. Contact us at ncep@amnh.org.

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Note to educators: to access presentations, teaching notes, exercise solutions, and associated files for these modules, visit our website (ncep.amnh.org), register as an educator, and search for module by title.

The Value of Systems Thinking in a Rapidly Changing World

Erin Betley, Eleanor J. Sterling, and Ana L. Porzecanski
Center for Biodiversity and Conservation, American Museum of Natural History, New York, USA

What did you eat today? Whether it was a meal shared with family and friends or a quick bite on the go, the food choices you made connect you to a global web of growing, trading, cooking, and eating, with implications for your health, the environment, and plants, animals, and people all around the world. There is tremendous value in the ability to zoom out and see the broader picture, especially for complex problems like how to manage equitable, sustainable food systems. For example, if we are aware of how dynamics within a food system might influence the food choices available to us, we may view our roles in the system, both as consumers and as citizens, in different ways. In this issue of Lessons in Conservation, we focus on systems thinking and how and why ST can help us see the broader pictures, and hence help us understand and act on challenges all around us. The materials featured in this issue emerged from collaborations among multiple organizations and researchers focused on how to teach and assess systems thinking within interdisciplinary STEM education.* They are part of an ongoing effort to assemble a collection of different ST methods and approaches that can be used across a range of decision-making contexts from individual to societal levels.

Why Is Systems Thinking (ST) Important? Why Is ST Critical to the Future of Conservation and Related Fields?

It may be a cliché, but the world is indeed changing rapidly. In the 21st century, challenges are unfolding in a context that is potentially more volatile, uncertain, and complex than before (Game et al. 2013). Conservation challenges stem from drivers that are both social and environmental, and they are increasingly dynamic. If conservation practice is to be effective, it must engage with those social-economic contexts—and ultimately transform the societal systems that drive biodiversity loss (Díaz et al. 2019). This transformation, defined by Díaz and coauthors as "a fundamental, system-wide reorganization across technological, economic, and social factors" aiming to make sustainability the norm, requires a systems view and systems thinking.

Systems thinking is both a set of tools and a way of seeing. It should form part of how we conceptualize and investigate problems and make decisions in the field of conservation because many conservation issues are "wicked problems"; due to their complex and interconnected nature with other problems, they are difficult or impossible to solve. For example, despite our best efforts, we will not be able to solve the problem of species or habitat loss once and for all. But, we can think through the scope of these problems, how they form part of a system and how that system functions, try to understand the patterns and drivers in that system, and determine where we might intervene to make positive change. For example, the increase in emerging diseases we see today is linked to, and primarily driven by, human impacts on ecosystems. Through deforestation, road building, and mining, and through the production and trade of livestock, timber, agricultural, and other products, we are increasing our contact with wildlife and hence their pathogens. This contact becomes direct when humans trade wildlife and derived wildlife products, and the human activities that drive climate change and biodiversity loss also drive pandemic risk (IPBES 2020). It's become clearer than ever how environmental destruction and degradation, and the behaviors and underlying values and mindsets

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*These collaborations include the Teaching Food Systems community of practice (https://www.ihn.cumc.columbia.edu/education/teaching-food-systems-community-practice-cop), as well as the team of researchers who led projects NSF DUE-1711260, and 1711411 Collaborative Research: Assessing "Systems Thinking" Skills and Learning in Interdisciplinary STEM Courses. For an example of project findings, see Gray et al. 2019.

that produce them, undermine our own well-being.

What is Needed, Especially in Teaching and Learning

Increasingly, we may find ourselves surrounded by the language of systems: "systems thinking," "systems approaches," "systems theory," "systems dynamics," "systems concepts," "systems science," "systemic change," "how to understand the system." Oftentimes the recognition that something is part of a system, or, more likely, of many nested systems, is an important first step towards deeper understanding of the linked social and environmental challenges we are trying to address. Systems thinking has been identified as a critical and important skill for conservation leaders in the 21st century (Bruyere et al. 2020), raising the question: how can we include it in our training and education, as we develop the leaders of the future? Navigating the evolving landscape of different approaches to teaching and learning about ST can be challenging and so, through this issue, we are bringing to the fore teaching materials to advance student ST skills that can be easily adapted for a range of different contexts, and a set of methods and tools that will expand as systems thinking is increasingly incorporated into our work and practices, in the classroom and beyond.

In this issue, we begin with a synthesis designed to be a succinct introduction to systems and systems thinking useful to any educators or students who are emerging systems thinkers. The synthesis reviews key questions a systems thinker asks, explores essential ST concepts, and provides brief descriptions of several ST frameworks and tools that can assist with: 1) understanding systems, 2) systems-oriented dialogue and reflection, and 3) co-designing responses that aim to promote system-wide change. The synthesis is accompanied by an adaptable presentation and teaching notes, which are available for educators to download at ncep.amnh.org. Two exercises leverage the content in the synthesis by focusing on two different ST tools: stakeholder analysis and a semi-quantitative modeling tool called Mental Modeler. Students use stakeholder analysis to explore a suite of issues ranging from public health initiatives like food labeling to human rights abuses in the fisheries industry, and use Mental Modeler to explore the current dynamics of and links between corn and beef production in the United States. These exercises, along with teaching notes that include information on assessment of ST in the Mental Modeler exercise, are the initial building blocks for a broader collection being assembled by NCEP that will include exercises on other ST tools, such as rich pictures.

Finally, this issue includes a set of materials on parasite biodiversity. The module (a synthesis and two exercises) focuses on introducing parasites and their ecological roles, yet they also demonstrate the importance of a systems lens. As the authors point out, more than 40% of known animal species are parasites, and while they are a major part of biodiversity they are seldom discussed in introductory biology courses. The exercises in this module bring students close to—even face-to-face with!—parasites, through a dissection activity that uses market-bought fish, and through the manipulation of real-world data on communities of parasites within coral reef fishes. Using these data, students explore whether and how human activity, specifically fishing, alters the number and type of parasites present within the fish.

Drawing from multiple examples, from the protozoan *Toxoplasma* to the Rinderpest virus, the Parasites Biodiversity Module illustrates how small or even microscopic parasites may have large effects on populations, entire ecological communities and, even global effects. These effects may unfold or increase over time—and ultimately even shape the evolution of species, both parasites and hosts. In this way, parasites help illustrate the importance of considering multiple scales, non-linear dynamics, and time delays, all of which are important systems concepts. Importantly, the authors also highlight important questions to consider as we face a dynamic future, such as how host-parasite interactions will be changed by a changing climate, and by increasing levels of invasive species. Overall, this new set of teaching materials helps provide a broader view of ecosystems and food webs revealing hidden complexity, and increasing our understanding of ecological systems. As the authors point out, "parasites have important roles to play in ecosystems and we ignore them at our own peril."

Systems thinking is not a new idea. It is inherent to so many different (particularly Indigenous) knowledge systems and ways of knowing deeply embedded in cultures around the world that it often is not named as a distinct concept (Sterling et al. 2020). But systems thinking has been having a renaissance during recent decades, beginning with work on operations research, industrial dynamics, and computer modeling and simulation, and the understanding of what it means to "think in systems" is increasingly codified into books, websites, and curricula. In the past few years, fresh ideas have emerged about how some of the foundational concepts of systems thinking can help bring about new understandings about sustainability, equity, and social justice (Powell 2010; Valley et al. 2020). In conservation, and many other arenas, we increasingly see a need to understand and embrace complexity, and the importance of systems awareness to illuminating key underlying mindsets, values, and paradigms; to envisioning sustainable futures; to linking knowledge to action; and to identifying pathways for change. These approaches underpin effective transformations towards equitable sustainability.

We hope that this issue of Lessons in Conservation gives you the confidence to incorporate systems thinking into your teaching and assessment, if you haven't already, and some methods and tools to use in your classroom. Many of these tools have the added benefit of being able to integrate into remote teaching and learning as well because they employ open-access web-based platforms and activities suitable for small groups in breakout rooms. The year 2020 has presented all of us with challenges compounded by other challenges. Not only can systems thinking help us to make sense of the bewildering set of events of this past year, from a global pandemic to social and political turmoil, but can point us forward towards transformation.

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Introduction to Systems and Systems Thinking

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ABSTRACT

Throughout our daily lives, we interact with countless systems, in ways that are obvious and not so obvious. More and more systems-related terms are emerging in the scientific literature, in curricula, and in popular media: systems thinking, systems approaches, systems analysis, systems dynamics, systems mapping, just to name a few. In an increasingly complex and interconnected world, thinking systemically can help us to understand, communicate, address, and educate about challenges we face. Yet if you want to start using this approach, it can be difficult to know how to start. Systems thinking is both an approach to seeing the world in a way that makes connections and relationships more visible and improves our decision-making abilities, and a set of methods and tools. This synthesis provides an overview of ways to think about systems as an initial step towards systems thinking, and of systems thinking tools that can be useful to educators and students in any discipline.

INTRODUCTION

"Let's face it, the universe is messy. It is non-linear, turbulent, and chaotic. It is dynamic. It spends its time in transient behavior on its way to somewhere else, not in mathematically neat equilibria. It self-organizes and evolves. It creates diversity, not uniformity. That's what makes the world interesting, that's what makes it beautiful, and that's what makes it work."

– Donella H. Meadows, Thinking in Systems: A Primer, p.181

WHAT IS A SYSTEM?

In order to think in systems, we must first understand what this term means. We encounter systems in many different contexts and situations—from circulatory systems to climate systems to healthcare systems to transportation systems. But what is a system? How would we know a system if we saw one, and why is it important to understand systems at all?

A system is a group of two or more related parts (sometimes referred to as elements, components, or stocks) that interact over time to form a whole that has a purpose or function (note, function and behavior are often used interchangeably in systems thinking literature, but for our purposes, we will use the term function). We can conceive of systems as physical entities that we can observe and empirically examine—like a tree or a subway system, or as abstract constructs we can use to understand our world—like a model of a cell or of the solar system (Systems in Evaluation TIG 2018). A system includes both parts and the relationships that hold the parts together—these can be physical flows (for example, the neural signals that allow us to sense our environment), or simply flows of information in a social system. Many parts can form a whole, but unless they depend on and interact with each other, they are simply a collection. Consider a jar of dried basil, a jar of cinnamon, and a jar of paprika—a group of spices that comprise a spice rack. Their function does not change if you add or remove spice jars or re-arrange them, because the spice rack is simply a collection. In contrast, your body is a system composed of multiple different, interacting, and interdependent organs or nested subsystems. A set of parts, arranged and connected, is essential for you to survive. Furthermore, these components can function together in ways that would not be possible for each part on its own, and as a system, exhibit properties that emerge only when parts interact with a wider whole (also known as emergent properties) (Box 1).

Box 1. Handy question guide: is it a system, or just a collection of stuff? (adapted from Meadows 2008).

- Are the parts identifiable? If yes, then...
- Do the parts interact with each other? If yes, then...
- Is there a difference between the combined interactions of the parts (or function of the parts together) compared to how each part behaves on its own? If yes, then...
- Does the function persist in a variety of situations?

If yes, then… it's a system!

Investigating the parts and interrelationships of systems helps us understand how they function (a term usually used for nonhuman systems, like a computer) or their purpose (a term usually used for human systems, like a government). Often the best way to discern the function (e.g., delivering potable water from a faucet) or purpose (e.g., educating a student) of a system is to observe how the system operates over time, in terms of growth, decline, oscillation, stasis, or evolution.

All systems have boundaries that define what is "in" and "out" of the system. Most bounded systems are nested or hierarchical; there can be purposes within purposes. Hierarchy is the arrangement of subsystems organized into larger and larger systems. An example of a hierarchy is an individual cell within your heart, which, in turn, is part of your circulatory system, which is in turn a subsystem of your body. A hierarchy not only gives a system stability and resilience but also reduces the amount of information that any part of the system has to track. For example, a ship's captain might not need to know about the individual action of every individual crew member because they trust those leaders to make appropriate decisions at their level.

Sorting Systems

Systems are often sorted into three general categories: simple, complicated, and complex (a fourth category, chaotic, is used to describe a system with weak connections between parts and no discernible patterns in function; this category is most often associated with the Cynefin framework, a conceptual model for decision-making used by systems thinkers) (Figure 1). It is important to understand the differences between these systems because they each call for different approaches for stakeholders who are managing the system or working to move it towards producing more desired outcomes.

- Simple systems are easily knowable—they have few parts with stable relationships, and the function of the system is predictable, for example, a pet goldfish in a bowl represents a simple system. The process of managing a simple system, or caring for your goldfish so it can survive and thrive, is relatively straightforward and does not deviate significantly given different contexts.

- Complicated systems are not simple but are definable, and subsequently solvable, and may require high levels of expertise in specialized fields to maintain the system. Systems can be technically complicated or socially complicated, or some combination of both. They do not adapt but rather have a high degree of certainty of outcome; for example, a computer represents a technically

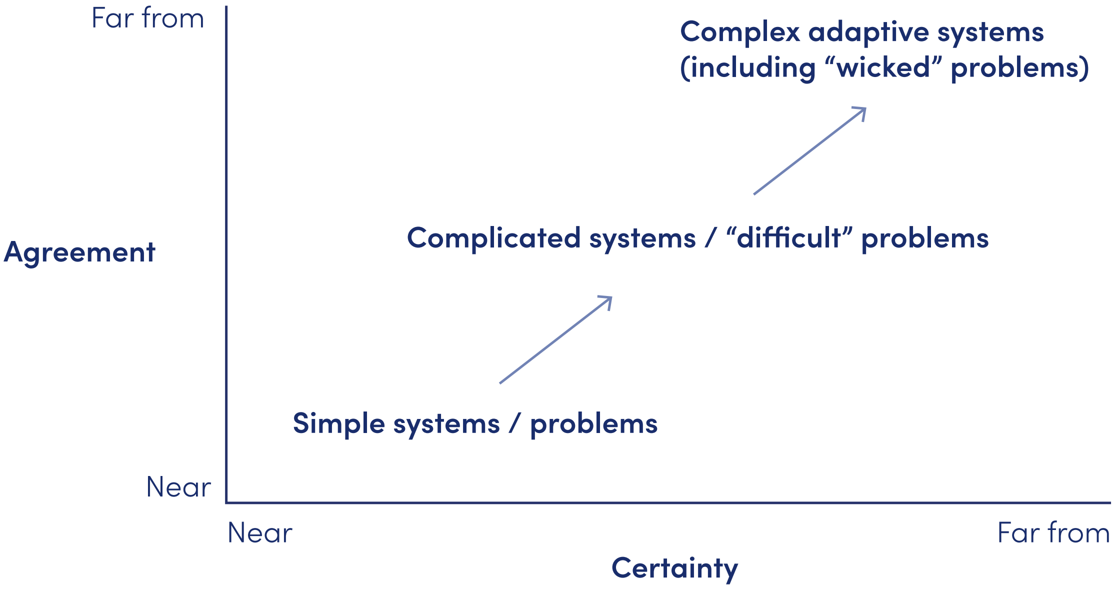


Figure 1. System typology for a system that needs improvement or a "problem." In this graph, the y-axis represents agreement between people thinking about the problem and x-axis is certainty about the nature of the problem. Image credit: modified from Allen and Kilvington (2018), based on frameworks by Ralph D. Stacey and Dave Snowden.

complicated system where outcomes can be determined: the computer is working properly, or it's not. Indicators of success or progress in managing complicated systems are directly linked through cause and effect. For the computer example, successful management requires a team with the proper expertise to maintain the system, diagnose malfunctions, and make repairs. A socially complicated system may involve different stakeholders with different perspectives and values; for example, scheduling times for classroom use in schools may be socially complicated, but it is generally solvable in the sense that a classroom schedule can be agreed upon and implemented. For socially complicated issues, the key to moving forward often comes down to building relationships, finding common ground, and creating space for respectful dialogue and differences of opinion.

- In contrast to simple and complicated systems, complex adaptive systems (CAS) have many different parts, and non-linear relationships with feedback loops across time and space (non-linear means that cause and effect of a system are not in proportion to one another, sometimes referred to as tipping points). While some complex adaptive systems are entirely human, these systems are usually a mix of interrelated human and non-human subsystems, and are dynamic, unpredictable, and change over time. They can also self-organize, evolve, and adapt.
    - Self-organization is the ability of systems to structure themselves without central control, to create new parts or relationships, and to learn and evolve in complexity.
    - Self-organized systems can exhibit emergent properties, a phenomenon that can refer to any kind of learning or new pattern that emerges from the complex interactions of a system's parts (the elegant changing shape of a flock of flying birds is an example of emergence).

The human immune system is an exquisite example of a complex adaptive system that is able to learn to defend the body against unknown pathogens through self-organizing, adaptive immunity. Democracy is another example of a complex adaptive system, continually evolving in unpredictable ways in numerous social and political contexts through time and space. If we want to influence a complex adaptive system to improve its trends and enable desired outcomes, one-size-fits-all approaches are unlikely to yield success. When we try to predict, specify, design, and force a CAS in a certain way, we may be misguidedly treating it as a complicated system. But if it is complex, different approaches are likely required to understand it and manage it. The approaches we use to understand

and maintain a complicated system like a computer will not yield success when applied to a CAS like the internet. For complex adaptive systems, especially if they are social in nature, some of the most effective management approaches work to understand the nature of the system from myriad stakeholder perspectives and recognize the uncertainty involved in the system during the process of defining it and enabling desired outcomes (for more details see methods developed by Peter Checkland and colleagues; Checkland 1999).

Management of complex adaptive systems is especially tricky for so-called "wicked" or intractable problems that are unsolvable in the conventional sense. Problems are termed "wicked" when they have multiple, often undefined, causes; little to no agreement on how to improve a situation that requires collective action among stakeholders with differing values and contested understandings of the problem, and cause-and-effect relationships that only became clear after the effects have already emerged. Human disease, refugee migration, and climate change are examples of wicked problems. While wicked problems have long, uncertain timescales and will never be "solved" in the conventional sense, we can work to understand these particular systems and make decisions that alter their function in ways that can promote progress towards desired outcomes.

WHAT IS SYSTEMS THINKING?

Investigating systems through "systems thinking" opens up countless possibilities for understanding and influencing the world around us. In their review of literature on "systems thinking," Arnold and Wade (2015) found no widely accepted definition for the term. Their proposed definition is that systems thinking is "a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviors, and devising modifications to them in order to produce desired effects." This can be a useful starting point in trying to understand systems thinking. Yet, across the literature, courses, professional development offerings, and websites that focus on systems thinking, there are numerous lists of the characteristics of a systems thinker, with some elements that overlap and some that do not. Faced with this landscape, how can we understand how systems thinking can be useful in our roles as students, educators, practitioners, and members of our communities? One path forward is to view systems thinking as both an approach to seeing the world—in a way that makes connections and relationships more visible and improves our decision-making abilities—and a set of methods and tools (Paxton and Frost 2018). In subsequent sections, we explore these two ways to engage with systems thinking.

When we use systems thinking as a way of seeing (a systems "lens") we see that the world is made up of parts that, in turn, connect and interact in dynamic ways to form a whole, whether we are looking at food systems, economies, or ourselves. With this ability to "see" where in a system and the relationships within it problems seem to originate, system thinkers can then think about ways to change the system, communicate with others to create new ways of thinking and seeing, and through this shared understanding, plan more effectively for the future. The key for systems thinking is that it is NOT about prediction or control, but about raising more questions to enhance understanding and seeking opportunities to "nudge" system function in desired directions (Box 2). Systems thinking helps with seeing that there is frequently not one single solution to a problem, but a set of coordinated actions that guide the system towards a desired state or outcome.

As systems thinkers ask these questions, they draw from several essential systems thinking concepts. Several of these concepts are used in other academic fields, though they have a specific meaning in the context of systems thinking. While the concepts are not unique to systems thinking, the full

Box 2. Questions a systems thinker asks when faced with a complex issue (adapted from Ponto and Linder 2011):

- What happened?
- What recurring events are we noticing?
- What length of time is long enough to see patterns in system function?
- What structures may be determining the function we see?
- What underlying beliefs, values, or assumptions are at play, including from or within ourselves?
- What are the feedbacks in this system?
- How can we define a boundary around this system? What is appropriate and useful for our goals?
- What other perspectives, methodologies, or disciplines might help us more fully understand this issue?
- Where in this system could we make small shifts that would make a big difference? What trade-offs exist? Is there a potential for unintended consequences?

array of concepts constitutes a distinctive approach to viewing the world. Below we review these key concepts:

What happened? What recurring events are we noticing? What length of time is long enough to see patterns in system function? What structures are in place that may be determining the function we see? What underlying beliefs or assumptions are at play, including from or within ourselves?

Each of these questions relate to how a system is structured and how it operates over time. Systems thinking emphasizes relationships and interactions between parts of a system, interrogating the nature of the relationships and discerning patterns or trends emerging from these relationships. System thinkers seek root causes, or the connections between events and the underlying structure of the system and paradigms or mental models (deeply held abstractions or generalizations about how the world works), which may be driving system function (Figure 2).

What Are the Feedbacks in This System?

Stocks are the foundation of any system—the parts of a system that can be measured. Stocks can be physical, for example, the temperature within your body, or not physical, for example, your happiness or well-being on a particular day. Stocks change over time as a result of flows, and can act as buffers or delays in a system. For example, since one property of water is that it can absorb a lot of heat before its temperature starts rising, the water within the human body can act as a buffer during changing ambient temperatures.

A feedback loop is a closed set of connections originating from a stock, through a set of decisions or actions that are dependent on the stock's level, that ultimately influence a flow to change the stock. Often the most important feedback loops provide information on how the system is doing relative to a desired state: a balancing feedback loop stabilizes a stock level, keeping a stock within a certain range—and opposing whatever directions of change are imposed on the system. An example of this type of balancing or negative loop is how your body regulates its temperature—raising it when the stock (i.e., temperature) is low, and lowering when the stock is too high. If you exercise, your

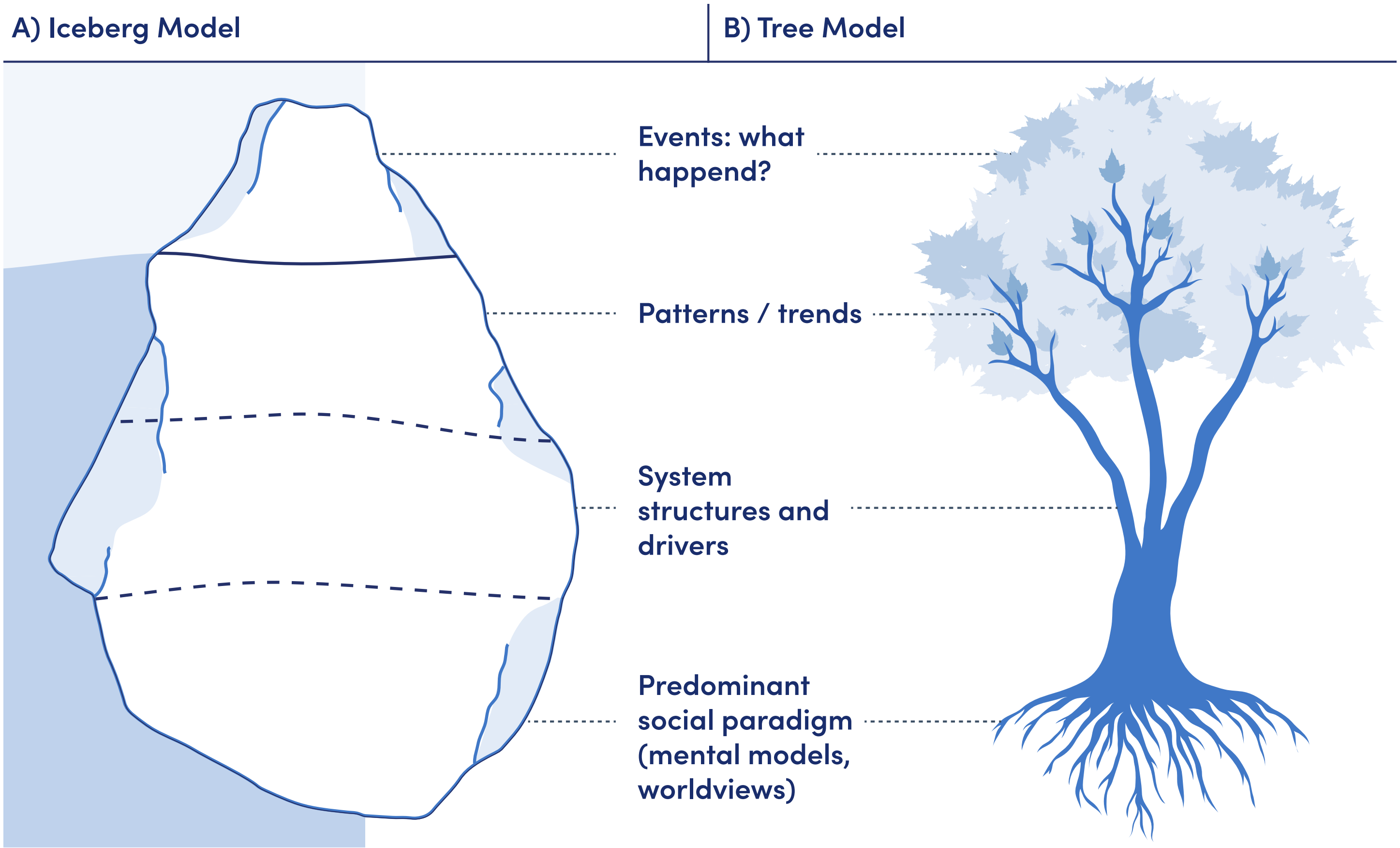


Figure 2. Adapted Iceberg Model. (2A) The "iceberg model" is a visual tool often used to examine the structures and mental models that underlie system function and create patterns of events over time. The tool differentiates the visible manifestations of the system (the "events," or "tip of the iceberg"), and the rarely seen, "below the surface," patterns, drivers, and paradigms that give rise to the events. (2B) Since this model of a static iceberg does not capture the dynamic interlinkages between the root structures and the surface events, we have adapted the iceberg model using the example of a tree to show these interlinkages between events (leaves that provide energy for the rest of the tree), patterns/trends (branches that support the leaves), structures and drivers (trunk that supports the branches), and predominate social paradigm (roots that support trunk, branches, and leaves). Image credit: Nadav Gazit/AMNH.

body activates your sweat glands to cool you down; and if you are cold, your body shivers to create warmth. In contrast, a reinforcing, or positive, feedback loop amplifies change in a stock, causing desirable ("virtuous" cycle) or undesirable ("vicious" cycle) outcomes, enhancing whatever direction of change is imposed on it; these loops are often referred to as snowballing changes, or chain reactions. One example of this type of system is an interest-bearing bank account—as the stock (i.e., account balance) increases, more interest is earned, increasing the stock, and so on. Without a counter-balancing reaction or process, a positive feedback loop has the potential to produce a runaway process, for example when population decline in a species can lead to loss of genetic diversity and increased likelihood of population extinction.

Systems can contain networks of reinforcing and balancing feedback processes of different strengths operating in different directions. If reinforcing loops and balancing loops are equal, a system may have a dynamic equilibrium that is maintained with a specific range of outcomes. As the relative strengths of feedback loops change, the function of systems change as well. For example, as feedback loops affect the changing stock of water in a river, the way the system operates changes, especially in times of flood or drought. Resilience—the capacity of a system to absorb, resist, or recover from stress, and adapt to change while maintaining valued functions and benefits (Stein

2013)—arises from a robust structure of many feedback loops that can work in different ways to maintain a system even after a significant disturbance. An example of a resilient system is a thermostat that can detect changes in a home's ambient temperature and adjust by engaging a heater or air conditioning system to raise or lower the temperature to the desired setting.

A system's structure is its interlocking stocks, flows, and feedback loops. Since the structure gives rise to function which reveals itself as a series of events over time, system thinkers must examine both the structure of a system and how it functions. Systems thinkers can also refer to system archetypes, or generic system structures that produce characteristic or common functions, in order to better understand systems and why particular system interventions may succeed or fail.

How Can We Define a Boundary Around This System? What Is Appropriate and Useful for Our Goals?

Any discussion about systems must also touch on boundaries, in terms of scope and scale. Although in theory everything is connected, what we know and perceive (i.e., mental models, or beliefs and assumptions about how the world works) has limits—and limits are called boundaries. Boundaries can be set to determine what is "in" and what is "out," what is important and unimportant, and to recognize who benefits and who is disadvantaged with this set of boundaries. As noted by Meadows (2008), systems rarely have universally agreed upon, legitimate boundaries and where to define a boundary around a system depends on the purpose of the discussion about that system—the questions we want to ask about the system and our value judgments. Frequently we draw boundaries based on the available data or based on the part of a system we know the best, thus missing important drivers. For example, a protected area may have an official boundary that does not encompass a whole watershed or connected landscape. Such a boundary may not be very helpful for understanding the dynamics of species or threats affecting the area. If boundaries are drawn too narrowly, the way the system operates can be surprising and our decisions can create unintended consequences or "side-effects" because we have not identified the major drivers of the system. If boundaries are drawn too broadly, they can conceal answers to the problem at hand or make the process of understanding the system and making decisions next to impossible. The most appropriate boundary for considering a system rarely coincides with named boundaries, such as academic fields or political boundaries. And importantly, drawing boundaries carries important ethical and practical implications. The act of defining a boundary makes what is outside the boundary marginal or secondary. While this boundary definition may be profound or unimportant, a systems thinker should always consider the consequences of exclusion, particularly when a boundary leads to marginalization.

What Other Perspectives, Methodologies, or Disciplines Might Help Us More Fully Understand This Issue?

Systems thinkers understand that there is tremendous value in the many perspectives of a system. When considering a problem, they ask:

- Who or what are the key stakeholders in this situation?
- What stakes (values and motivations) do they/we have?
- What are the different ways in which the situation can be framed or understood—by whom?
- How do these different framings affect the way in which stakeholders act—when things go their way/when things do not go their way?

Systems thinkers also understand the value of using diverse methodologies for learning how systems are organized, how they operate over time, and how they can be better governed. Another way to understand this approach is methodological pluralism (i.e., using different methods or techniques in combination); for example, mixed methods that use quantitative or qualitative methods to study a system (Jackson 1997). Finally, by working across disciplines and sectors, systems thinkers can help to create a shared vision, common set of goals, mutual understanding, and shared expectations for all stakeholders.

Critical systems thinking is an approach to dealing with complexity that emphasizes understanding the strengths and weaknesses of various approaches and learning how to employ them in combination (Sova et al. 2015; Jackson 2019). When considering stakeholders, critical systems thinkers ask:

- Who has power?
- Who is defining the system, its structure and function?
- Who is excluded from the decision-making process?
- Whose knowledge counts in the system? Whose knowledge is actively disappeared or diminished by other stakeholders?
- What are the historical and current power dynamics between stakeholders and how does that impact our understanding of the system?
- How are benefits and harms/burdens distributed within the system?

Where in This System Could We Make Small Shifts That Would Make a Big Difference? What Trade-Offs Exist? Is There a Potential for Unintended Consequences?

Systems thinkers who are considering how to make change in a system to bring about desired outcomes often work to identify leverage points, or places within a complex system where a shift in one place can produce changes elsewhere in the system. One way to envision leverage points was proposed by Donella Meadows (1999), an influential systems thinker, in her compilation of 12 different leverage points, or places to intervene in a system, ranked by least to most effective in terms of systems change (note, other systems thinkers might identify different dimensions than the list below, or assign different rankings, so this ranked list can be seen as a discussion prompt):

12. Constants, parameters, numbers (e.g., subsidies, taxes)
11. Sizes of buffers, relative to their flows (e.g., inventories)
10. Structure of stocks and flows (e.g., transportation networks, population age structures)
9. Length of delays, relative to the state of system change (e.g., time a price takes to adjust to supply/demand imbalance)
8. Strength of balancing/negative feedback loops, relative to the impacts they are trying to correct against (e.g., removal of subsidies that can lead to longer term economic or environmental damage)
7. Gain around reinforcing/positive feedback loops (e.g., progressive income tax)
6. Structure of information flows (i.e., who does and does not have access to information) (e.g., information about the commodity prices)
5. Rules of the system (e.g., incentives, constraints in a trade system)
4. Power to add, change, evolve, or self-organize structure (i.e., to allow a system to self-organize by making any of the changes listed above, for example, a self-organizing system that changes its own feedback loops over time)
3. Goals of the system (e.g., goal of keeping a market competitive in capitalist economy)
2. Mindset or paradigm out of which the system arises (e.g., economic growth is always the answer to our problems)
1. Power to transcend paradigms (i.e., realizing that no one paradigm is true)

We can envision the relative strength of leverage points by returning to our adapted iceberg (tree) model (Figure 3). As symbolized by the transformational impact of rain, the deeper down we go into the levels of this model, the more leverage we have to change system function. In order for rain to affect the growth of a tree, it needs to be absorbed by the roots. This means that if we want to change how a system operates, understanding and investing in the root levels—such as mental models—can have more lasting effects on how the system works than simply trying to respond to a specific event. Meadows' ranking of leverage points has been adapted for use in many different applications, for example, as an analytical framework for urban-led change (Angheloiu and Tennant 2020) and for transformational change in sustainability science (Abson et al. 2017). Recent scholarship on amplifying the impact of sustainability initiatives to foster transformative change calls for change beyond the more mechanistic interventions at the top of Meadows' list (shallow leverage points), to deeper levels and more fundamental transformations of systems. This is termed "scaling deep" in Lam et al.'s 2020 integrative typology of eight amplification processes: stabilizing, speeding up, growing, replicating, transferring, spreading, scaling up, and scaling deep.

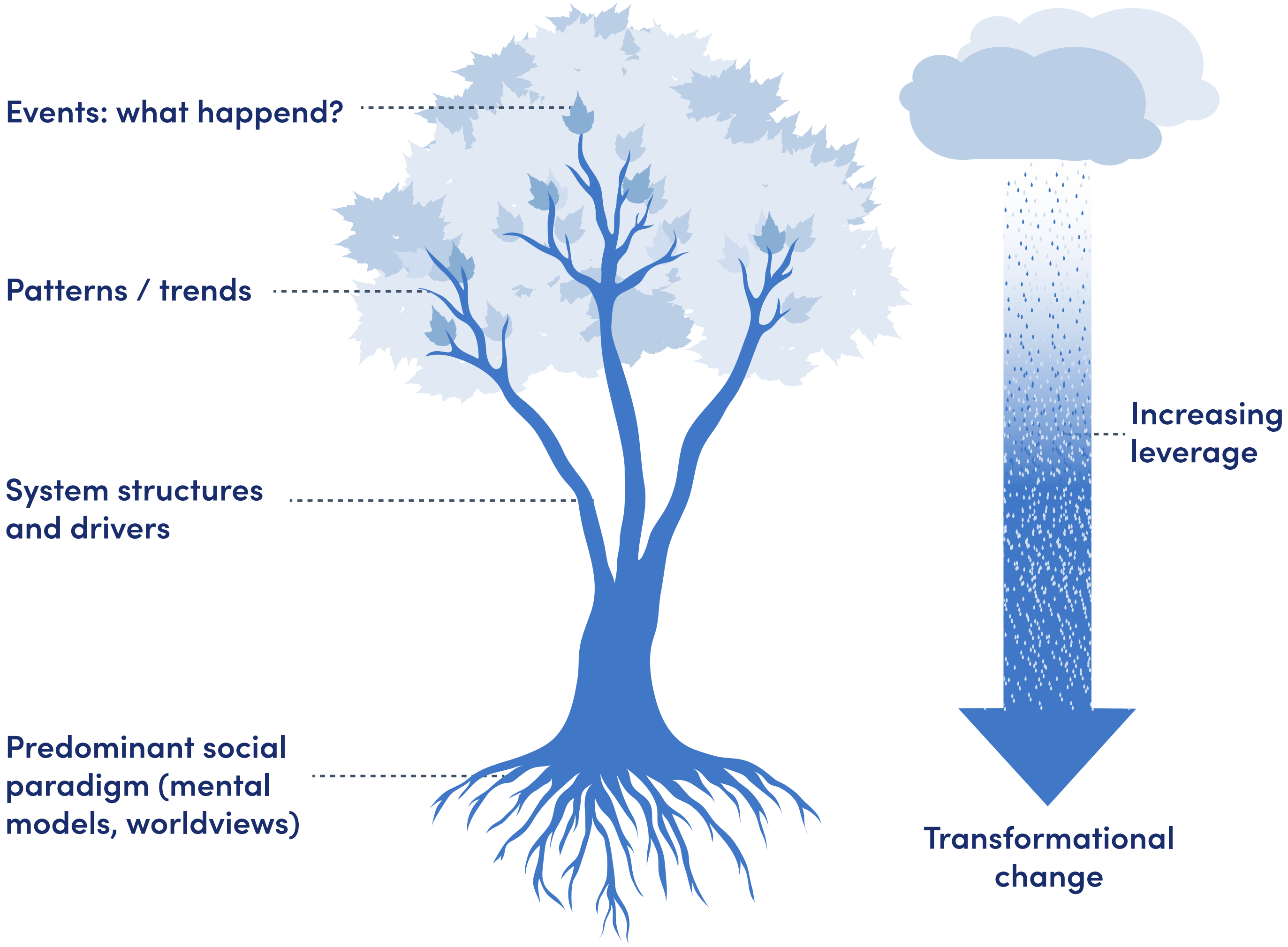


Figure 3. Adapted iceberg model from Figure 2B with points of increasing leverage. As symbolized by the transformational impact of rain, the deeper down we go into the levels of this model, the more leverage we have to change system function. Rainfall can be partitioned by trees into three fractions: rain intercepted by vegetation and evaporated before it reaches the soil, rain flowing down the branches and trunk of the tree that can be absorbed by the tree bark before it reaches the soil, and rain that reaches the ground directly or after contacting the tree canopy and is taken up by the roots of the tree (Crockford and Richardson 2000). Image credit: Nadav Gazit/AMNH.

Trade-offs occur when an aspect of a system is reduced or negatively affected as a consequence of an increase or shift in another aspect. In some cases, a trade-off may be an explicit choice made by actors in the system, but in others, trade-offs arise without intention or even awareness that they are taking place. For instance, concentrating only on ensuring low costs for food without thinking about pollution or worker's rights could result in negative consequences for the environment and for human well-being (Committee on a Framework for Assessing the Health, Environmental, and Social Effects of the Food System 2015). As noted above, unanticipated or unintended consequences can also arise when there is a mismatch between systems' boundaries and the complexity of the system, leading to "surprises." Systems thinkers are able to use their understanding of systems to analyze trade-offs and make informed choices.

In sum, the value of systems thinking is that it can help us to understand the world around us. Many of the complex adaptive systems in our world are unpredictable, uncontrollable, and understandable only in general ways—but systems thinkers can see that there is a wide range of choices before us. They see systems that can be designed and redesigned, and assumptions and trade-offs that can be anticipated and learned from. As Donella Meadows (2008) argues, systems wisdom can be gleaned from understanding the history of a system and how and why it works, as well as by challenging mental models, sharing information, paying attention to what is important and not just what is measurable, designing feedback policies for systems with feedback loops, and locating responsibility within a system.

SYSTEMS THINKING FRAMEWORKS AND TOOLS

For those interested in learning more about systems and systems thinking, there can be a formidable number of places to start. There is no one widely accepted way to "do" systems thinking. Many different scholars and practitioners have presented their own approaches or frameworks about system thinking, each with their unique terminology and points of emphasis. While mapping the landscape of these frameworks can be useful (see below for a selection), what these frameworks have in common is the use of the systems concepts covered above to think about a particular system, problem, or intervention.

- Meadows (2008) is a primary source for the above overview and focuses on the basics of defining systems and using a systems thinking lens to bring about change in the world (Meadows 2008 and http://donellameadows.org/systems-thinking-resources/).
- Paxton and Frost (2018) is a primary source for the above overview and describes an experiential, multi-disciplinary curriculum that uses systems thinking to frame and analyze global health policies and practices in order to train students to be effective and innovative global health leaders.
- Williams and Imam (2007) draw from decades of scholarship and theory on systems to develop a framework that focuses on interrelationships, perspectives, and boundaries as three core concepts; and the Systems in Evaluation Topical Interest Group of the American Evaluation Association adds a fourth concept to that list: dynamics (Systems in Evaluation 2018).
- Cabrera and Cabrera (2015) draw from the field of cognitive science to develop a systems thinking framework that focuses on distinctions, relationships, perspectives, and boundaries.
- Eoyang (2007) draws on human systems dynamics theory and focuses on concepts of containers, differences, and exchanges. This framework is closely associated with complexity theory, which focuses on dynamics of uncertainty and disagreement over time in a system.
- Reynolds and Holwell (2010) provide a practical guide that outlines five systems approaches that: explore the dynamics of how societies emerge, how organizations create viability, how to facilitate chains of argument through causal mapping, how to embrace a multiplicity of perspectives identifying purposeful activity and how to look for the bigger picture across multiple disciplines.

Similar to the varied ways to approach systems thinking, there are many tools for systems thinking that can be used as stand-alone techniques for learning and exploration, or in combination to achieve deeper insights into systems. Tools for systems thinking can be qualitative, semi-quantitative, or quantitative and also can be grouped by function: understanding the system (and why particular interventions succeed or fail), dialogue and collaboration, and designing responses that aim to promote system-wide change. Many different tools can be used in different combinations to arrive at projected needs. Here we will highlight just a few useful tools that illustrate these functions; for more extensive lists of tools, please see resources compiled by:

- Learning for Sustainability: https://learningforsustainability.net/systems-thinking-tools/
- Systems Thinking Tools: A User's Reference Guide: https://thesystemsthinker.com/wp-content/uploads/2016/03/Systems-Thinking-Tools-TRST01E.pdf
- Williams, B., and R. Hummelbrunner. 2010. Systems concepts in action: A practitioner's toolkit. Stanford: Stanford Business Books.

Tools that can help with understanding the system (and why particular interventions succeed or fail) and allowing us to visualize it:

- **Iceberg model visualization of a problem (qualitative)**: the iceberg model can be used to encourage systemic thinking and help contextualize an issue as part of a whole system. By connecting an event—a single incident or occurrence—to patterns of how a system operates, systems structures, and mental models, the iceberg model allows you to see the structures underlying the event, hidden below the surface (see Figures 2, 3 for our adapted version of this model using the metaphor of a tree rather than an iceberg).

- **System archetypes (qualitative)**: system archetypes are generic structures that produce characteristic or common functions.

- **Rich picture diagrams (qualitative)**: rich pictures (or mind maps) use diagrams, cartoons, symbols, or words to explore and define a system by creating an unstructured description of it. It is called a rich picture because it illustrates the richness and complexity of a situation (Figure 4).

- **Scenario analysis and visioning (qualitative)**: scenario analysis/development and visioning are methods of developing alternative futures derived from discussions data, trends, assumptions, and

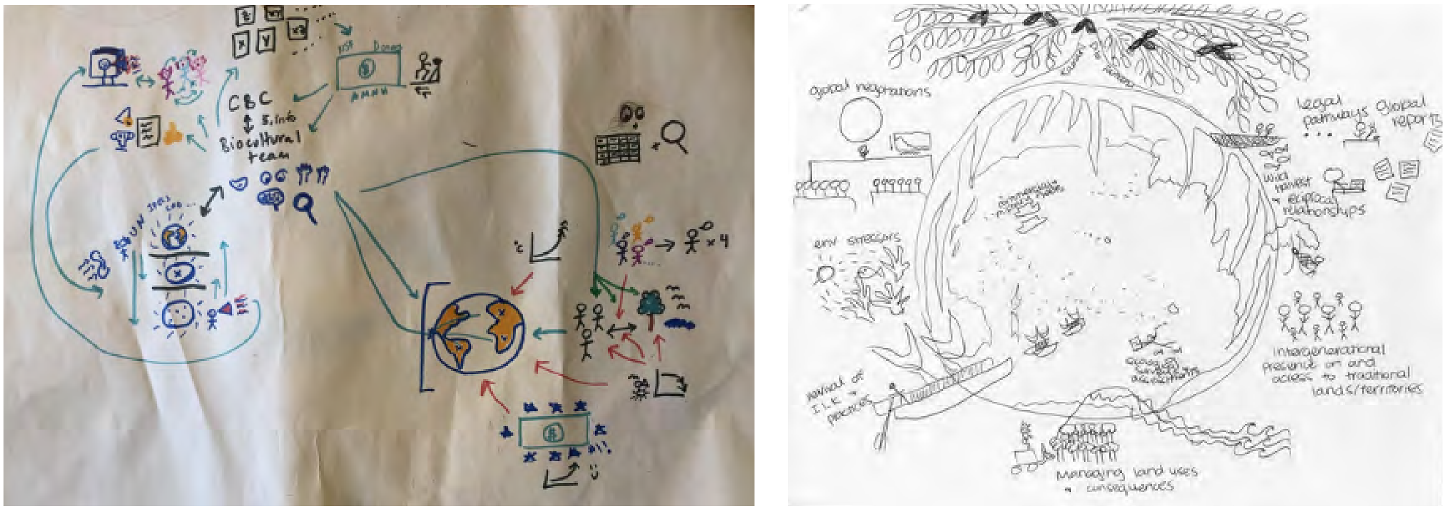


Figure 4. Examples of rich picture diagrams.

areas ripe for more understanding. Analysis can include backcasting, which is a planning method that starts with defining a desired future and then working backwards to identify actions that will connect that envisioned future to the present, and forecasting, which involves predicting the future based on analysis of current trends.

- **Causal loop diagrams (semi-quantitative)**: Causal loops help us understand how changing one part of a system can have unexpected consequences, or feedback, on other parts of the system or the functioning of the system itself. In turn, we are then able to evaluate the effect of these connections, whether to balance a trend, or reinforce it. Causal loop diagrams (CLD) can help make mental models visible by identifying key parts of the system and how they influence one another (Figure 5).

- **Trend mapping or change over time graphs (semi-quantitative)**: change-over-time (also known as behavior-over-time) graphs are a tool to make system behavior (or function) more visible (Figure 6). They can show us how a specific variable changes over time, or trends, and allow us to compare that with other variables. What is most critical to observe is the pattern (the shape of the line) and the points where the line changes shape or direction. When a particular change persists over time, there are likely feedback loops creating this consistent pattern. Systems thinkers toggle between considering structure (diagrams of causal loops for example) and function (change over time graphs) in order to understand a system.

- **Quantitative modeling (quantitative)**: quantitative modeling uses numbers and mathematical equations to represent a system.

Tools that help with dialogue and reflection:

- **Stakeholder analysis (qualitative)**: a stakeholder is any person, group or institution with an interest or "stake" in a problem, project, or system. Stakeholder analysis is a way to learn about stakeholder interests, relationships, and behavior, to understand the perspectives of stakeholders, and to assess how they may influence decision-making. Stakeholder analysis tools can range from stakeholder maps to stakeholder grids. For an example of an exercise using this tool, please see NCEP's Systems Thinking Collection: Stakeholder Analysis Exercise (available from ncep.amnh.org).

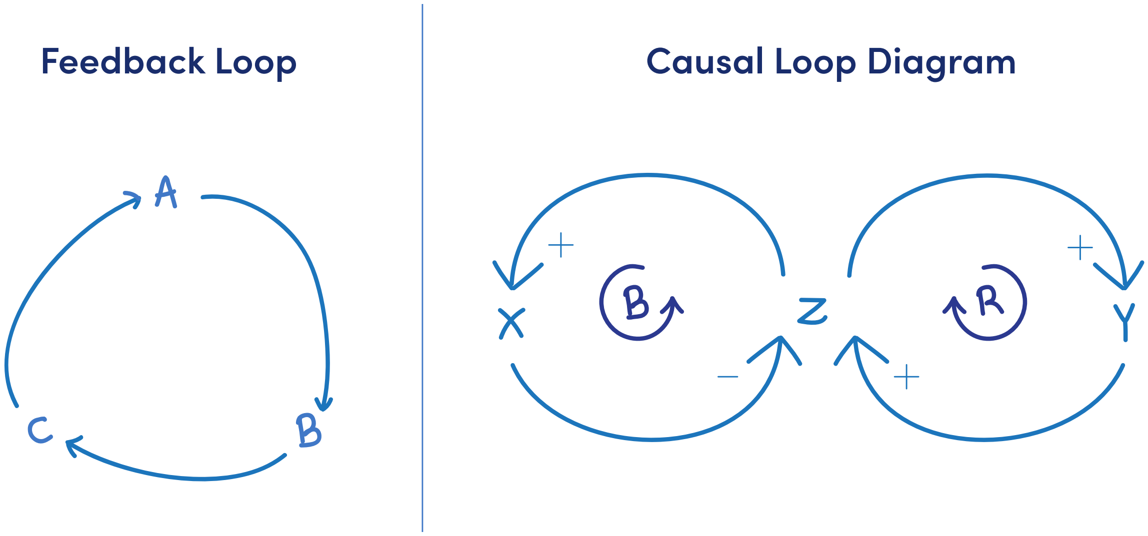
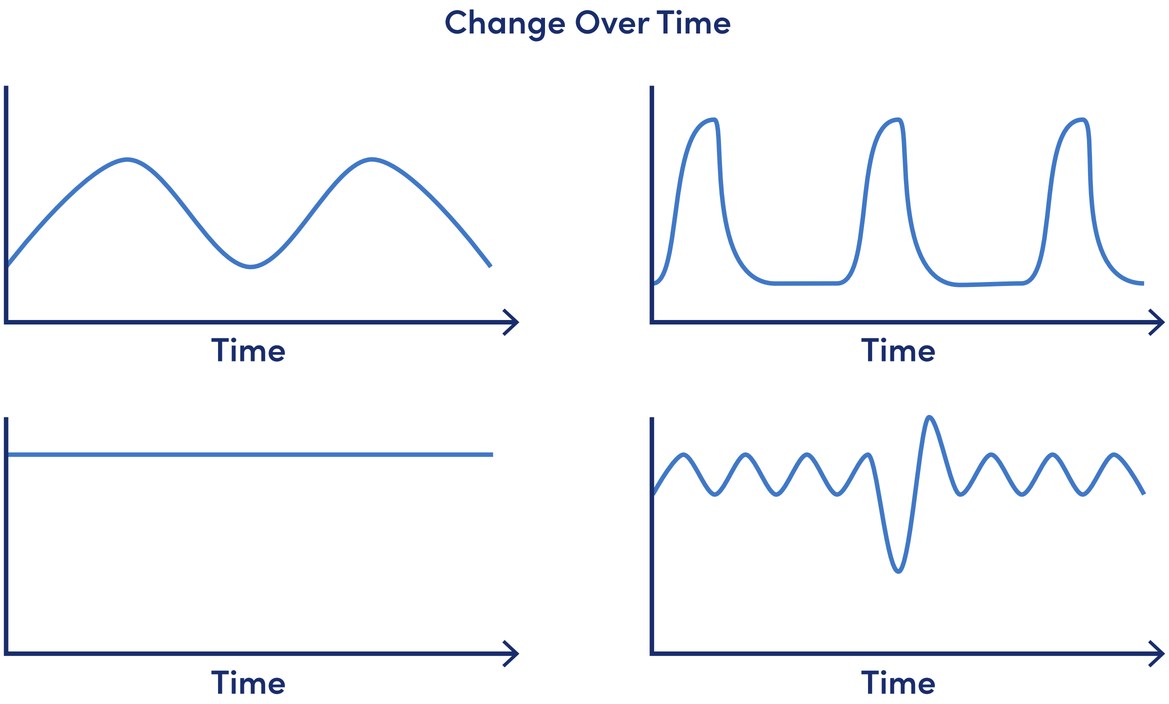


Figure 5. Causal loop diagram (right) and causal or feedback loop (left). A causal loop is a visual tool which shows how two or more system parts or variables influence each other (A affects B, B affects C, and C in turn affects A). Casual loop diagrams can help clarify balancing (B) or reinforcing (R) loops connecting variables.

Figure 6. Change or behavior over time graphs.



- **Circular dialogue (qualitative)**: circular dialogue is a facilitated technique, adapted from role-playing, where participants have the chance to perceive a given situation from at least three different perspectives. Guided by facilitators, participants communicate with each other in a structured way, interviewing and observing each other, with the goal of a dialogue that promotes critical appreciation, generates or validates experience, and illuminates opportunities to promote system-wide change.

Tools that help with co-designing approaches to promote system-wide change:

- **Conceptual/concept models or maps (qualitative):** conceptual/concept models or maps are representations of a system, composed of concepts that facilitate knowledge about, understanding of, or simulation of what the model or map represents (for this particular systems thinking tool, modeling and mapping terms generally refer to the same process).

- **Scenario planning (qualitative)**: scenario planning is a strategic planning method to assess possible future events and alternative possible outcomes.

- **Multi-level stakeholder influence mapping or power mapping techniques in a system (qualitative)**: these methods elucidate power dynamics between actors in complex systems.

- **Participatory mapping and participatory modeling (qualitative and quantitative):** through participatory methods for mapping and/or modeling, the implicit and explicit knowledge of participants contributes to support decision-making.

- **Human-centered design (qualitative and quantitative)**: human centered design draws from participatory action research to focus on the users of a system, their needs and requirements and often integrates technology or other useful tools in order to alleviate problems related to the system.

- **DSRP method (qualitative):** DSRP is a set of systems thinking techniques, developed by systems theorist and cognitive scientist Derek Cabrera, that focus on distinctions, systems, relationships, and perspectives and uses guiding questions and diagrams.

- **Cynefin framework (qualitative)**: the Cynefin framework was developed by an IBM scientist as a conceptual framework for decision making. The framework consists of these domains or decision-making contexts defined by the nature of the relationship between cause and effect: simple/obvious/clear, complicated, complex, and chaos/chaotic.

- **Fuzzy cognitive mapping (FCM) with Mental Modeler (semi-quantitative)**: FCM is a form of conceptual mapping where qualitative static models are developed and then translated into semi-quantitative dynamic models. Mental Modeler is a free modeling software that allows for the creation of fuzzy cognitive maps. For an example of an exercise using this tool, please see NCEP's Modeling Links between Corn Production and Beef Production in the United States: A Systems Thinking Exercise using Mental Modeler (available from ncep.amnh.org).

- **Agent-based modeling (quantitative)**: agent-based modeling is a computational model for simulation of the actions and interactions of agents (e.g., stakeholders) to assess their effects on the whole system.

SYSTEMS THINKING FRAMEWORKS AND TOOLS

There are numerous software platforms and resources to support systems thinkers; below is a selection of open access options:

- Kumu: an interface that allows for the creation of system maps, causal loop diagrams, stock and flow diagrams, stakeholder analysis, social network analysis
  - Free personal accounts, paid organizational accounts: https://docs.kumu.io/
- Fil Salustri's Design WIKI: description and resources for free, online system diagram makers:
  - https://deseng.ryerson.ca/dokuwiki/design:system_diagram
- Insight Maker: an interface that supports the creation of rich pictures, causal loop diagrams which can be turned into powerful simulation models using system dynamics and agent-based modeling
  - Free personal accounts: https://insightmaker.com/
- Mental Modeler: an interface that helps individuals and communities organize their knowledge in a format that can be used for scenario analysis
  - Free personal accounts: http://www.mentalmodeler.org/
- Systems Thinker: a repository of articles, case studies, and how-to guides on systems thinking
  - https://thesystemsthinker.com/
- Waters Center for Systems Thinking: listing of courses and studios offered; a repository of lesson plans, facilitation guides, assessments, videos, webinars, and articles; and interactive "14 Habits of a Systems Thinker" cards
  - Free personal accounts: https://thinkingtoolsstudio.org/
- Open access Tools:
  - https://www.presencing.org/resource/tools (provided by Presencing Institute)
  - https://reospartners.com/publication-type/tools/ (provided by Reos Partners)

ASSESSING SYSTEM THINKERS: HOW CAN WE MEASURE SYSTEMS THINKING SKILLS?

In an inherently complex world, acquiring knowledge and skills in systems thinking is a lifetime pursuit. For systems thinkers at every end of the spectrum from beginners to more advanced practitioners, it is useful to be able to gauge systems thinking proficiency: in other words, how do we know if we are progressing in systems thinking?

To assess the learning progression of system thinking, Gray et al. (2019) find that it can be useful to evaluate how well a systems thinker understands four fundamental dimensions of systems thinking: system structure, system function, identification and negotiation of leverage points, and trade-off analysis.

- System Structure: System thinkers use a combination of logic, conceptual understanding, and evidence supported by scientific research to discern system structure. Can a systems thinker identify the conceptual boundaries of a system, and the relationships between parts, including feedbacks?
- System Function: The structure of a system influences how a system functions, and function can be evaluated by measuring changes in quality or quantity of the system's components and connections over time or through qualitative descriptions of system function that can reveal thinking about how a system functions or operates. System thinkers can identify the outcomes of the system.
- Identification and Negotiation of Leverage Points: Once a systems thinker is able to demonstrate understanding of structure and function of a system they can identify places to intervene in a system that can leverage change throughout the system. They can then test a variety of possible actions and solution pathways towards a goal or preferred state.
- Trade-off Analysis: System thinkers recognize that any change to a system will cause changes to other structures and functions within that system—i.e., trade-offs. They are able to anticipate potential trade-offs and foresee adverse effects when trying to modify a system to achieve desired outcomes.
- For an example rubric and guidance on how to assess a systems thinking exercise, please see Systems Thinking Using Mental Modeler: Assessment and Teaching Notes (available from ncep.amnh.org).

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Modeling Links Between Corn Production and Beef Production in the United States: A Systems Thinking Exercise Using Mental Modeler

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LEARNING OBJECTIVES

After this exercise, students will be able to:

- Analyze complex problems within food systems and create responses that aim to promote systems-wide change, using systems thinking skills;
- Use the systems thinking tool Mental Modeler to represent the current dynamics of and links between corn and beef production in the United States, drawing from credible sources of evidence; and
- Create a model that can be used to explore key systems thinking concepts including boundaries, leverage points, and trade-offs in relation to industrial crop and animal production.

BACKGROUND

What are food systems? There are numerous definitions and different categorizations of the idea of food systems. Chase and Grubinger (2014) define food systems as "an interconnected web of activities, resources, and people that extends across all domains involved in providing human nourishment and sustaining health, including growing and production, processing, packaging, transportation, distribution, marketing, consumption, and disposal of food. The organization of food systems reflects and responds to social, cultural, political, economic, health, and environmental conditions and can be identified at multiple scales, from a household kitchen to a city, county, state, or nation." Parsons et al. (2019) differentiate the food system ("interconnected system of everything and everybody that influences and is influenced by the activities bringing food from farm to fork and beyond") from a food system (the food system in a specific place or context) from food systems (the totality of different types of food systems in different contexts). Other ways to conceptualize these systems are as 'foodscapes' and 'foodways' that encompass the dynamic and reciprocal relationships between people and the places and spaces where we acquire food, prepare food, talk about food, exchange food, or generally gather meaning from food (Sterling et al. In prep).

A complex and interlinked food system delivers approximately 135 pounds of red meat and poultry per person consumed in the United States every year (USDA 2019). In recent years, food journalists and activists have pointed to the links between corn production and beef production in this country and sought to further connect these to a host of social and environmental consequences.

In preparation for this exercise, students should review the following required and recommended articles and commentaries on food systems, and beef and corn production in the United States.

Required Readings

- Betley, E., et al. 2021. Introduction to Systems and Systems Thinking. Synthesis. Network of Conservation Educators and Practitioners, Center for Biodiversity and Conservation, American

Museum of Natural History, New York, NY. Available from https://ncep.amnh.org (17 reading pages).
- Foley, J. 2013. It's Time to Rethink America's Corn System. Available from https://ensia.com/voices/its-time-to-rethink-americas-corn-system/?viewAll=1 (9 reading pages).
- Pollan, M. 2002. Power Steer. New York Times, March 31, 2002. Available from http://www.nytimes.com/2002/03/31/magazine/power-steer.html (18 reading pages).

Recommended Readings

- Chase, L.C., and V. Grubinger. 2014. Chapter 1: Introduction to Food Systems. Food, Farms, and Community: Exploring Food Systems. University of New Hampshire Press, Durham, NH, USA (14 reading pages).
- Corah, L. 2008. ASAS Centennial paper: development of a corn-based beef industry. Journal of Animal Science 86:3635–3639. Available from https://doi.org/10.2527/jas.2008-0935 (4 reading pages).
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INSTRUCTIONS

This exercise uses a free, web-based systems thinking tool: Mental Modeler software (www.mentalmodeler.org). Prior to completing this exercise, you should review the educational materials available from www.mentalmodeler.org/#resources, in particular the videos listed on the Mental Modeler Instructors Guide, including "Introduction to Fuzzy Cognitive Maps" (5 minutes) and "Introduction to Mental Modeler" (13 minutes). These videos introduce the Mental Modeler software and its theoretical underpinning, and the various software capabilities used in this exercise on creating a model and running scenarios with the model. As you progress through the assignment, the videos "Evaluating and Improving Your Model 1" and "Evaluating and Improving Your Model 2" may also be helpful.

You will create a model using the Mental Modeler software (www.mentalmodeler.org, username: mentalmodeler, password: mentalmodeler) that represents your understanding of the current dynamics of and links between corn and beef production in the US (see Appendix 1). You will need to incorporate at least two environmental impact components[1] from the list below (or you can present an argument for an impact not listed) and at least three key "sustainability" components, with the option of two others listed below. You will submit your model (.mmp file) and a Word or text document with a written summary of your model, following the detailed instructions below.

Model (.mmp File)

Your model should include:

1. The components that comprise the relevant "parts" of the system. To ensure your model is not overly complicated and hard to interpret, do not use more than 25 components in your final model—be careful to include the most important ones.
   a. Corn production and beef production must be included.

   b. At least 2 components must be "impact" components (environmental impacts of agriculture from this list), or you can include your own choice for an impact, with written justification:
      - Climate Change
      - Water Pollution
      - Gulf of Mexico dead zone
      - Herbicide-tolerant weeds
   c. These 3 key "sustainability" components:
      - Human health: A state of complete physical, mental, and social well-being (as defined by the as defined by the World Health Organization; https://www.who.int/about/who-we-are/constitution).
      - Healthy environment: An environment is healthy when its physical, chemical, and biological components, and their interrelationships, are able to withstand stressors and maintain or achieve a desired state.
      - Economic health: Increases in economic growth and development, generally indicated through increased gross national product on a large scale or income on a small scale and individual and citizens' well-being.
   d. You may also choose to supplement with one or both of these additional "sustainability components" (optional):
      - Social equity: Equal opportunity in a safe and healthy environment. This can also include equality of outcome, for example, in relation to food justice, with four dimensions of equity: distributional, procedural, recognitional, and contextual (Friedman et al. 2018).
      - Cultural integrity: Ensuring that a group's values, norms, practices, systems of meaning, ways of life, and other social regularities are respected (adapted from Kreuter et al. 2003).
2. The directional relationships[2] between these components.
3. The degree of the positive or negative influence (using the sliding bars on the links between components in Mental Modeler) that one component has on another. See Tip #3 below.

Important tip: Be sure to periodically save your model to your computer as you go, downloading iterative versions of your work to your computer. One trade-off with a browser-based tool is that a mistakenly closed browser window with an unsaved model can delete ALL YOUR WORK. Don't let this happen to you!

As you begin to add components of the food system to the model, add their relationships to each other (positive or negative). Specifically, think about what parts of the food system impact, or are impacted by, the components you start with. As you complete this part of the exercise, where appropriate and particularly for critical or unusual relationships/components, enter the evidence (in the notes section of Mental Modeler on the left-hand side of the program) you are using to determine the components you choose and the relationships you define. For example, if you are citing a peer-reviewed paper, include at minimum the author(s) and date in the notes, and you should include the full citation in your model summary below. If you do not have any evidence from peer-reviewed publications, provide your reasoning for the chosen components and relationships/weights.

You will define the components that seem relevant to this issue based on your understanding. There are a few things to remember when you make your model:

Tip #1
"Defining Components" (e.g., boxes) need to be things that can increase or decrease in quality or quantity. For example, these may be things like (a) access to healthy food, (b) food prices, (c)

amount of cropland, or (d) greenhouse gas emissions. All of these things can increase or decrease. The components should not be things like (e) policy, since "policy" is not something that can increase or decrease (existence and enforcement of specific government regulations can increase or decrease). You can add as many components as you think is necessary to represent the system, by clicking on the "add component" button at the top of the modeling screen, up to a maximum of 25 components.

Tip #2
"Defining Relationships" between components can either be positive or negative. For example, as soil fertility increases, corn production may also increase. Therefore, you might draw a positive arrow from the component "soil fertility" to the component "corn production."

Tip #3
"Defining Degree of Influence" represents the weightings you give to the positive or negative relationships that you define between components. For example, a rainstorm may increase the amount of flooding slightly (represented by a small positive relationship defined between these two components) but a hurricane may increase the amount of flooding a great deal (represented by a high positive relationship defined between these two components). In general, it is best to assign relative strength of influence as high (value between 0.7–1), medium (value of 0.4–0.7), and low (0.1–0.4).

As you complete this part of the exercise, check each component and relationship. Are components able to increase and decrease in response to relationships with other components? If not, can you phrase the component in a different way so that it becomes something that increases or decreases? Reflect on the reasons for making the relationship. Is it fundamentally important to the model? Are the relationships sound? Are there missing intermediary/mediating components[3] that should be added to create direct relationships? Be sure to think about what drives the system and how all the different parts of the system interact with and relate to each other.

Next, refine your model. Start by examining your model and identifying 2 or 3 components that have a disproportionate impact on the overall sustainability of the food system (as measured by changes in your 3 required components of human health, healthy environment, and economic health; and social equity, and cultural integrity if you chose those as well). *Make sure Mental Modeler Scenario Tab is set to hyperbolic tangent* (*not sigmoid, which may be the default*). Navigate to the scenarios tab and play with increasing or decreasing the value (between -1 and 1) of these components one at a time. The impact on other components in the model as a result of the scenario will appear in the interface to the right. Next, evaluate how these changes affect other components of your model—this is called scenario analysis. If scenario analysis delivers illogical results, refine your model and continue an iterative process of adjusting the model, running the scenario, adjusting the model, etc. This process of refinement may also involve adjusting or removing relationships for several reasons: the evidence for the relationship mismatches with the scenario analysis results, the relationship is not direct (if it is indirect, you may add a component to better illustrate the relationship), or you were able to refine your model to focus ONLY on what you feel are the most important components and relationships. Recall that this model is your vision of how the system works, based on high-quality evidence for components and relationships. This step is where you test whether or not the model reflects your understanding of the system and its function.

Once you feel your model structure is robust and not in need of further refinement, again conduct the scenario analysis process described above, focusing on increasing or decreasing high leverage points[4] that may make the system more sustainable, as measured by impacts on your 3 required components from this list: human health, healthy environment, economic health, social equity, and cultural integrity. Recall from the video "Introduction to Systems Thinking and Modeling," high leverage points are places within the system where a relatively small amount of force can be applied strategically to make a relatively large change to a system. Simply, you want to find components within your model where a small change results in large desired changes for your sustainability components (human health, healthy environment, economic health, social equity, and cultural integrity). These leverage components can be ones that are either directly connected to the sustainability components, or indirectly connected. Once you have identified possible high leverage points, think about possible interventions[5] (represented by components) that you can insert into your model in places that will have an impact on the overall system. Then run scenarios with your interventions and your leverage points in an attempt to increase the overall system sustainability.

Calculating Network Properties of Your Model

After you have made your model and are happy with it, you can assess its network properties through an automated process in the Mental Modeler software. To see the metrics, navigate to the "Preferred State and Metrics" tab. On the left, you will see how many components you have in your model, how many connections, the density[6], # connections/component, # of driver components[7], # of receiver components[8], # of ordinary components[9], and your complexity score[10]; and on the right you will see your components listed along with their scores for indegree[11], outdegree[12], and centrality[13], along with their type (see Glossary below defining all these terms).

Model Summary (Word or Text Document)

The Model Summary will have 4 parts:

1. A screenshot of your model (take a screenshot or use the "camera" tool in the modeling screen)
2. A short narrative summary of your model (1/2 page, single-spaced, on what you included in your model and why, including why you chose your 3 sustainability components).
3. Your answers to the following questions:
    a. Reflect on the boundaries you have set for your model. What was your reasoning for components you decided to include or exclude?
    b. Based on the notes that you entered into your model, what sources of evidence did you draw on to determine your components and define your relationships?
    c. Describe in detail your scenario analysis process.
        – First, did any scenarios prompt you to refine your model by adjusting components, relationships, or degree of influence? If so, which scenarios and how was your model refined?
        – Second, once your model was not in need of further refinement, identify the scenarios you ran on the 2 or 3 components with a disproportionate impact on the overall sustainability of the system (as measured by impacts on your 3 required components from this list: human health, healthy environment, economic health, social equity, and cultural integrity). Evaluate how these changes affected other components of your model (feel free to use screenshots of your scenarios for these answers).
    d. Based on your model, what components disproportionately influence and/or are disproportionately influenced by corn production and beef production in the US? How did you determine the influence of these particular components?
    e. In terms of approaches that might address issues related to corn and beef production in

the US in the future, identify any leverage points that already existed in your model or that you added to your model as a result of your scenario analysis, and identify any interventions that you added to exert force on the leverage points and cause components to increase or decrease in order to make the food system more sustainable (i.e., a preferred state).
   f. Referring explicitly to your model, what are the trade-offs involved in the leverage points in your model? Which components increased or decreased and by how much, and what does this lead you to conclude about the feasibility of the interventions you have suggested?
   g. Reflecting on the process of creating your model, did this process change the way you think about or approach future food system scenarios? Why or why not?
4. A literature cited section, reflecting all the evidence you entered as notes in your model to support your choices of components and relationships.

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APPENDIX 1

Additional prompts for current dynamics of and links between corn and beef production in the US, drawing from articles and commentaries as preparation for exercise:

- Corn production
  - Versatility of the corn crop: high yield, processed into numerous food and non-food products include biofuels and animal feed

  - Corn fed to cattle results in meat and dairy products for human consumption
  - Significant environmental impacts due to expansive cropland devoted to growing corn monoculture; inputs including soil, water, and fertilizer
  - Health impacts of processed foods made with corn
  - Economic impacts of consolidated corn production supply chain
  - Labor impacts, livelihoods, debt, loss/atrophy of localized knowledge, impacts on farm communities in terms of population decrease and decrease in tax base and social services
- Beef production
  - Efficiency of industrial animal production system, as narrowly defined in terms of economic cost of production
  - Significant environmental impacts due to high concentration of animals prior to slaughter
  - Health impacts of diets high in red meats and processed meats, extensive use of antibiotics
  - Economic impacts of consolidated beef production supply chain
  - Dangerous, dirty, and demeaning jobs in slaughterhouse and meat packing plants, migrant labor
  - Animal welfare issues

GLOSSARY

1. **Component**: a box in the mental model representing a part of a system that can measurably increase or decrease. The five starting components we have given you vary in our ability to adequately measure them.
2. **Relationships/connections**: directional connections (can be one-way or feedback) between two components, also including the weight of the relationship. Relationships can be direct, between two components, or indirect, which means they have mediating components that help to explain the connections.
3. **Mediating/intermediate component**: a component that mediates between two other components, helping to explain the connection in a measurable way.
4. **Leverage point**: the place in a system or model where an intervention will be more powerful (i.e., create more change) and be at a lower cost than it would at other points. Some systems thinkers distinguish high leverage points where the change is outsized in comparison to the intervention from low leverage points, where the system impact is relatively minor.
5. **Intervention**: pressure or action (i.e., policy creation or grassroots action, changes in social norms) that can be applied at an intervention point to create change.
6. **Density**: ratio of components to relationships/connections.
7. **Driver component**: component with arrows out and no arrows in.
8. **Receiver component**: component with arrows in and no arrows out.
9. **Ordinary component**: component that is not a driver component or a receiver component.
10. **Complexity score**: degree of receiver to driver variables present across the model. Intended to account for feedback loops.
11. **Indegree**: metric calculated on the basis of the number of arrows in.
12. **Outdegree**: metric calculated on the basis of number of arrows out.
13. **Centrality score**: metric calculated by summing indegree plus outdegree.

Additional terms:

- **Central component**: component with the highest centrality scores.
- **Intervention point**: places in the system where a change can be made. The change could have a small or large impact on the system.

Systems Thinking Collection: Stakeholder Analysis Exercise

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ABSTRACT

During this exercise, students will read readings on stakeholder analysis, then research case studies related to food, health, and/or environmental systems and work in small groups to use the systems thinking (ST) tool "Stakeholder Analysis" to understand the system presented in the case. As defined by Varvasovszky and Brugha (2000), stakeholder analysis is an "approach for generating knowledge about actors—individuals and organizations—so as to understand their behavior, intentions, relationships, and interests; and for assessing the influence and resources they bring to bear on decision-making or implementation processes." We have adapted this approach to more explicitly center discussions of power, social justice, and four dimensions of equity (distributional, procedural, recognition, and contextual).

LEARNING OBJECTIVES

- Examine a diversity of stakeholders relevant to specific topics in health, food, and environment, and compare their varying viewpoints, degrees of influence and power, and involvement in the topic;
- Research the specific topic and select relevant evidence supporting stakeholder positions;
- Describe applications of stakeholder analysis as a systems thinking tool, and how it can support systems analyses.

EXERCISE OUTLINE

Prior to class, you will complete a series of readings on stakeholder analysis and current issues. This will prepare you for an exercise using ST to analyze a specific issue or problem based on a selected case study. The instructor will work with your class to identify intriguing current health, food, and environment policy issues. The best topics will relate to complex adaptive systems and/or center on problems with no easy policy solution. There should be some controversy, with various institutions or segments of society disagreeing on the analysis of the issue, its importance, or its resolution. It is best for students to identify current issues of interest to them.

Regardless of the topic chosen, the instructor and students will need to identify readings for each topic from both scientific journals and journalistic pieces, with at least two from the peer-reviewed literature. You will read the articles before class and identify, through discussion with your classmates, a particular question as a focus for your stakeholder analysis.

This exercise consists of five steps:
Step 1. Brainstorm topics and complete readings and research as homework
Step 2. View presentation on stakeholder analysis
Step 3. Initial reflection on the topic
Step 4. Analysis of stakeholders, in small groups
Step 5. Report back by the groups and final reflection

Steps for Students

Step 1

At least one week prior to the class session, you will brainstorm with your fellow students and instructor a range of possible topics of interest. You will be placed into a small group depending on the topical issue you select, and then your group will identify and complete readings as homework, in addition to the recommended readings listed below. Student-selected readings should be from peer-reviewed literature, gray literature, or popular media. Purdue University has published helpful tips on assessing the credibility of a source including a series of questions to consider about the source centering on authorship, date of publication, and author's purpose (Purdue OWL 2020).

Step 2

Your instructor will introduce the stakeholder analysis tool in a PowerPoint presentation. This presentation provides a definition for stakeholders and information on stakeholder analysis, including details on the uses of and optimal timing for application of the tool in addition to how the tool can allow for exploration of issues of power and equity. The presentation then reviews the steps of a stakeholder analysis: preparation, conducting the analysis, organizing and analyzing the data, and presenting and using the findings. A worked case study is provided on a hypothetical watershed management proposal so you can explore completed examples of a stakeholder table and grid.

Step 3

As a class, you will discuss the selected case studies with your instructor to ensure you are prepared to undertake the exercise.

Step 4

After completing the readings as homework, you will work in your small group on identifying a specific focus to use for a stakeholder analysis. Then your group will complete a stakeholder table and an influence/power and involvement grid (see figures and further instructions below).

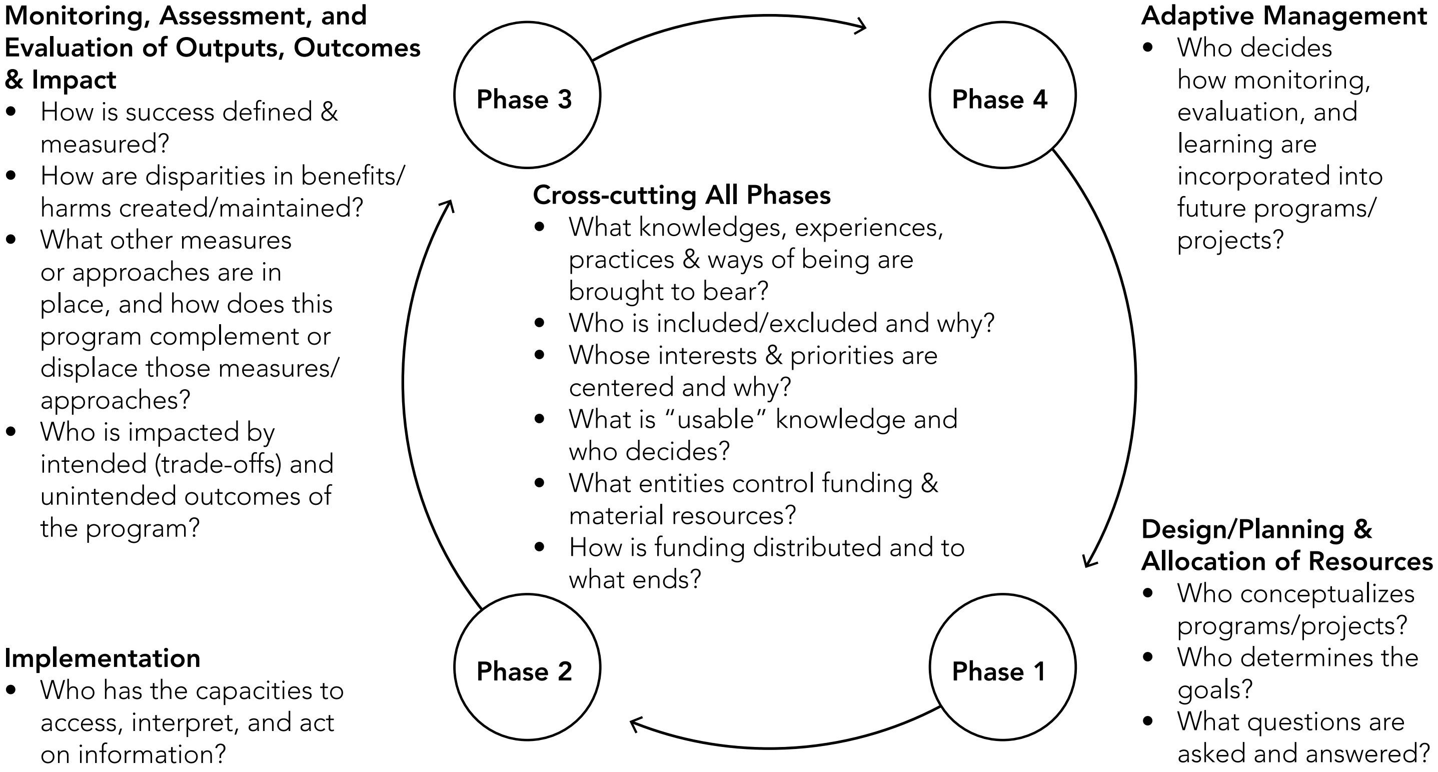
There are many tools available to conduct a stakeholder analysis, and it can be helpful to employ a multiplicity of tools in combination to reveal different angles on a specific topic or issue from the perspective of stakeholders. For this exercise, you will focus on the following tools:

- A stakeholder table allows you to aggregate information on the different stakeholders related to a problem or issue.
- A stakeholder grid allows you to visualize or map the relative influence (on one axis) and relative level of involvement (on the other axis) of each of the stakeholder groups. This technique can be used either alone or in conjunction with the previously discussed table.

With your group, discuss and decide which key stakeholders are most relevant to the topic by assessing the following:
- Potential stakeholders from different sides of the issue.
    - You might consider: Who should be included? Do they represent a variety of different sectors and roles? Why or why not?
    - You should consider marginalized communities that exist in the country/locale relevant to your topic and include them in your stakeholder analysis. For example, in the United States, the marginalized communities might include undocumented immigrants, African Americans, and Native Americans. In another country, marginalized communities might include people

of ethnic minority status, Indigenous People, people of lower class or caste, or religious minorities. Sexual minorities (in US terminology "2SLGBTQ+") are almost universally vulnerable and you should consider their potential involvement in a stakeholder analysis.
- Involvement in the issue (a stakeholder's relationship to the issue or involvement in a process related to the issue, including how any changes in the issue may impact them).
- Position toward the issue. Position (whether supportive or opposed, or non-mobilized if no effort has yet been made to mobilize their support or opposition) may be obvious from the homework readings, but if not, speculate on their likely position.
- Influence/power to control what decisions are made.
  - You might consider how central each stakeholder group is to decision-making processes and also consider heterogeneity within stakeholder groups: What sub-groups or individuals hold formal or informal positions that allow them to make decisions on behalf of the group they represent?
- Relationships with other stakeholders (key relationships between stakeholders, i.e., influence, deference, antagonism, and also including any historic or current inequities or relations of oppression that influence whose knowledge is valid, whose knowledge and experiences are dismissed or disappeared).

As you discuss your assessments with your group members, you should also consider a series of questions following the phases of an intervention cycle (Figure 1). Your answers to these questions may result in changes to your table and/or grid as you complete it in parallel with your discussion.



Monitoring, Assessment, and Evaluation of Outputs, Outcomes & Impact
- How is success defined & measured?
- How are disparities in benefits/harms created/maintained?
- What other measures or approaches are in place, and how does this program complement or displace those measures/approaches?
- Who is impacted by intended (trade-offs) and unintended outcomes of the program?

Adaptive Management
- Who decides how monitoring, evaluation, and learning are incorporated into future programs/projects?

Cross-cutting All Phases
- What knowledges, experiences, practices & ways of being are brought to bear?
- Who is included/excluded and why?
- Whose interests & priorities are centered and why?
- What is "usable" knowledge and who decides?
- What entities control funding & material resources?
- How is funding distributed and to what ends?

Design/Planning & Allocation of Resources
- Who conceptualizes programs/projects?
- Who determines the goals?
- What questions are asked and answered?

Implementation
- Who has the capacities to access, interpret, and act on information?

Figure 1. Key stakeholder questions related to influence and power, along an implementation cycle (adapted from Daly 2020).

Instructions for Completing Stakeholder Table

Using the column headers shown below (Table 1), construct a table of the stakeholders most relevant to your group's topic. Considering the scope of the topic selected, identify groups of people, organizations, or individuals that represent the stakeholders. Discuss some strategies or opportunities for the topic to be re-configured to take the stakeholders' involvement and risks into account. If possible, copy the stakeholder table below into an internet-based spreadsheet software program, such as Google Sheets, to allow easy group sharing and editing.

Stakeholder Grid

Create a stakeholder grid (Figure 2) by writing down each stakeholder from your table in the grid location that best describes that stakeholder's influence/power on the topic, and involvement relative to the other stakeholders represented.

When different stakeholder groups fall near each other on the grid, this cluster of stakeholders may be expected to form coalitions on a particular issue. Draw circles around these clusters from the same block in the grid and with similar positions that you would expect to work together towards common goals.

Next, look across the grid and consider which coalitions may be aligned and draw arrows between them—for example, between a cluster with high involvement and low influence and a cluster with high influence to identify potential allies for lower power groups.

After completing the table and grid, reflect with your group on your work and what insights you have gained from the process. You might also discuss the strengths and limitations of the tools used, and brainstorm what additional tools might have been useful in your work. Some possible questions to spark this discussion are below:

- Did the tools surface stakeholders you had not thought of at first?
- Are some stakeholders more visible than others?
- Are there stakeholders that could still be missing from your analysis? Why might that be?
- How does the heterogeneity of a stakeholder group affect determination of the group's decision-making power? How might you need to consider different individuals or sub-groups in a broader stakeholder group?
- Are there stakeholders who are not included in decision-making processes? Why might that be?
- If there are individuals or organizations made up of individuals with diverse social identities in the

Table 1. Stakeholder table, adapted from Varvasovszky and Brugha (2000). For involvement and influence/power, possible responses are high, medium, medium-high, medium-low, and low along with a descriptive rationale for the response. For position, possible responses are supportive, non-mobilized, and opposed with a descriptive rationale for the response.

Stakeholder	Characteristics			
	Involvement in the issue	Position	Influence/power	Relationships with other stakeholders, including historical and current forms on inequities and oppression

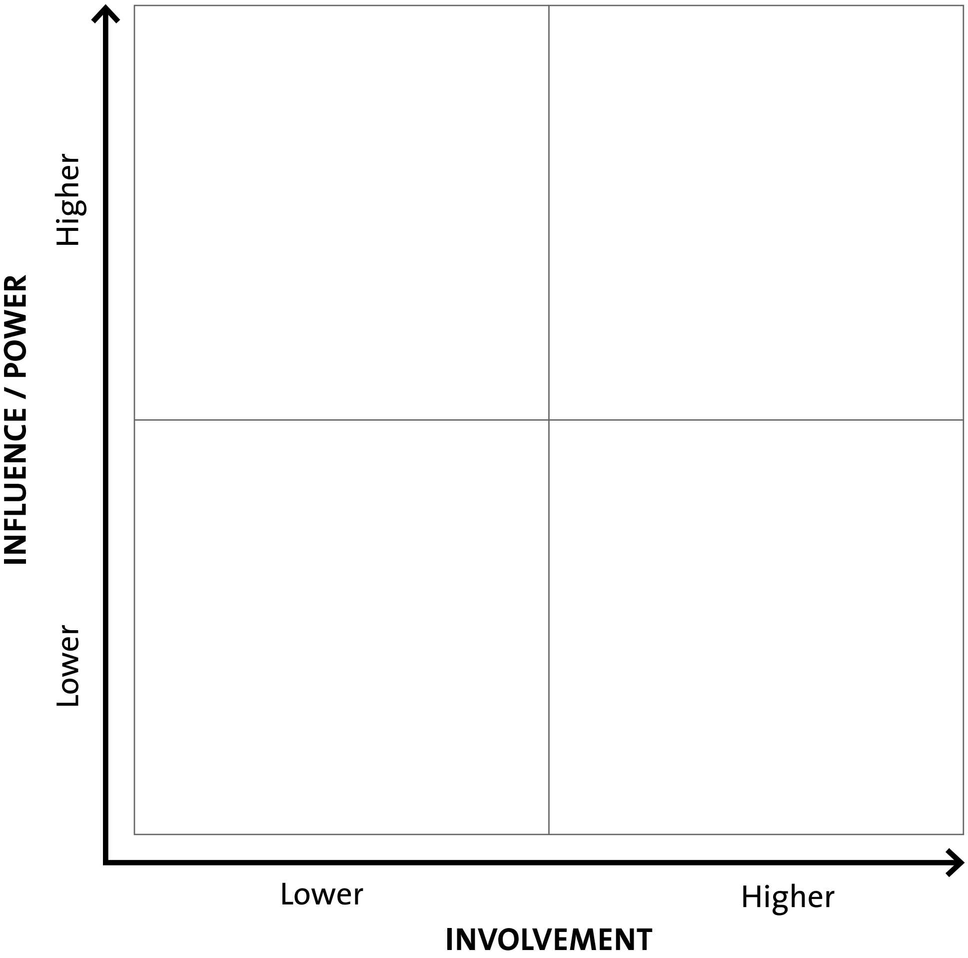


Figure 2. Stakeholder grid.

stakeholder category, what are the implications on decision-making processes? Who ultimately benefits from the system? Are the intended (trade-offs) and unintended outcomes within the system that disproportionately impact low income individuals/communities, BIPOC, women, 2SLGBTQ+, or other marginalized groups?
- What was most challenging about the analysis and why?
- Should all stakeholders be engaged in similar ways? What could be pros and cons of doing this?
- What additional information you need to identify stakeholders and their involvement. Where might you get that information?

Step 5

Following small group discussion of the table and grid, each group will then report to the whole class their main insights and the consensus of their reflection at the end of Step 4. With your instructor, discuss how other stakeholder tools might help with identifying stakeholders and determining their relative influences on decision-making.

Recommended Readings

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Parasite Biodiversity

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ABSTRACT

A parasite is an organism that lives in an intimate and durable relationship with its host and imposes a cost on that host, in terms of its ability to survive, grow, and/or reproduce. Despite the fact that more than 40% of animal species are parasites, parasitism is rarely discussed in introductory biology courses. This may be because parasites are often hidden within their hosts—and therefore easy to ignore. But parasites have important roles to play in ecosystems and we ignore them at our own peril. In this module, students have the opportunity to discover the hidden world of parasites: they will come face to face with living parasites, learn about what differentiates parasites from free-living species, observe some common adaptations to a parasitic lifestyle, explore the ecological role of parasites in food webs, and assess how parasite abundance might change in a changing world. To accomplish these goals, this module includes an introductory PowerPoint presentation (including a video of parasite ecologist Dr. Chelsea L. Wood delivering this introductory lecture) and two exercises.* The first exercise is a wet lab that involves dissecting an easy (and disturbing) source of live parasite material: fresh fish from your local seafood market. The second exercise is a computer lab that will allow students to engage with real data to answer the question: how do human impacts on ecosystems change the abundance of parasites in wildlife? This module will introduce students to the basics of parasite ecology and provide an opportunity to practice their data analysis and interpretation skills.

INTRODUCTION: THE HIDDEN WORLD OF PARASITES

A parasite is an organism that lives in an intimate and durable relationship with its host[1], and imposes a fitness cost[2] on that host (Combes 2001). Parasites are everywhere, but they are often ignored due to their small size and cryptic[3] nature. Perhaps forty percent of all animal species are parasites (Dobson et al. 2008), and virtually all animals are infected by at least one species of parasite (Poulin and Morand 2000).

There are several types of close interactions that are similar to, but different from, parasitism. Parasites are different than symbiotic mutualists[4], or organisms that provide beneficial services for their host (Boucher et al. 1982; Thrall et al. 2007). For example, photosynthetic algae that live within corals and provide them with energy derived from the sun are engaged in a mutualistic, not parasitic, interaction with their host (Baker 2003). Parasites also differ from micropredators[5] and other free-living organisms[6], in that they must reside in association with their host for at least part of their life cycle. Micropredators (unlike parasites) do not live in intimate association with their prey, but rather feed in short bursts, interspersed with long periods of a free-living lifestyle. Examples of micropredators include mosquitos, bed bugs, and leeches. Micropredators take small, non-lethal meals from many hosts, whereas parasites exploit only one host per parasitic life stage (Poulin 2011a).

How many parasite species are there on the planet Earth? Considering that parasites are a diverse and complex group of animals, providing one accurate number of their species richness is nearly

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*Note to educators: to access presentation, video, teaching notes, and exercise solutions for this modules, visit our website (ncep.amnh.org), register as an educator, and search for the module by title.

impossible. However, we can certainly put parasite diversity into perspective. For example, it is estimated that there are more than 70,000 species that attach externally to hosts (Poulin 2011b). The parasitic lifestyle is represented across nearly all taxa, and there are a reported 7,000 species of parasites known to infect crustaceans (Boxshall and Hayes 2019). In one of the most speciose ecosystems on the planet—the Great Barrier Reef—it was estimated that there are more than 20,000 parasites of fish (Rohde 1976); this number doesn't even account for parasites of invertebrates like corals and mollusks. Research is ongoing to identify and describe new parasite species and to refine these estimates of parasite biodiversity.

Two types of parasites—pathogens and macroparasites—are distinguished from one another by their mode of reproduction. Pathogens tend to be small, multiply within or on their host and to have very short generation times[7] in relation to their host (e.g., many parasitic bacteria, viruses, and fungi; Swinton et al. 2002). If a host is infected with a pathogen, it will ultimately succumb to the multiplying pathogen unless the host's immune defenses limit pathogen multiplication. In contrast, macroparasites do not multiply within their host and include some arthropod, flatworm, and nematode parasites (Poulin 2011a). Macroparasites can range in size from very small (invisible to the naked eye) to large (e.g., parasitic nematodes that inhabit sperm whale placentas can reach up to 8.4 meters long; Gubanov 1951). Macroparasites have longer generation times than pathogens and tend to accumulate slowly within a host because each individual requires an independent infection event. Although their growth rate and generation times are often different, both types of parasites can cause disease, which is defined as the fitness loss of a host due to parasitic infection. Macroparasites can be either endoparasites (i.e., parasites that live within the body of their host) or ectoparasites (i.e., parasites that live on the external surface of their host).

Humans have been aware of the existence of parasites for thousands of years. Both Hippocrates and Aristotle documented several parasites in their written works (Hoeppli 1956; Trompoukis et al. 2007) and parasites have also been discovered in ancient humans [e.g., Egyptian mummies (Gonçalves et al. 2003) and Ötzi the Ice Man (Dickson et al. 2000)]. Much of what we know about parasites is focused on parasites of humans and the diseases they cause. In fact, one of the first Nobel Prizes was awarded to Ronald Ross in 1902 for his research on the life cycle of the protozoan parasite, malaria. However, parasite ecology—the study of how parasites interact with other organisms and their environment—is a relatively new science. Despite the fact that humans have lived in association with parasites for millennia, there are still many important unanswered questions in parasite ecology and fundamental scientific discoveries yet to be made.

An important part of parasite ecology is discovering, identifying, and naming new parasites. Early parasitology[8] focused on identifying and naming new parasites of humans. While our understanding of parasites has grown considerably in recent years (e.g., Smit et al. 2014), efforts to identify and name new parasites are an ongoing project. For example, a recent paper estimated that 85–95% of helminths (i.e., parasitic worms such as nematodes, flukes, and tapeworms) of vertebrates are unknown to science (Carlson et al. 2020). Today, scientists use a range of tools to visualize parasites, including dissecting microscopes, compound microscopes, and scanning electron microscopes (SEM). The names of new parasite species have also become more creative over time. In the past, parasites were primarily named for their appearance or the location of first discovery. For example, *Gnathia trimaculata* is named for having three spots ("tri" meaning three; Coetzee et al. 2009), *Gnathia masca* is named for have a face that appears to be wearing a mask (Farquharson et al. 2012a), and *Cymothoa sodwana* (a tongue-eating parasite) is named due to its prevalence[9] in Sodwana Bay, South Africa (Hadfield et al. 2013). Recently, a few parasite names have been dedicated to popular culture icons, such as musicians (e.g., Bob Marley, *Gnathia marleyi*; Farquharson et al. 2012b), politicians (e.g., President Obama, *Baracktrema obamai*; Roberts et al. 2016), and television characters (e.g., Xena, Warrior Princess, *Elthusa xena*; van der Wal et al. 2019). There is room for creativity and exploration in parasitology, as many currently undescribed species still await discovery.

Why are parasites rarely discussed? This is probably because parasites tend to be hidden within their hosts—and therefore easy to ignore. Although some parasites can cause disease, parasites as a whole are diverse and their contribution to ecosystem functioning is complex and often positive (Hudson et al. 2006; Kuris et al. 2008; Nichols and Gómez 2011). Despite their small size, parasites have important roles to play in ecosystems, and we ignore them at our own peril.

PARASITES IN YOUR LIFE

Where might you encounter parasites in your daily life? If you own pets or livestock, you might be familiar with the practice of "deworming" these animals. Antihelminthics are medications that treat infections of flatworms and roundworms, which animals can be exposed to in their environment. Parasitic worm infections in pets can vary in severity, from symptomless to severe; for example, heartworms can be fatal in dogs (Conboy 2011).

Humans can occasionally contract parasitic worm infections from their pets. One example is a single-celled parasite that is transmitted from cats to humans. *Toxoplasma gondii* is transmitted from cats through contact with cat feces, or from eating undercooked meat (especially pork, lamb, beef, and venison; Tenter et al. 2000; CDC 2010a). This parasite is found around the world, and an estimated 40 million people are infected with *Toxoplasma* in the United States alone (CDC 2010a). While toxoplasmosis (infection with *Toxoplasma gondii*) generally has mild flu-like symptoms which go unnoticed, this parasite can cause serious problems for pregnant women (who can transmit the parasite to their fetus) and immunocompromised individuals. This is why you may have heard that women should not clean litter boxes while they are pregnant.

Toxoplasma is a particularly fascinating parasite, due to its ability to manipulate the behavior of its host. In its lifecycle, *Toxoplasma* alternates between a host that it infects and uses temporarily (usually a small rodent, e.g., a rat), and its definitive (final) host[10], a cat (Beverley 1976; Dubey 2016). *Toxoplasma* manipulates its rodent host to become more vulnerable to predation by the definitive host (the cat). To do this, *Toxoplasma* changes neural pathways and activity in infected rodents, inhibiting their fear response and replacing it with sexual attraction to the smell of cat urine (Berdoy et al. 2000). These newly emboldened rodents are more likely to approach and be eaten by cats, transmitting *Toxoplasma* in the process. Humans are generally dead-end hosts[11] for *Toxoplasma* (in general, people are infrequently eaten by felines), but neurochemical processes similar to those in rats can affect infected humans as well (Webster 2001). Rather than causing sexual attraction to cat urine, however, *Toxoplasma* causes emboldened, sometimes reckless behavior due to an inhibited fear response. For example, *Toxoplasma* may influence the behavior of individuals in business and entrepreneurial settings (Houdek 2017). Researchers have found that college students infected with *Toxoplasma* are more likely to major in business, and in particular in "management and entrepreneurship" (Johnson et al. 2018). Furthermore, at an entrepreneurial event, individuals who were infected with *Toxoplasma* were 1.8 times more likely to have already started their own business than other attendees (Johnson et al. 2018). In addition to these specific instances, there is evidence that country-level patterns of *Toxoplasma* infection may even influence human culture (Lafferty 2006). This demonstrates how even a tiny, single-celled parasite can cause significant change at a global scale.

Another group of parasites you might encounter are seafood parasites. A variety of parasites infect fish, and a few of these parasites can be transmitted to humans, such as the broad fish tapeworm, *Diphyllobothrium latum*, (Figure 1; Scholz et al. 2009; Kuchta et al. 2013) and anisakid nematodes, *Anisakis* and *Pseudoterranova* spp. (Figure 2; Oshima 1987). The fish tapeworm is one of the largest tapeworms that can infect humans, growing up to 30 feet long (CDC 2010b). Human infection occurs when an individual eats raw or undercooked fish, although freezing fish thoroughly before eating or cooking the fish prevents the threat of infection (CDC 2010b). Anisakiasis (infection with anisakid nematodes) can also result from ingestion of raw or undercooked fish, and often is evidenced by symptoms that resemble food poisoning. Consequently, in the USA, the Food and Drug Administration mandates that all fish destined to become sushi (other than tuna) is thoroughly frozen before sale and consumption.

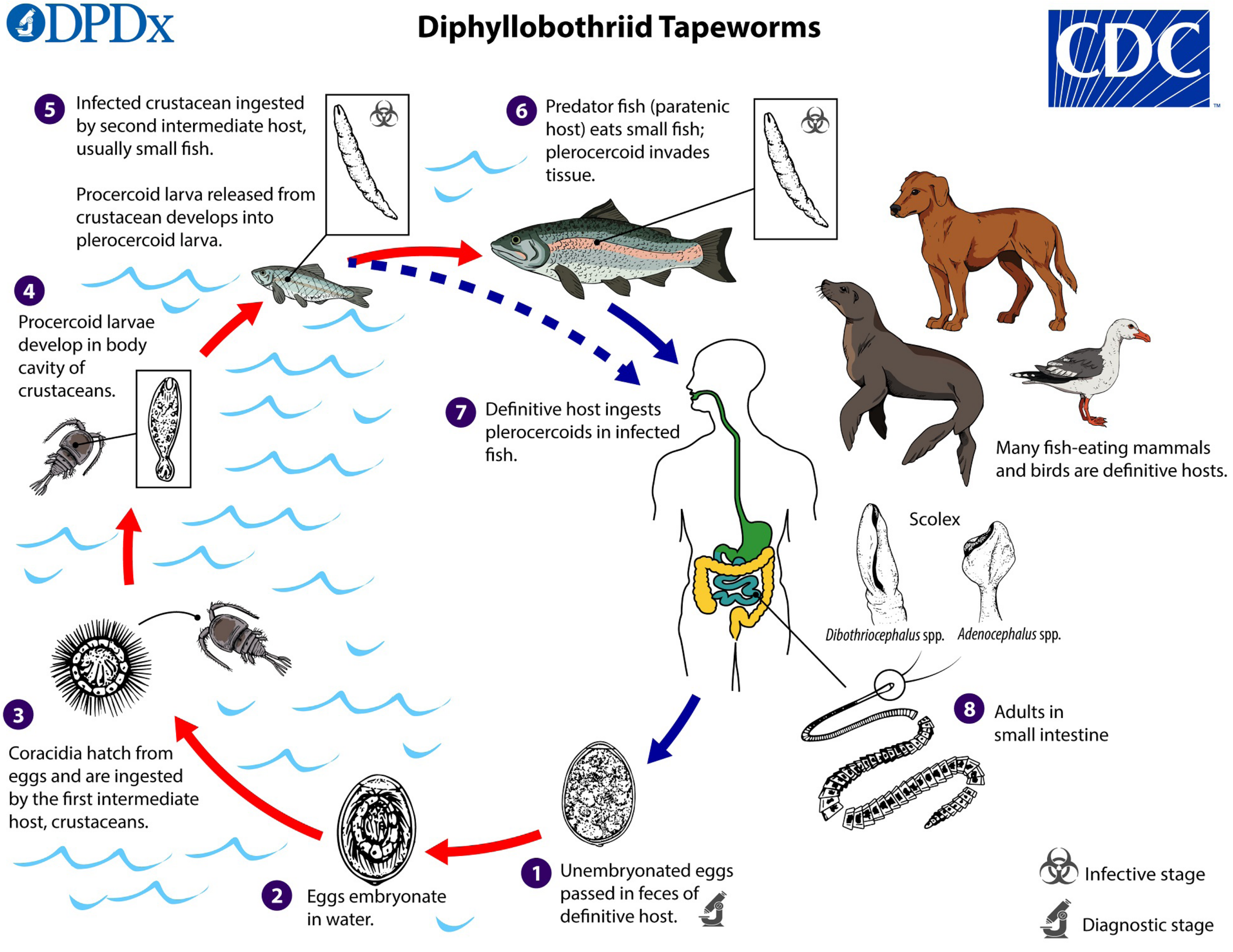

Figure 1. Life cycle of a parasitic cestode (*Diphyllobothrium* spp.). This group of tapeworms completes most of its life cycle in freshwater organisms (e.g., crustaceans and fish) before becoming mature in a human host, where they can cause the disease diphyllobothriasis. For a complete description of the *Diphyllobothrium* spp. life cycle, go to: https://www.cdc.gov/dpdx/diphyllobothriasis/index.html. (2002; CDC/Alexander J. da Silva, PhD; Melanie Moser). Image credit: DPDx/CDC (public domain).

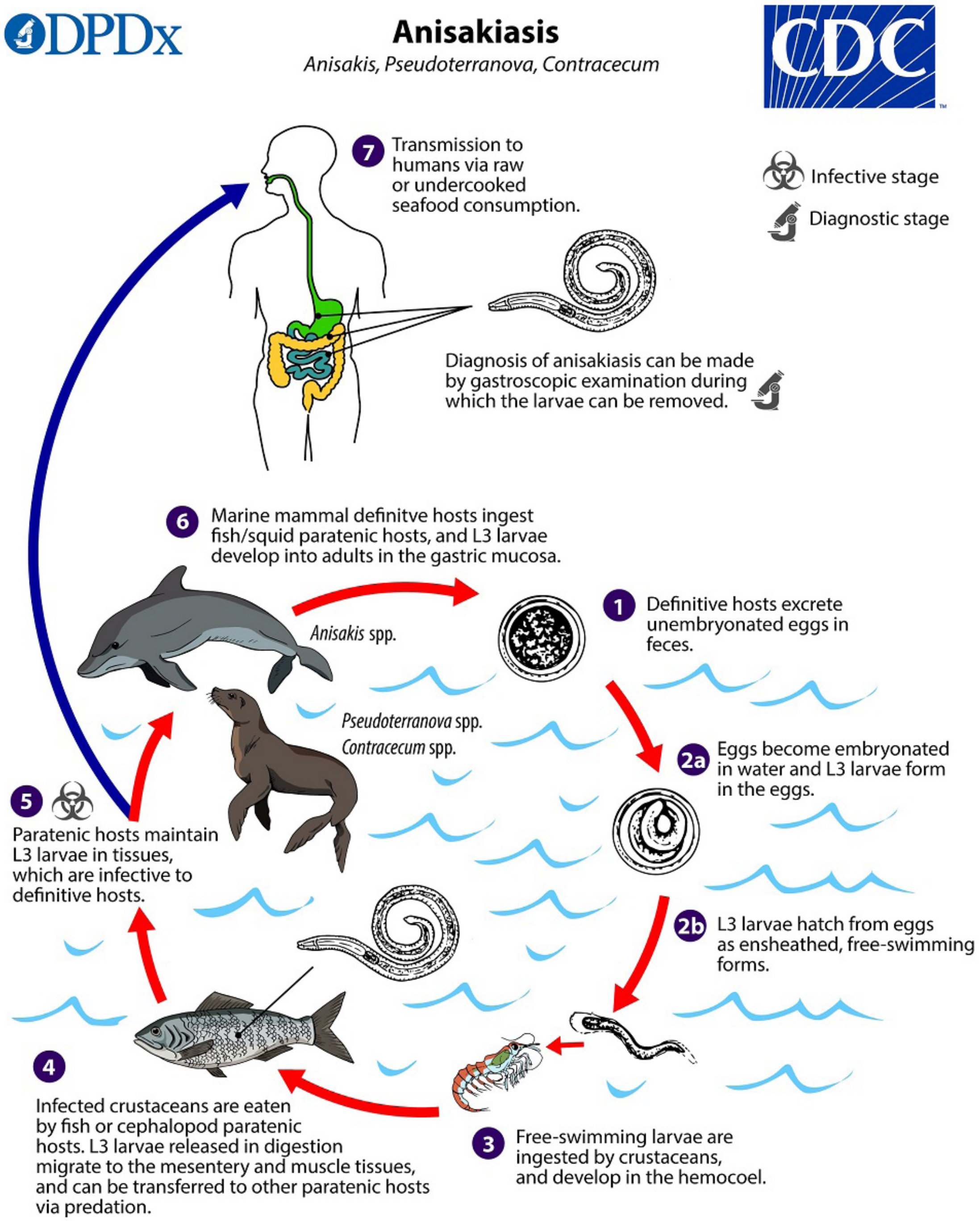

Figure 2. Life cycle of parasitic nematodes (*Anisakis*, *Pseudoterranova*, and *Contracecum*) which can cause anasakiasis in humans and marine mammals. For a complete description of the life cycle of *A. simplex* and *P. decipiens*, go to: https://www.cdc.gov/dpdx/anisakiasis/index.html. (2002; CDC/Alexander J. da Silva, PhD; Melanie Moser). Image credit: DPDx/CDC (public domain).

Toxoplasma gondii and the "sushi" parasites are only a small fraction of parasites that affect humans. For example, approximately one billion people are currently infected with the human roundworm, *Ascaris lumbricoides* (CDC 2010c). In this synthesis, we'll talk primarily about the broader diversity of parasites—not only those that affect humans but also the many parasites found across the animal kingdom.

ADAPTATIONS TO A PARASITIC LIFESTYLE

With the advent and advancement of molecular techniques such as genome sequencing (Poulin and Randhawa 2015), new parasite species continue to be identified and described. Historically, species identification of parasites was based only on morphological differences, but we now pair morphological differences with genetic analyses to define parasite species (Nadler and De León

2011; Hoogendoorn et al. 2019; Lisitsyna et al. 2019). In doing so, scientists have realized there are many more species than was previously thought, and some are cryptic, meaning that two similar parasites may look nearly the same to the naked eye and under magnification but differ substantially in their DNA sequences (Soldánová et al. 2017; Welicky et al. 2017). New species of parasites are being found so frequently that they are regularly documented in parasitology journals (e.g., *Journal of Parasitology*, *International Journal for Parasitology*, *Parasitological Research*). However, identification is merely a first step in understanding parasite biology, and we must also know the life cycle of parasites. Unfortunately, this is challenging; for example, only 1% of the nearly 400 described trematode worm species from the Great Barrier Reef have fully described life cycles (Cribb et al. 2014, 2016; Huston et al. 2016).

Parasite life cycles can be difficult to describe because many parasites have multiple hosts during their lifetime and each parasite must be tracked through each host (e.g., Huston et al. 2016). Parasite life cycles may include direct transmission or complex lifestyles (Combes 2001). Parasites with direct life cycles are those in which a parasite infects a single host throughout its entire life span, whereas complex life cycles include several transitions between host species during the lifespan of a single parasite. We provide specific examples of these life cycle types below.

Direct Life Cycles

Parasites with direct transmission only infect one host species over the course of their life cycle. An example of a group of directly transmitted parasites are the strongyloid nematodes. This group of roundworms typically infect the gastrointestinal tract of mammals such as sheep (Figure 3), cattle, reindeer, and muskoxen. For example, *Ostertagia gruehneri* is a strongylid nematode that is found in reindeer (Hrabok 2006), and *Trichostrongylus axei* is found in sheep (Roeber et al. 2013). Both

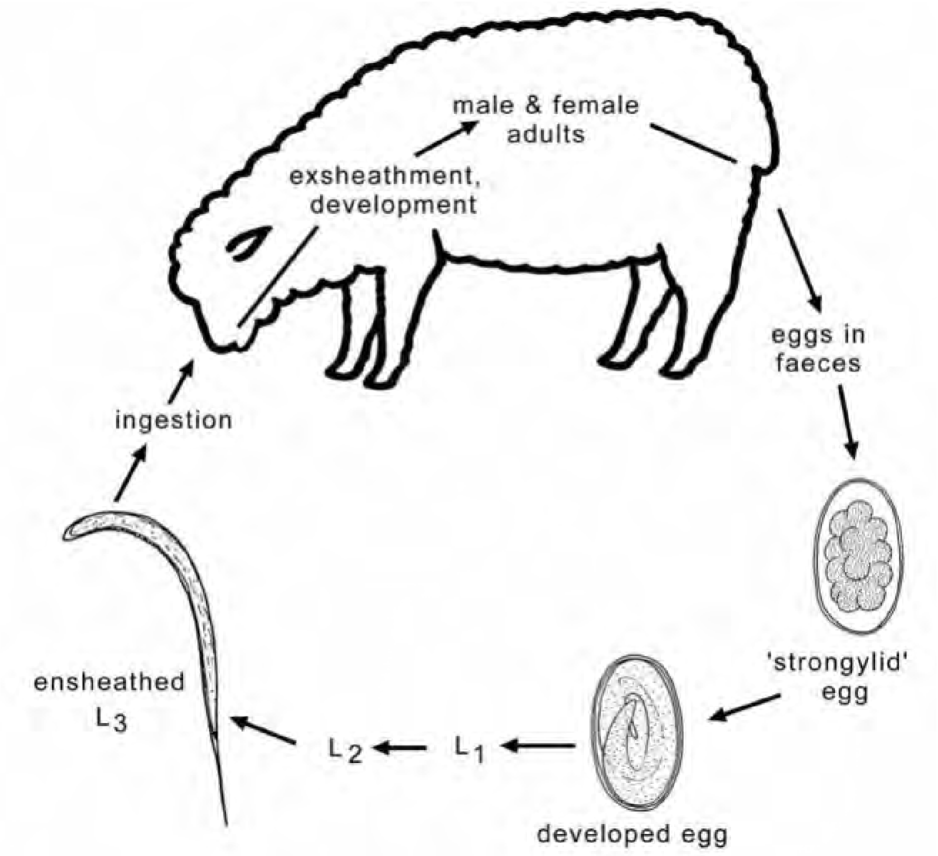

Figure 3. Life cycle of gastrointestinal nematodes (Order Strongylida) that infect sheep (Roeber et al. 2013). For most of their life cycle, these nematodes are free-living, with their first-, second-, and third-stage larvae (L1, L2, and L3, respectively) living in the environment. The L3 larvae are incidentally consumed by the sheep during grazing. Once inside the sheep, these parasites mature to the fourth larval (L4) stage and migrate to the gastrointestinal tract of the sheep where they become adults. Image credit: Roeber et al. 2013 (CC BY 2.0).

of these nematodes follow a similar life cycle. The nematodes mature and sexually reproduce in the gastrointestinal tract of their host, where they are passed onto the pasture in feces. Next, the nematode eggs undergo development in the "strongylid" phase before becoming a fully developed egg. After this, the egg hatches, and matures from the first larval stage to the second larval stage via molting. Then the larvae undergo a third developmental stage that is followed by incidental ingestion by the host. As the host grazes on the pasture, the parasite's life cycle is renewed.

Complex Life Cycles

Complex life cycles involve a transition between at least two hosts. These hosts are always different species and are often completely unrelated (e.g., a single parasite could inhabit a snail, a fish, and a bird during its life cycle). Intermediate hosts[12] are hosts infected with larval parasites, while definitive hosts (or final hosts) are hosts in which a parasite reaches adulthood and reproduces sexually. A parasite species may have more than one intermediate host in its life cycle (see Figure 4). An example of a parasite with a complex life cycle is the trematode, *Euhaplorchis californiensis* (Figure 4), which infects California horn snails (intermediate host), California killifish (intermediate host), and shorebirds (definitive host) during its life cycle (Lafferty and Morris 1996). This parasite also manipulates its second intermediate host. When *E. californiensis* infects the killifish, it migrates into the cranium, encysting on the surface of the brain (Martin 1950). It alters the behavior of the fish, changing brain chemistry (Shaw et al. 2009) and causing it to exhibit behavior easily seen by birds, such as jerking, flashing, and surfacing (Lafferty and Morris 1996). These behaviors cause an infected killifish to be 10–30 times more likely to be eaten by its definitive host, a shorebird (Lafferty and Morris 1996). Although this life cycle and apparent mind control may seem unique, these sorts of behavioral changes are common across many parasites with prey hosts that will be eaten by predator hosts. The ecological interactions among parasites, their hosts, and their environment are complex, and this next section will focus on how parasites can shape the ecosystems they inhabit.

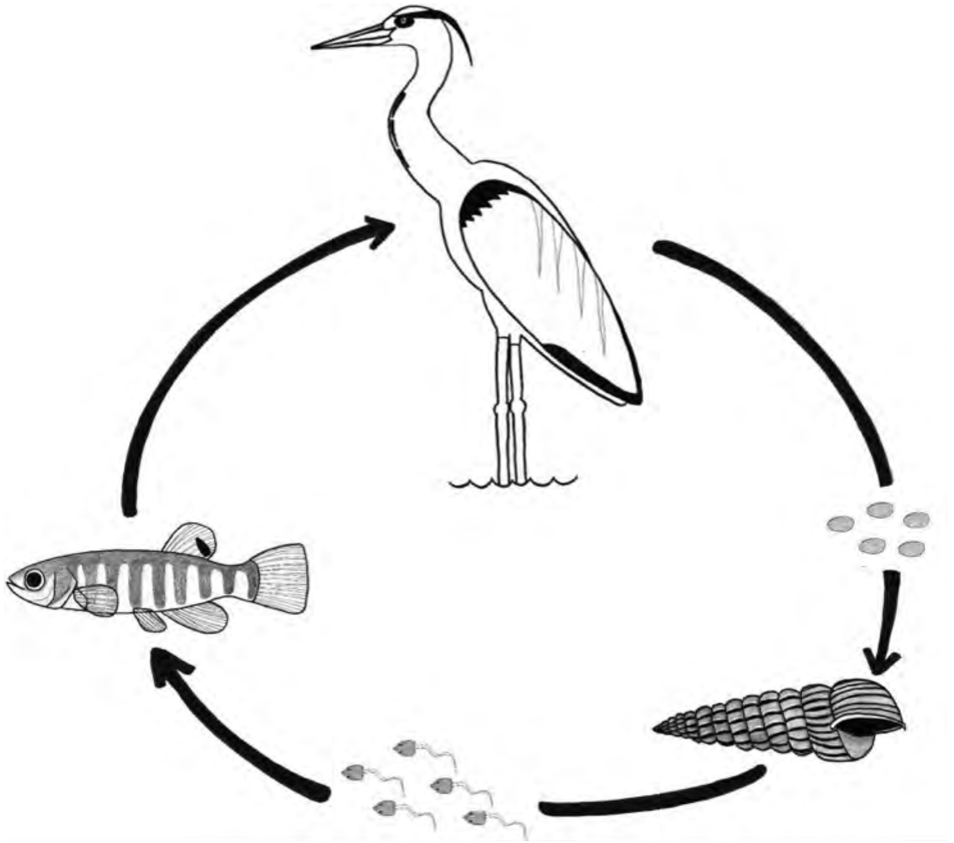

Figure 4. Life cycle of *Euhaplorchis californiensis*. The eggs of *E. californiensis* are shed in the feces of shorebirds (the definitive host), and then eaten by horn snails (the first intermediate host) where they undergo asexual reproduction. Next, the larvae of *E. californiensis* (cercariae) are shed from the snail into the water where they swim until they encounter a killifish (the second intermediate host). The infected killifish is eaten by a shorebird, and the cycle begins again. Image credit: Danielle Claar.

THE ECOLOGICAL ROLE OF PARASITES

Parasites have fundamental effects on ecosystem function, but this is seldom evident. They influence individual behavior, health, and distribution of their hosts, as well as the composition and diversity of ecological communities. These individual- and community-level effects can translate into changes in ecosystem function and the distribution of biodiversity, and they have shaped the evolution of life itself.

Parasite Effects on Individuals

As we have already seen in the examples of the brain cysts in the killifish and *Toxoplasma* in rats, parasites can influence the behavior of their hosts (Barnard and Behnke 1990; Barber et al. 2000; Hughes et al. 2012). Another well-researched example of behavioral manipulation is the interaction between the tapeworm *Schistocephalus solidus* and its second intermediate host, a three-spined stickleback (a small freshwater fish). When a stickleback is infected with *Schistocephalus* (Figure 5), the fish swims closer to the water's surface, is bolder, and is more likely to ignore overhead stimuli (e.g., they are less frightened of potential bird predators; Giles 1983). This is a clever behavioral manipulation by the parasite. By making the stickleback more visible in the water column, the parasite increases the likelihood that its intermediate host (the stickleback) will be eaten by its definitive host (a wading bird; Barber and Scharsack 2010). Once the stickleback and tapeworm are ingested by the bird, the parasite can continue its lifecycle and reproduce, shedding a new generation of tapeworm eggs into the environment (Figure 5).

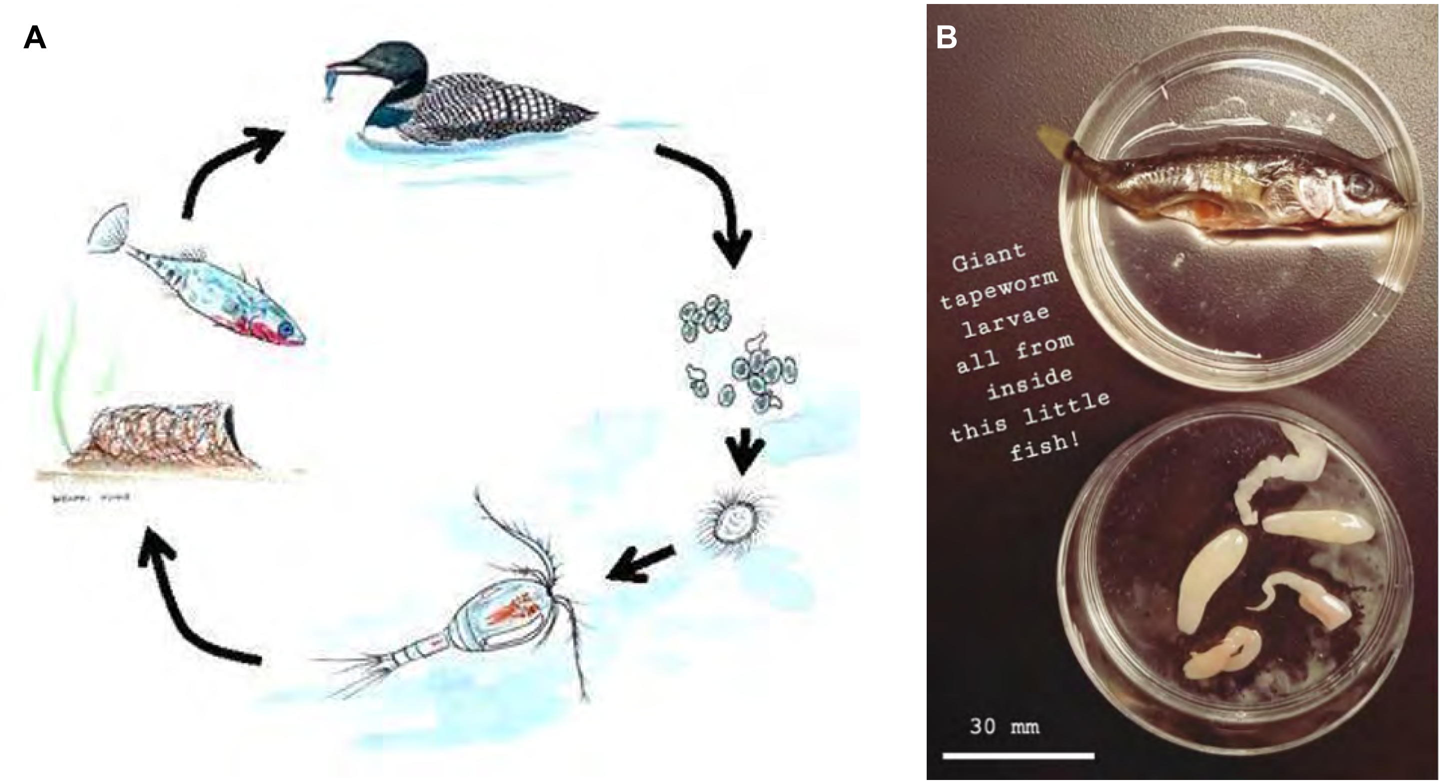

Figure 5. (A) Life cycle of *Schistocephalus solidus*. *Schistocephalus* eggs are excreted in the feces of water birds. These eggs hatch and become coracidia (the first larval stage). Coracidia are ingested by a copepod (the first intermediate host) where they continue to develop as the second larval stage (procercoids). Next, the copepod is eaten by a stickleback fish, and the plerocercoid (third larval stage) of *Schistocephalus* continues to develop in the abdomen of the fish until the fish is consumed by a wading bird and the cycle continues (Weber et al. 2017) (B) Photo of stickleback dissection. All *Schistocephalus solidus* tapeworm plerocercoids in the bottom petri dish came from this one stickleback. Image credits (L-R): Weber et al. 2017; Katie L. Leslie.

Parasites also affect individuals by affecting host reproduction. If hosts spend enough energy fighting against or accommodating their parasites, their reproductive output (i.e., the number of offspring they can produce) can be decreased. Additionally, some parasites purposefully castrate or sterilize their host, so the host is completely unable to reproduce (Kuris 1974). This strategy is fairly common in the marine realm, where, for example, many types of larval trematodes can castrate snails, and parasitic isopod and barnacle species can castrate their host crustaceans (Lafferty and Kuris 2009a). Even some vertebrate hosts can be parasitically castrated, such as the five-lined cardinalfish (Fogelman and Grutter 2008). As "body snatchers," parasitic castrators usually block host reproduction for the remaining life of the host.

Finally, and perhaps most obviously, parasitic infection can cause loss of fitness and even death. Depending on their parasite load, a host might have mild to moderate disease symptoms, which may remain relatively stable over the lifetime of the host, or they may progress to severe disease symptoms and ultimately die as a result of their infection. The impact of macroparasites on hosts is dependent on the number of parasites that a host is exposed to and the relative disease potential of those parasites (Anderson and May 1978). So, if a human is infected by only one hookworm, they may display no noticeable disease symptoms, but if it is exposed to 100 hookworms, they may become severely anemic. Conversely, the impact of pathogens is less dependent on the number of parasites to which a host is initially exposed (Anderson and May 1979). This is because pathogens reproduce within the host. Causing the death of their host is not an ideal situation for most parasites. The host provides habitat and nutrition for a parasite, so it is against the interest of the parasite for its host to die. One exception is diseases that are spread from carcasses to living hosts via contact transmission (e.g., anthrax, Ebola). Another obvious and common exception, discussed earlier in the context of *Toxoplasma* and *Schistocephalus* infections, is trophic transmission, or when the parasite has a complex life cycle that necessitates their intermediate prey host (in these cases a rat and a stickleback fish) to be eaten by a predator definitive host (respectively a cat and a wading bird).

Parasite Effects on Populations

The effects of parasites on individual hosts can lead to broader impacts on host populations (Wood and Johnson 2015). Crustacean parasites can reduce growth, reproduction, and survivorship of reef fishes[13], which leads to population regulation and strengthens density-dependent interactions. A study of the bridled goby (*Coryphopterus glaucofraenum*) infected with the copepod gill parasite *Pharodes tortugensis* showed that parasitic infection prevalence increased the negative effects of high host density on host survival (i.e., a high density of gobies was associated with increased mortality in such populations). This effect was disproportionately worse for infected compared to uninfected gobies (Forrester and Finley 2006). Parasitism may also influence host populations by inducing boom-and-bust cycles in host population size (Hudson et al. 1998). For example, red grouse populations (a valuable game bird in the United Kingdom) typically experience boom-and-bust cycles (i.e., high population density followed by crashes to low population density). When these grouse populations were treated with an antihelminthic to clear parasitic nematode (*Trichostrongylus tenuis*) infections, these cycles were dampened, causing a more consistent population density of grouse over time (Hudson et al. 1998). This suggests that parasitism drives cyclical population sizes in red grouse and may influence other parasitized populations in a similar way. Finally, parasitic castration (discussed above) can also influence host populations. Although castration is an individual effect, it directly influences reproduction. Therefore, the intensity of infection by parasitic castrators can drive host population size (Kuris 1974; Blower and Roughgarden 1987). These types of effects on host populations can link individual effects of parasitism to community- and ecosystem-wide effects.

Parasite Effects on Communities

Another important ecological role played by parasites is regulating host community structure and biodiversity. By regulating host populations, some parasites can influence the outcome of competition of hosts in the environment (Mordecai 2011). Specifically, this occurs when parasites limit the population size of the numerically dominant host, allowing rarer hosts to persist and even thrive. Specialist parasites may facilitate species coexistence by keeping a singular dominant species in check while allowing rare species to persist (Fenton and Brockhurst 2008; Grewell 2008). Generalist and specialist parasites can also regulate community composition on a diel (daily) cycle. For example, parasites can influence the timing of host foraging and cleaning activity patterns (Sikkel et al. 2004; Sikkel et al. 2006) and when hosts leave and return to their daytime and nighttime habitats, such as the daily migration of French grunts (a Caribbean fish) between reef and seagrass habitats (Welicky and Sikkel 2015; Sikkel et al. 2017). Parasitism may also influence niche partitioning; for example, parasitism by a fungus alters competition among two species of tropical spider, allowing one species to live adjacent to riverbanks but excluding the other and limiting its distribution to further away from the river margin (Cardoso et al. 2018). Finally, parasites can increase biodiversity and alter community structure concurrently by introducing new diseases, bacteria, and viruses to hosts which in turn reduces host abundance by decreasing their survival rate and fitness (reviewed in Hadfield and Smit 2019). While several such examples of parasite influence on community ecology have been documented, it is likely that many more exist, waiting to be discovered.

Parasite Effects on Food Webs

Parasites can influence not only individuals and communities but can also cause changes that cascade throughout ecosystems (Figure 6; Buck and Ripple 2017). For example, rinderpest, a morbillivirus related to measles in humans and distemper in canines, caused an ecosystem cascade when it underwent a series of outbreaks in Africa (Holdo et al. 2009). Rinderpest outbreaks decimated ungulate (e.g., wildebeest and buffalo) populations. This caused cascading effects on both vegetation and tree communities which are shaped by ungulate grazing, as well as predator populations (e.g., lions and hyenas) that consume ungulates (Dobson et al. 2006). Widespread extermination of rinderpest after the development of a vaccine caused another cascade that allowed savannah ecosystems to rebound towards a pre-outbreak baseline ecosystem structure (Dobson et al. 2006).

Another example of a parasite-induced cascade was the epidemic mortality of the Caribbean black-spined sea urchin (*Diadema antillarum*; Figure 6; Lessios 1988). This urchin was a keystone herbivore in the Caribbean until the 1980s when a host-specific bacterial pathogen wiped out approximately 98% of the urchin population (Lessios 1988). The urchins were a keystone species because they were keeping macroalgae communities in check via grazing. When the urchin population was decimated, the keystone was metaphorically removed and the rest of the community shifted and macroalgae overgrew the reef—transitioning the system from being coral-dominated to algae-dominated (Hughes 1994).

Furthermore, parasites may strengthen trophic interactions and maintain a "cohesive matrix" of food web interactions (Lafferty et al. 2006). Specifically, parasites may affect food web stability and structure by altering the interactions that are represented in a typical food web model (Lafferty et al. 2008). Specifically, the presence of parasites increases the number of links (i.e., interactions between two organisms) in a food web, which can help stabilize food web structure, even under external stressors. However, the incorporation of parasites into food web models is still in its infancy, and more research is needed in order to build, understand, and analyze how food web dynamics change when parasites are included.

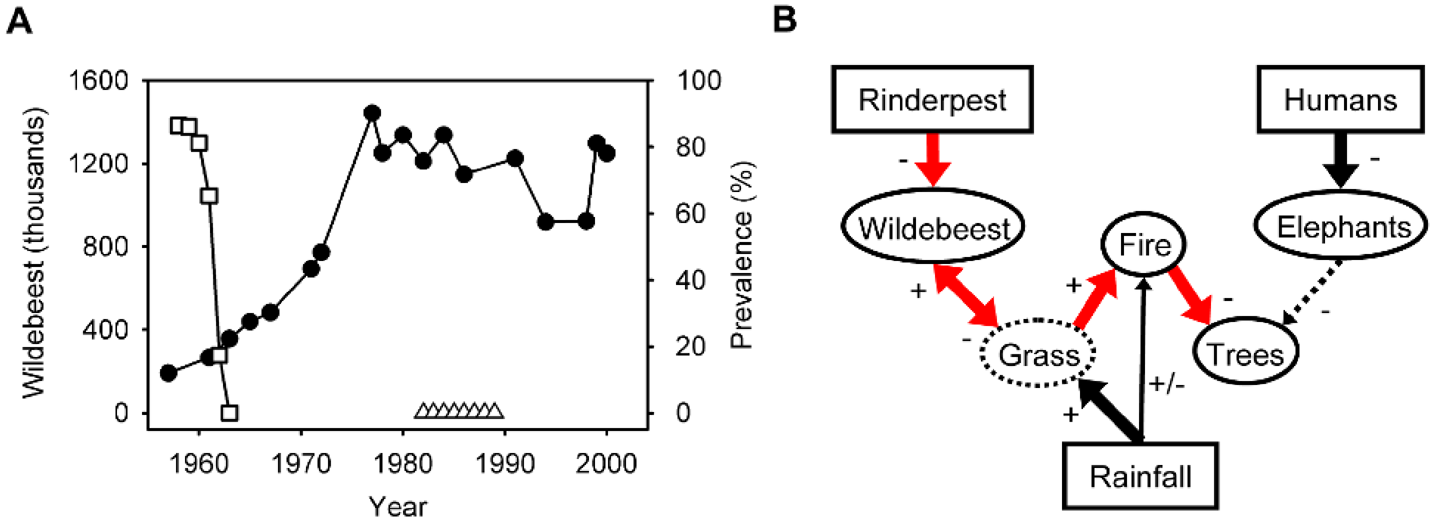

Figure 6. Rinderpest-mediated regulation of ecosystem dynamics (Holdo et al. 2009). (A) Serengeti wildebeest population (filled circle) and rinderpest seroprevalence reported for the periods 1958–1963. (B) Inferred causal relationships driving tree population dynamics in the Serengeti. The dominant effects are shown with thick arrows. Highlighted in red is a four-step pathway of causality linking rinderpest with tree population dynamics. Rinderpest decreases wildebeest populations, which in turn consume less grass. The increase in grasses also increases the risk for fire, which also burns down trees. This leads to multiple pressures on elephant populations, both from direct human impacts and from altered tree popullations. The grass compartment, as an unobserved variable, is shown in dotted outline. Image credits: Holdo et al. 2009 (CC BY).

Parasite Effects on Evolution

Parasitism can drive the evolution of species, both parasite and host, in a number of ways. First, parasitism can induce an evolutionary arms race between a parasite and its host (Medel et al. 2010). This occurs when the parasite damages the host (i.e., causes decreased fitness of the host), and the host responds by improving their defenses against that parasite. In turn, as long as these defenses do not completely clear the parasitic infection, the parasite may evolve novel strategies to circumvent host defenses. This can become an ongoing cycle: host improves defenses, parasite circumvents defenses, host reinforces defenses, and so on. This cycle is termed the “Red Queen hypothesis,” a name inspired by a quote from the Red Queen in Lewis Carroll’s *Through the Looking-Glass*: “Now, here, you see, it takes all the running you can do, to keep in the same place” (Van Valen 1973, 1977). This type of arms race or competition has enabled the development of several amazing adaptations and may have even been responsible for the evolution of sex (Hamilton 1980; Lively 2010). This is because asexual populations are clonal (i.e., genetically identical), while sexual populations allow for selection of traits that can defend them against parasites. Co-evolution can either be driven by the Red Queen effect (i.e., the evolution of host defenses and parasite virulence[14]) or by evolution of both the parasite and the host to their environment.

Parasitism may also drive the evolution of sexual selection in some species (Clayton 1991). For example, the eyebrow coloration of red grouse (mentioned above) is driven by their interactions with parasites (Hamilton and Zuk 1982). The eyebrows of male grouse are red, and some individuals have a drab, rust colored red while others have brilliantly red eyebrows. Research has shown that the redness of these feathers is an “honest signal” of the male’s resistance to parasitism by the gut nematode *Trichostrongylus tenuis* (Hamilton and Zuk 1982). This is because production of the carotenoid pigments that make male grouse feathers bright red is energetically costly. Infected males must invest a disproportionate amount of energy responding to parasitism by *T. tenuis*. This depletes energy reserves which might otherwise have been used for coloration. During mating, females tend to select for showier, more brightly colored males, which increases their fitness by producing offspring that are more likely to inherit resistance to *T. tenuis*. Carotenoid production (and associated red coloration) is also associated with exposure to, and resistance from, parasites in fishes such as the three-spined stickleback (Folkstad et al. 1994). These are just a couple of examples of how parasitism can influence evolution and sexual selection, but many more examples exist across the animal kingdom.

PARASITES IN A CHANGING WORLD

Links between host–parasite interactions and the surrounding environment are complex and highly variable (Wolinska and King 2009; Mostowy and Engelstädter 2011). Parasitism may be affected by a number of environmental factors, such as climate change (Marcogliese 2001), fishing or harvest of host species (Wood et al. 2010), pollution (Sures 2008), and habitat loss (Mbora and McPeek 2009). The effect of environmental changes on parasite survival and reproduction can be non-linear (i.e., context dependent; Kutz et al. 2014), therefore, it is often difficult to predict how climate change and other human-caused changes to the environment will alter parasitism. Climate change and other stressors will most likely instigate increased abundance of some parasites, while decreasing the abundance of others. Since parasites are strictly dependent on their hosts, changes to host populations may cause the decline, or even loss, of parasite species. As Lafferty (2013) commented, "Parasites, due to their strict dependency on hosts, are sensitive members of communities. They are likely to disappear before their hosts and therefore can make good indicators of ecosystem complexity, decreasing with degradation." Parasites may be our "canaries" in the global climate "coal mine."

Parasites, Biodiversity Decline, and Co-Extinction

Parasites are particularly susceptible to declining host biodiversity (Lafferty 2012). Biodiversity decline occurs when environmental and human-caused stressors cause the extirpation[15] or extinction[16] of one or more species in an ecosystem. Biodiversity decline can happen as a result of a number of influences, including exploitation (e.g., overharvest, overfishing), habitat degradation, loss, and fragmentation. Since many parasites rely upon multiple hosts to complete their life cycle, the loss of only one host could cause the extirpation of a parasite from an ecosystem (Lafferty and Kuris 2009b; Byers et al. 2011). Further, many parasites are host-specific (i.e., they can only associate with one host species during each life stage). If a host species is lost from an ecosystem, all its host-specific parasites are lost as well (Lafferty 2012).

One of the biggest threats to parasite biodiversity is co-extinction. Co-extinction occurs when the extinction of a host species causes the extinction of all of its associated parasite species (Dunn et al. 2009). For example, recent research has used coprolites (fossilized dung) from extinct moa birds in New Zealand to demonstrate that the extinction of these bird hosts caused the co-extinction of multiple gut parasites (Boast et al. 2018). Co-extinction may be caused by habitat loss, overharvest of hosts, ecosystem degradation, or a number of other human-caused factors. Since most hosts contain multiple parasite species, many of which remain undescribed, it is likely that many co-extinctions happen quietly and that many parasite species are lost before they are even discovered (Strona 2015).

Parasites and Climate Change

Climate change can alter parasitism, either by increasing or decreasing parasite transmission (Marcogliese 2008; Pickles et al. 2013). Gradual climate warming can change both host and parasite distributions (Dobson and Carper 1992; Marcogliese 2001; Polley and Thompson 2009). These changes in distributions can cause the introduction of hosts and/or their parasites to new geographic regions, and therefore may expand a parasite's range (Epstein 2010). Two examples are the oyster parasite, *Perkinsus marinus*, on the east coast of the United States (Ford and Smolowitz 2007) and bird parasites along elevation gradients (Zamora-Vilchis et al. 2012). Alternatively, warming may lead some geographic regions a parasite had previously inhabited to become uninhabitable. This can cause the parasite's range to either contract (i.e., get smaller) or to shift (i.e., stay the same size but move towards areas with suitable temperatures; Epstein 2010). Warming may also speed up a parasite's life cycle (e.g., Macnab and Barber 2012). In the Arctic, rapid warming has increased the number of times parasites can reproduce during each summer, which has led to an increase in parasitic nematode infections in reindeer and musk ox populations (Kutz et al. 2005).

Parasitism can also be affected by climate oscillations, such as El Niño, which can cause both short-term warming as well as changes to rainfall patterns (Mouritsen and Poulin 2002; Claar and Wood 2020). Climate oscillations can cause outbreaks in human pathogenic diseases such as chikungunya, hantavirus, Rift Valley fever, cholera, plague, and Zika (Anyamba et al. 2019). Although climate oscillations may limit the range of some parasites, they can also cause outbreaks in marine and wildlife diseases (Harvell et al. 2002; Mouritsen and Poulin 2002). These outbreaks can significantly impact conservation efforts by rapidly altering the balance between hosts and parasites.

CALL FOR PARASITE RESEARCH

Parasite research is a growing field, but there are many things that we still do not know. Many questions remain including: how does parasite burden change with increasing sea water temperature? How does parasite intensity vary between invasive and native species? And how can parasite ecology inform public health? Whether you are interested in behavior or ecology or history or physiology or biodiversity or climate change, there's a world of fascinating parasite research just waiting to be explored.

SUGGESTED SUPPLEMENTARY READING

RESEARCH AND SYNTHESIS ARTICLES

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POPULAR SCIENCE

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- McAuliffe, K. 2012. How your cat is making you crazy. The Atlantic. https://www.theatlantic.com/magazine/archive/2012/03/how-your-cat-is-making-you-crazy/308873/
- Cohen, J. 2017. Reciprocal effects: new paradigm for describing trophic cascades caused by infectious agents. University of California – Santa Barbara. Science Direct. https://www.sciencedaily.com/releases/2017/07/170720133058.htm

TEACHING RESOURCES

- Primer on disease ecology: https://www.nature.com/scitable/knowledge/library/disease-ecology-15947677
- Teaching resource (includes field labs): https://www.researchgate.net/profile/Gregory_Sandland/publication/228796011_Understanding_Ecological_Principles_through_Parasitological_Pedagogy/links/09e4150a39c464e495000000/Understanding-Ecological-Principles-through-Parasitological-Pedagogy.pdf

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GLOSSARY

1. **Host:** an organism that provides a resource (i.e., nutrition, mobility) for the parasite(s) that infests/infects it, and experiences a fitness cost as a result of infection
2. **Fitness cost:** a reduction of an organism's ability to survive, grow, and/or reproduce
3. **Cryptic:** hidden and hard to see
4. **Symbiotic mutualists:** an organism that lives in an intimate and durable relationship with its host, and provides a fitness benefit to that host (i.e., an increase in an organism's ability to survive, grow, and/or reproduce; Douglas 2010)
5. **Micropredator:** organisms that take small meals during a short interaction time, but do not live in a persistent interaction with a host
6. **Free-living organism:** an organism that does not live in or on another organism; most free-living organisms are host to parasites and/or symbionts
7. **Generation time:** time between two consecutive generations within a population; the average time between birth and reproduction
8. **Parasitology:** the study of parasites
9. **Prevalence:** the total proportion of infected hosts within the host population
10. **Definitive host:** the host in which a parasite reaches sexual maturity and reproduces
11. **Dead-end host:** a host that a parasite can infect, but from which the parasite cannot continue its life cycle
12. **Intermediate host:** a host in which a parasite undergoes development and growth
13. **Fishes:** a group of multiple fish from multiple species. In contrast to the plural fish, which references multiple fish from one species

14. **Virulence:** a parasite's ability to infect or damage its host
15. **Extirpation:** complete loss of a species from part of its range; the species may be gone from an ecosystem or region, but still persists in other areas
16. **Extinction:** complete loss of a species from its entire range; no individuals of the species remain

Parasite Biodiversity: Fish Dissection and Assays for Parasites

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ABSTRACT

This exercise is a wet lab that involves dissecting an easy (and disturbing) source of live parasite material: fresh fish from your local seafood market. Students will search for both ectoparasites (on the outside of the host) and endoparasites (inside the tissues of the host). They will create a lab notebook entry, and they will also discuss observations of parasites within their fish and patterns among other fish dissected in the class.

INTRODUCTION

It's tough to learn fish ecology without ever seeing a fish in its natural habitat. By the same token, it's tough to learn parasite ecology without ever seeing a parasite in its natural habitat. For endoparasites, the innards of hosts are prime habitat; getting to know the parasites often involves getting your hands dirty. To view parasites in their natural habitat, dissection of freshly killed hosts provides the best material for examining living parasites.

In this lab exercise, you will be examining and dissecting freshly collected teleost (i.e., bony) fishes. Fishes serve as intermediate and/or definitive hosts for a diversity of parasites—you may be surprised to find that a fish you might purchase from the market has many parasites living in and on it.

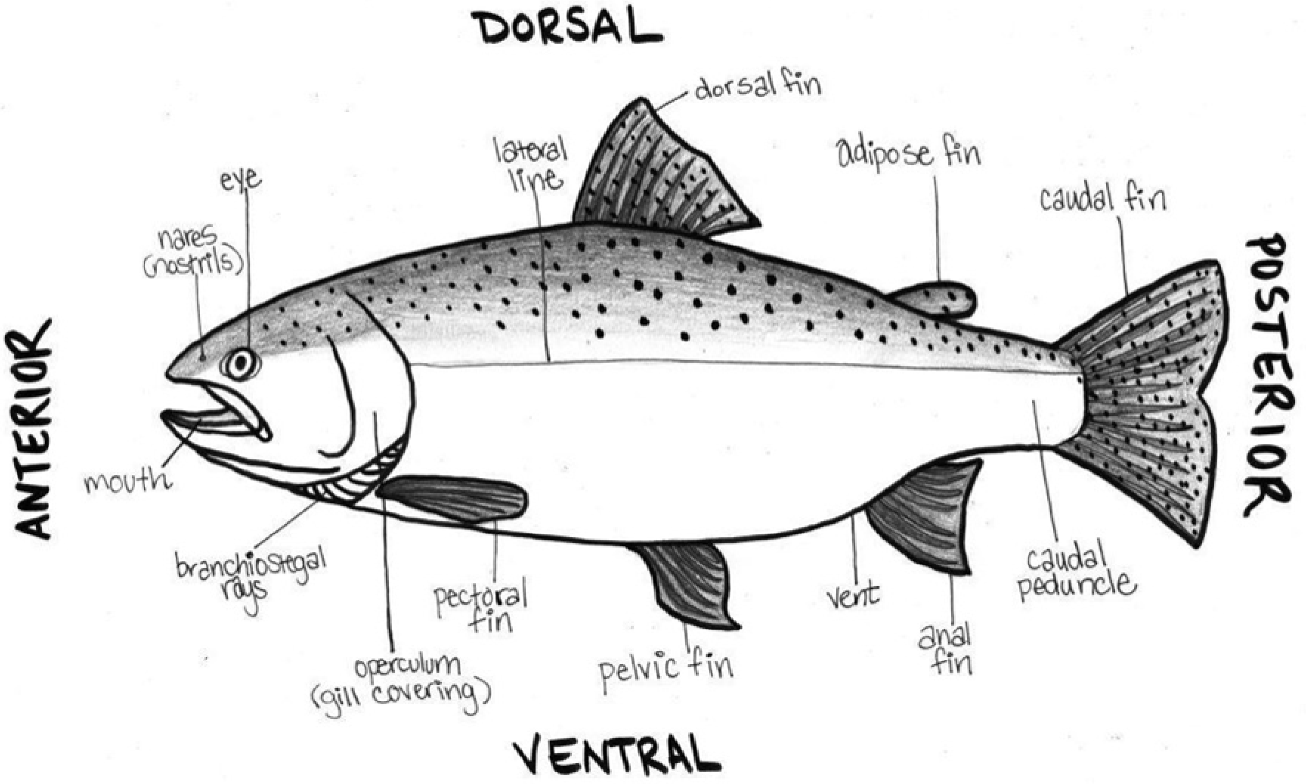
In order to find parasites within your host fish, you will need to develop a "search image." A search image is a picture in your mind that you can match to the outside world to recognize an organism. The better your search image is, the easier it will be for you to see parasites in host tissues, but it takes time and care to develop a search image. You will be searching for both endoparasites (i.e., parasites that live within their host), and ectoparasites (i.e., parasites that live on the external surface of their host). Many parasites are small, so make sure to take your time while dissecting your fish. Review the representative drawings of fish anatomy (Figure 1) and fish parasite taxa (Figure 2) before you begin your dissection.

LEARNING OBJECTIVES

By the end of this exercise, students will be able to:

1. Safely perform a parasitological dissection of a fish.
2. Locate parasites within host tissues.
3. Classify parasites found into broad taxonomic groups.

a. External



b. Internal

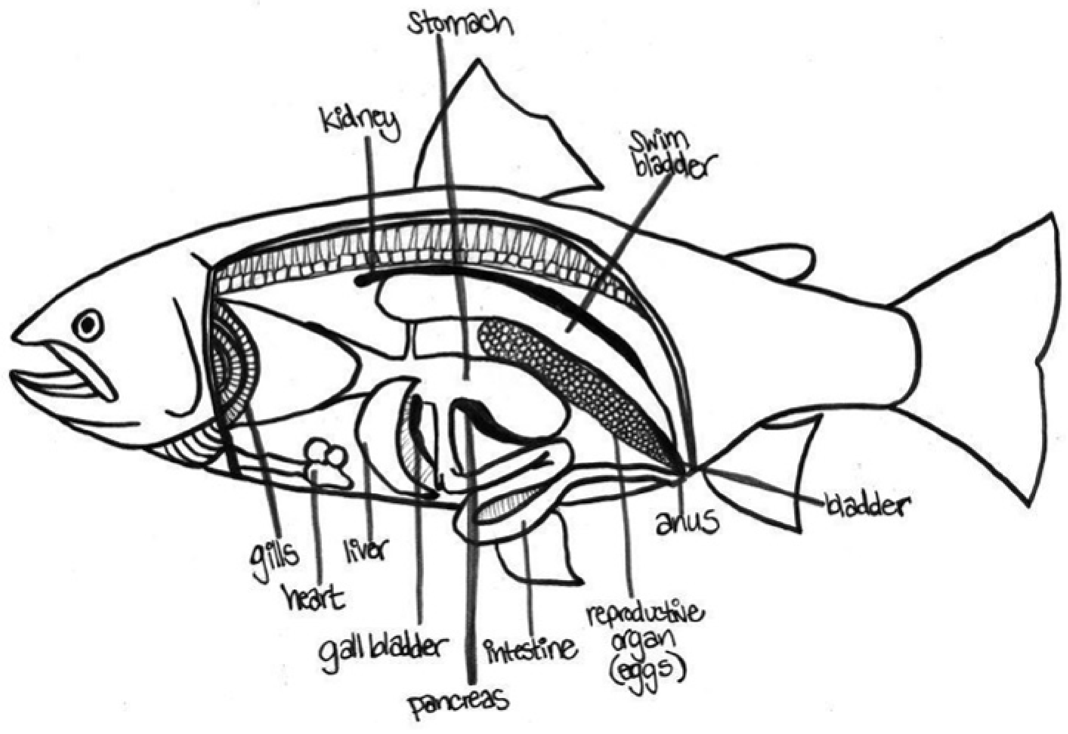


Figure 1. Teleost fish anatomy. a) External anatomy, b) Internal anatomy. Image credit: Danielle Claar.

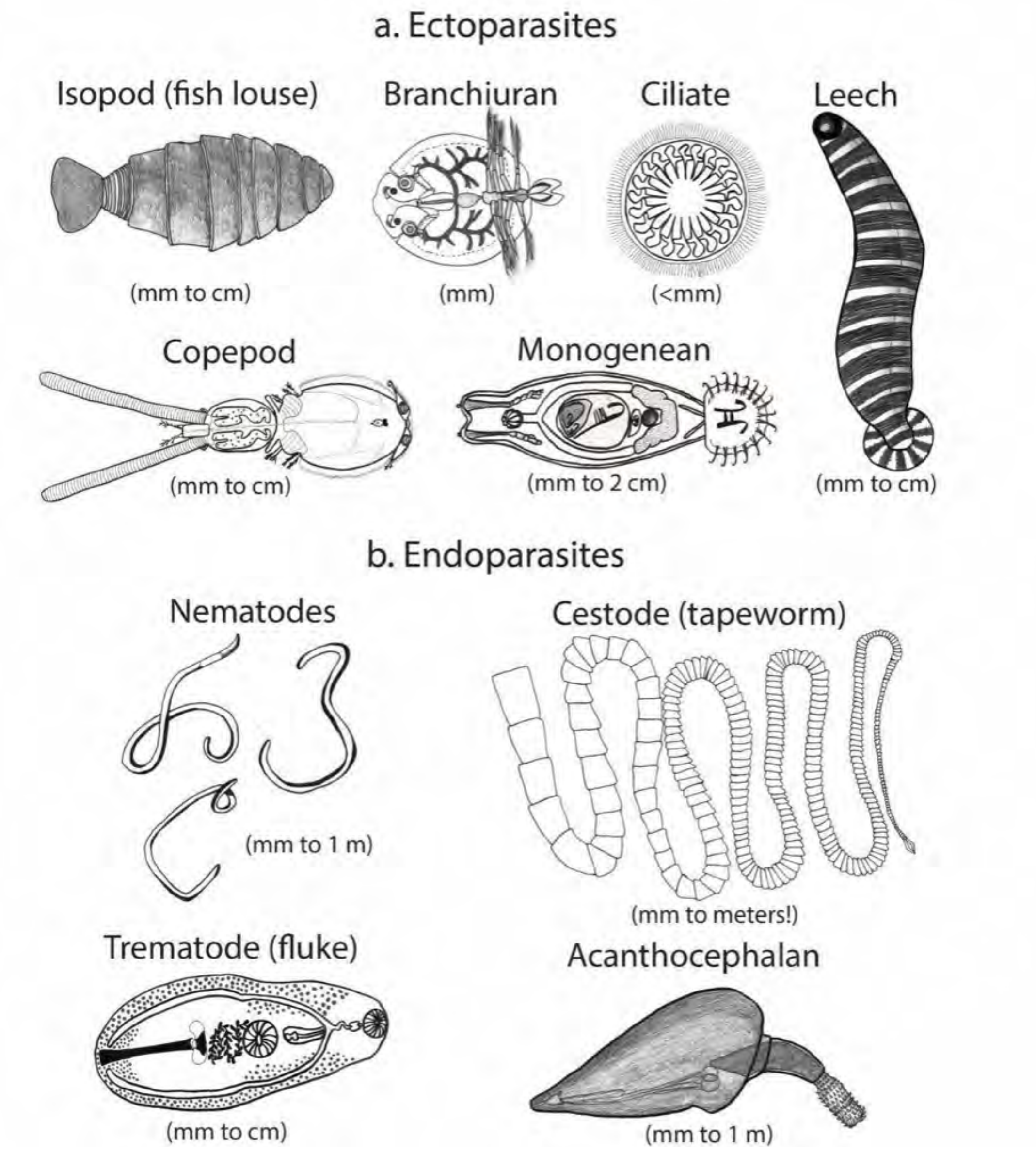


Figure 2. General types of fish parasites. a) Ectoparasites, which are found on the external surface of their host, and b) endoparasites, which are found internally within their host. Note that images are not to scale, but an approximate scale is provided for each parasite type. Image credit: Danielle Claar.

MATERIALS

- Fish
- Dissection tray
- Ruler to measure fish size
- Probes
- Small, fine-tipped forceps
- Dissecting scissors
- Scalpel
- Glass microscope slides and cover slips
- Glass dishes/watch glasses/bowls
- Squirt bottle of salt water
- Dissecting microscope/stereomicroscope and compound microscope

FISH DISSECTION PROCEDURE

Before Dissection

1. Read Box 1 to review all safety recommendations.
2. Confirm you have the needed materials (listed above) and obtain your fish and place it on a dissection tray.
3. Review the "Expected Results" section of the Student Resources handout, to get an idea of what you are likely to find.
4. In a lab notebook, record the species of the fish that you will dissect and the collection data supplied (this information will be provided by your instructor).
5. Record the length measurements of the fish: total length, standard length, and fork length (see Student Resources Figure 4 for how these measurements are made). Be sure to always use metric units (e.g., cm, mm)

Box 1. Safety recommendations

1. Wash your hands thoroughly with soap and water after handling fish.
2. Wear protective gloves. This is mostly to protect your nose—fish are smelly and handling them without gloves will leave your hands smelling fishy for days.
3. Beware of fish's sharp parts. Many fish species have sharp dorsal spines, so be especially carefully when holding the fish from the dorsal side.
4. When using scissors, scalpels, or knives, always make sure that you are cutting away from yourself and that your lab partner is standing behind you or at a safe distance. Handle sharp objects with care.
5. You might think it's a good idea to eat a filet from your fish after you dissect it. Do not do this. To be safe for consumption, fish filets need to be maintained at a cool temperature (40°F or below) and in a clean place (i.e., not a dissection pan). As fish warms to room temperature, dangerous bacteria can grow on it. For more information on safe handling of fish intended as food, check out the US Food and Drug Administration website.

Documenting Your Observations

This is a three point overview that you should read through prior to starting the parasite assays. The actual steps of the assays are in the sections below.

1. As you dissect your fish, you will remove each parasite you find and place it in its own bowl or watch glass (you can put parasites that are the same type and found in the same location together in one bowl). For each parasite, record the site of infection, how many parasites were present, the approximate size of the parasite, and any other distinguishing features in your lab notebook.
2. For some parasites, you may want to view them more in depth using a compound microscope. To do this, place the parasite on a slide with a drop of salt water and cover with a cover slip. Start with the lowest power on the microscope and increase magnification as necessary (but do not use oil immersion).
3. In your lab notebook, you will sketch the parasites that you see in the host (see Student Resources for an example). Don't forget to record the size of the parasite and/or the magnification used, if viewed with a microscope. You can also take pictures of parasites by holding a camera or phone to the eyepiece of the microscope. Even if you take pictures of the parasites with a camera/phone,

it is worth drawing each parasite, as drawing can help you notice distinguishing features. You are required to draw at least one parasite in your lab notebook for this exercise.

Ectoparasite Assay

Be sure to read through each step completely before starting the procedure and review the Student Resources handout.

1. Develop a search image for the parasites that you might encounter (Figure 2). Pay particular attention to the general shape as well as the size range of each parasite taxon, and where you found them on the host. Which parasites might you be able to see with your naked eye and which will need magnification to identify?
2. Search for ectoparasites: copepods, branchiurans, isopods, leeches, and monogenes. Examine the skin, fin rays, and lateral line with your naked eye, and then remove the fins using either the scalpel or scissors and use a dissecting scope to search for smaller parasites that may be hiding in the fin tissue.
3. Check for ciliates: carefully scrape mucus from the fish's lateral line using either a razor blade or a glass slide and use a compound microscope to search for ciliates.
4. Probe the mouth and nasal capsules of the fish to check for parasites.
5. Check for monogenes on the gills: examine the gills while they are still in the fish, and then carefully remove the gills by snipping the ends of them with scissors and examine them under a dissecting microscope.

Endoparasite Assay

Be sure to read through each step completely before starting the procedure and review the Student Resources handout.

1. With a sharp scalpel or dissection scissors, make a cut from the vent to the operculum on the abdomen/ventral side of your fish, but slightly off the midline so you avoid cutting through the digestive tract. The incision depth needed varies by fish and takes some practice. Begin gently and shallowly, and then cut deeper. If the fish has large/tough scales (that make it difficult to cut through) you may need to remove them by scraping before making the incision.
   - If using a scalpel, make multiple shallow cuts to avoid damaging internal organs.
   - If using scissors, carefully lift the skin away from the internal organs so that you are only cutting the skin and muscle, and not anything inside of the fish.
2. To open the fish for endoparasite examination, use the scalpel or scissors to cut two more perpendicular incisions—one behind the operculum perpendicular to the original cut towards the spine and another in front of the vent perpendicular to the original cut towards the spine.
3. To view the internal organs (see Student Resources Figure 5), either open this flap of skin/muscle or remove it, being careful not to cut the vent or other internal organs in the process.
4. If possible, determine and record the sex of your fish. If the fish is female, also record its reproductive status (see Student Resources Figure 6).
5. Remove the entire digestive tract (esophagus to vent) by snipping with scissors at the top near the esophagus and at the bottom near the anus. Place it in a dish, being careful not to puncture any part of it in the process. If you do accidentally puncture it, pay close attention to any material that comes out—noting which part of the digestive tract it came out of, and placing it in a separate bowl if possible. This could be mucousy material, or identifiable organisms like a smaller fish or crab.

6. Check the body cavity and mesenteries (surrounding connective tissue) for the presence of nematodes and cestodes.
7. Find and remove the gallbladder; place it in a small bowl with salt water.
8. Open the stomach. Record any contents found—you may be able to identify the fish's last meal. Carefully examine the stomach contents for parasitic nematodes, and record what you find.
9. Examine the intestine—this is often a hotspot for parasites. Search for adult nematodes, cestodes, and acanthocephalans with your naked eye, and then use the dissecting scope to search for trematodes. You can use a squirt bottle with salt water to "clean off" and more clearly view parasites that you find, just make sure you check that what you are rinsing away doesn't contain other, smaller parasites.
10. Search for encysted nematodes and cestodes within the fish's muscles.

Gallbladder: Myxozoa Assay

Be sure to read through each step completely before starting the procedure and review the Student Resources handout.

Myxozoa are parasitic cnidarians (i.e., they are related to jellyfish). They are very tiny, so the only way you can see them is to view them on a compound microscope.

1. The gallbladder should be in a separate bowl or watch glass. Using a scalpel and forceps, macerate (thoroughly cut up/open) the gallbladder.
2. Examine the gallbladder for myxozoan parasites (Figure 3) by pipetting a small amount of liquid (about a drop) onto a glass slide. View the slide under a compound microscope to search for myxozoans.

Recording and Collating Data

In your lab notebook, document every parasite you see. This includes writing down the identity of the parasite (see Figure 2), the approximate number you observed, the site of infection within the host, and the approximate size of the parasite. See the example lab notebook entries (Figures 7 and 8). When you draw a fish or parasite in your lab notebook, it is important to add a scale for the size of that organism (e.g., the scale bar with 1cm at the bottom of Figure 7).

As you finish your dissection, please write on the board the number and identity of each parasite your group found within each host tissue. If you don't find many or any parasites, try to examine some of the parasites your classmates have found. Make sure you write down the overall results in your own lab notebook before you leave.

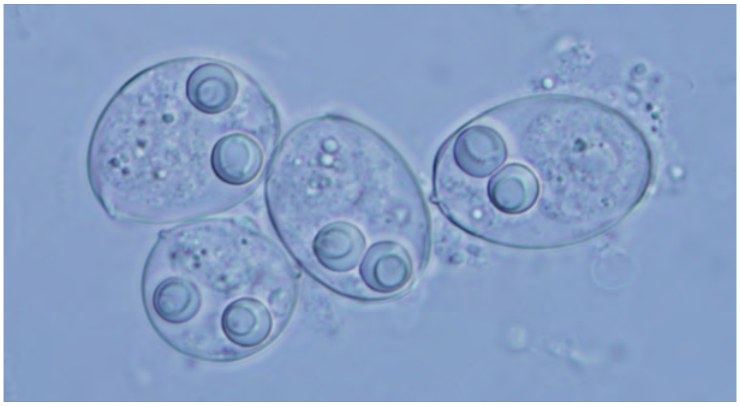


Figure 3. Myxozoa (*Sinuolinea* sp.) from a monkfish (*Lophius piscatorius*). Image credit: Ivan Fiala/ToL (CC BY-NC 3.0).

STUDENT RESOURCES

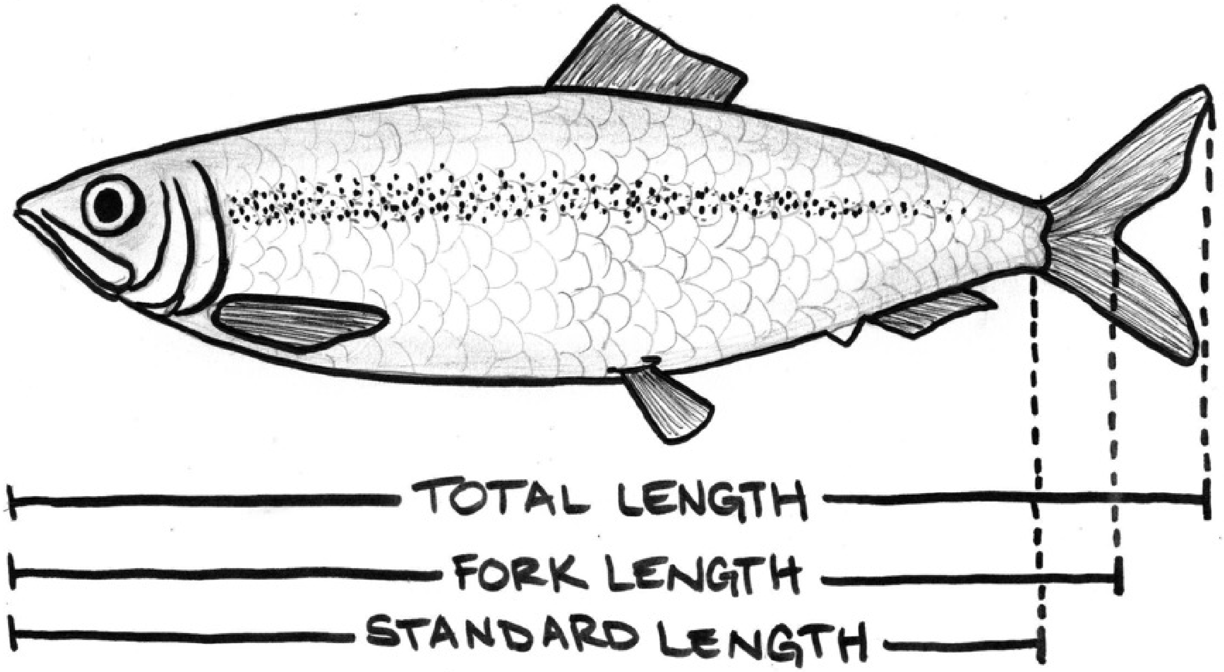


Figure 4. Measuring total length, standard length, fork length. Note: not all fish have forks, so for those fish you only need to measure the standard and total length. Image credit: Danielle Claar.

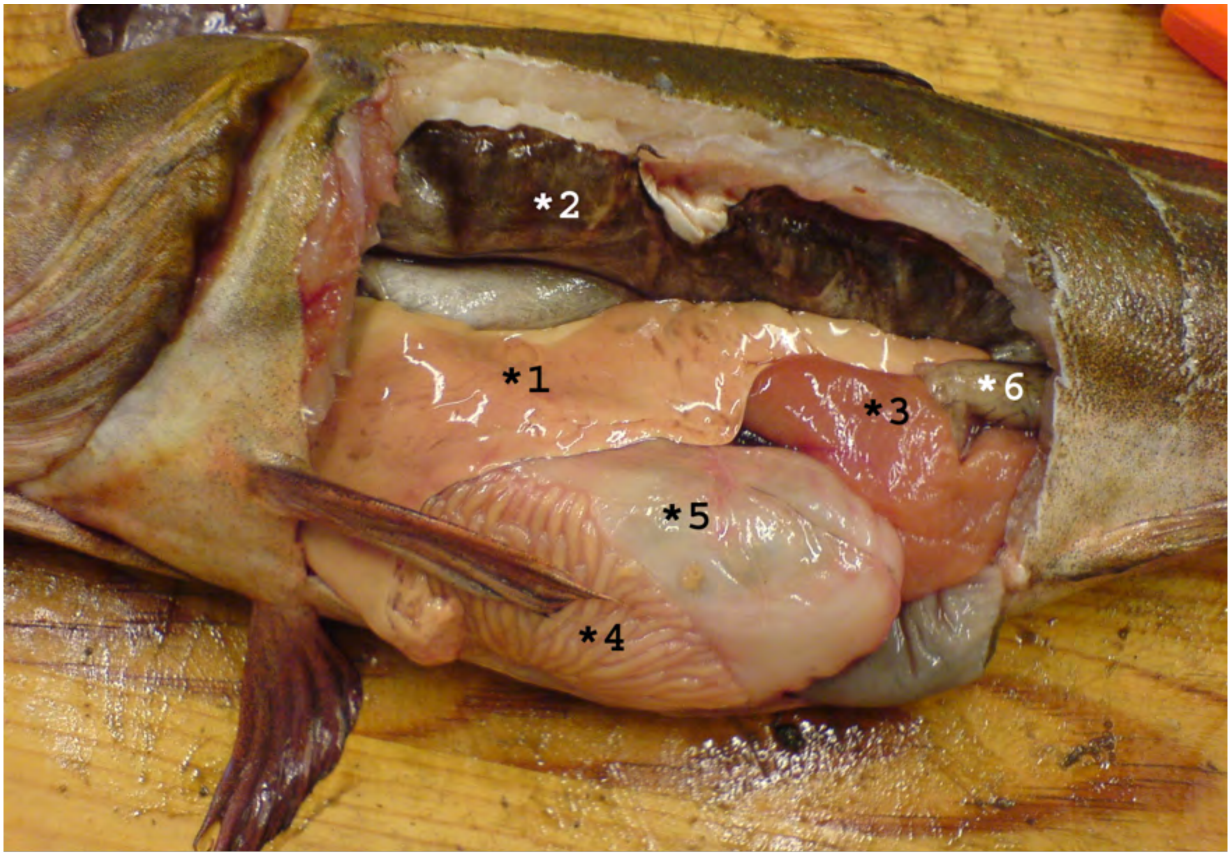


Figure 5. Internal fish anatomy image. 1) liver, 2) swim bladder, 3) ovaries/roe, 4) duodenum, 5) stomach, 6) intestine. Image credit: H. Dahlmo/Wikimedia Commons (CC BY-SA 3.0).

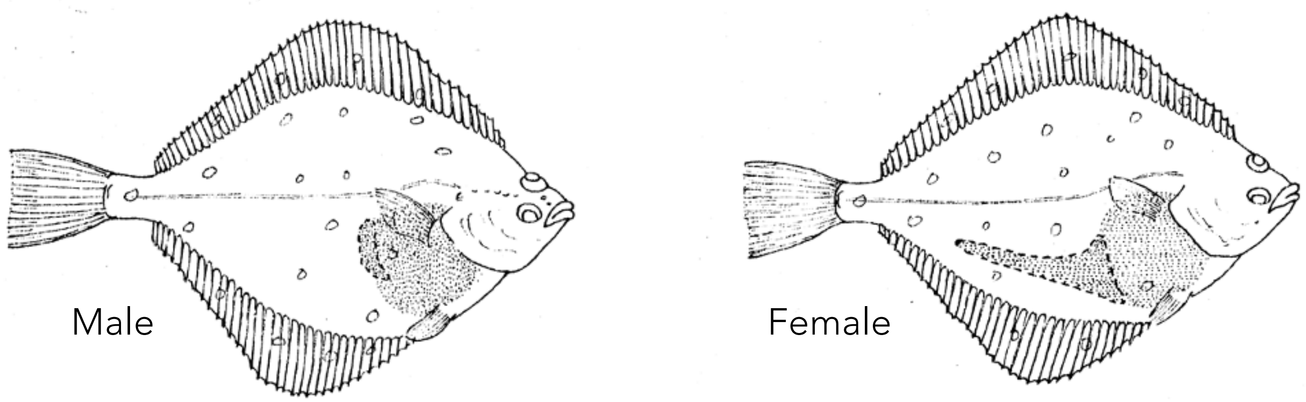


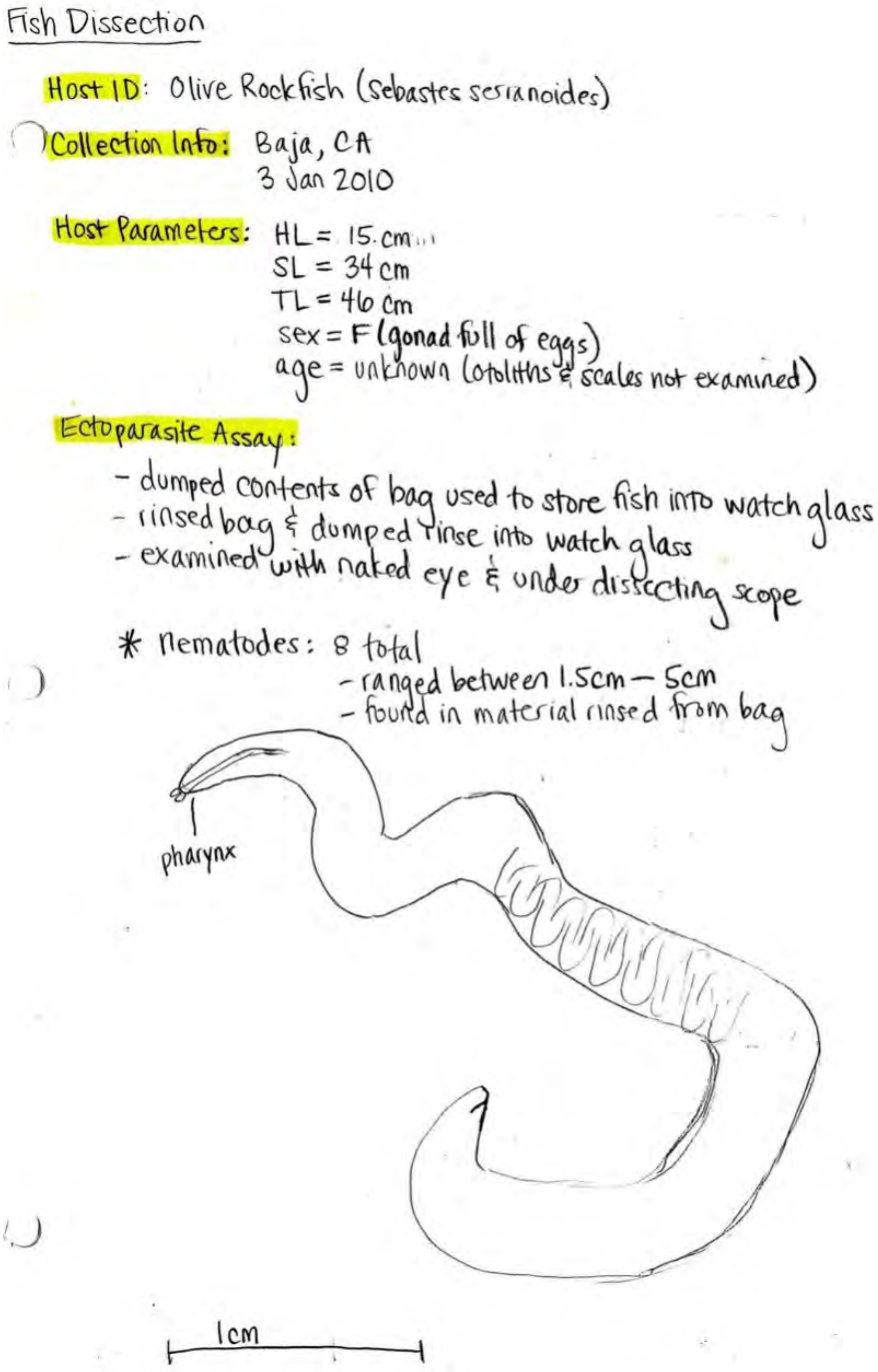
Figure 6. How to determine the sex and reproductive status of your fish. In flatfish (flounder, sole, etc.) the gonads can be found posterior to the body cavity: one on each side of a bony plate. Both testes and ovaries will appear triangular in shape, although ovaries will be more elongate towards posterior (as seen in shaded areas with dotted line borders in the images above). Image credit: Food and Agriculture Organization of the United Nations.

- For most fish (other than flatfish, see Figure 6), the gonads will be on the outer edge of the body cavity and can be found by tracing two structures attached bilaterally to the vent. Male testes will generally be elongated, sometimes stringy in appearance. Testes appear smooth in coloration and texture. Female ovaries will be plump and grainy in appearance when examined—the more defined the granulation, the more developed are the eggs.
- Females with ovaries that are smoother in color are usually designated F1 (least reproductively developed). Females with ovaries of moderate granularity are designated F2 (intermediate reproductive development). And females with clearly visible, defined eggs in their ovaries are designated F3 (highly reproductively developed, or ripe). See https://www.necropsymanual.net/en/teleosts-anatomy/reproductive-system/ for more photos of fish gonads.

Expected Results

Common infection sites in teleost (i.e., bony) fishes include:

- Exterior surface (including fins) – copepods, branchiurans, ciliates, isopods, leeches, monogenes
- Lateral line – copepods
- Gills – copepods, isopods, monogenes
- Stomach – nematodes
- Intestines – cestodes, nematodes, trematodes, acanthocephalans
- Muscles and mesenteries – larval nematodes, larval cestodes, larval trematodes
- Gall bladder – myxozoans



Fish Dissection

3

Host ID: Olive Rockfish (Sebastes serranoides)

Collection Info: Baja, CA
3 Jan 2010

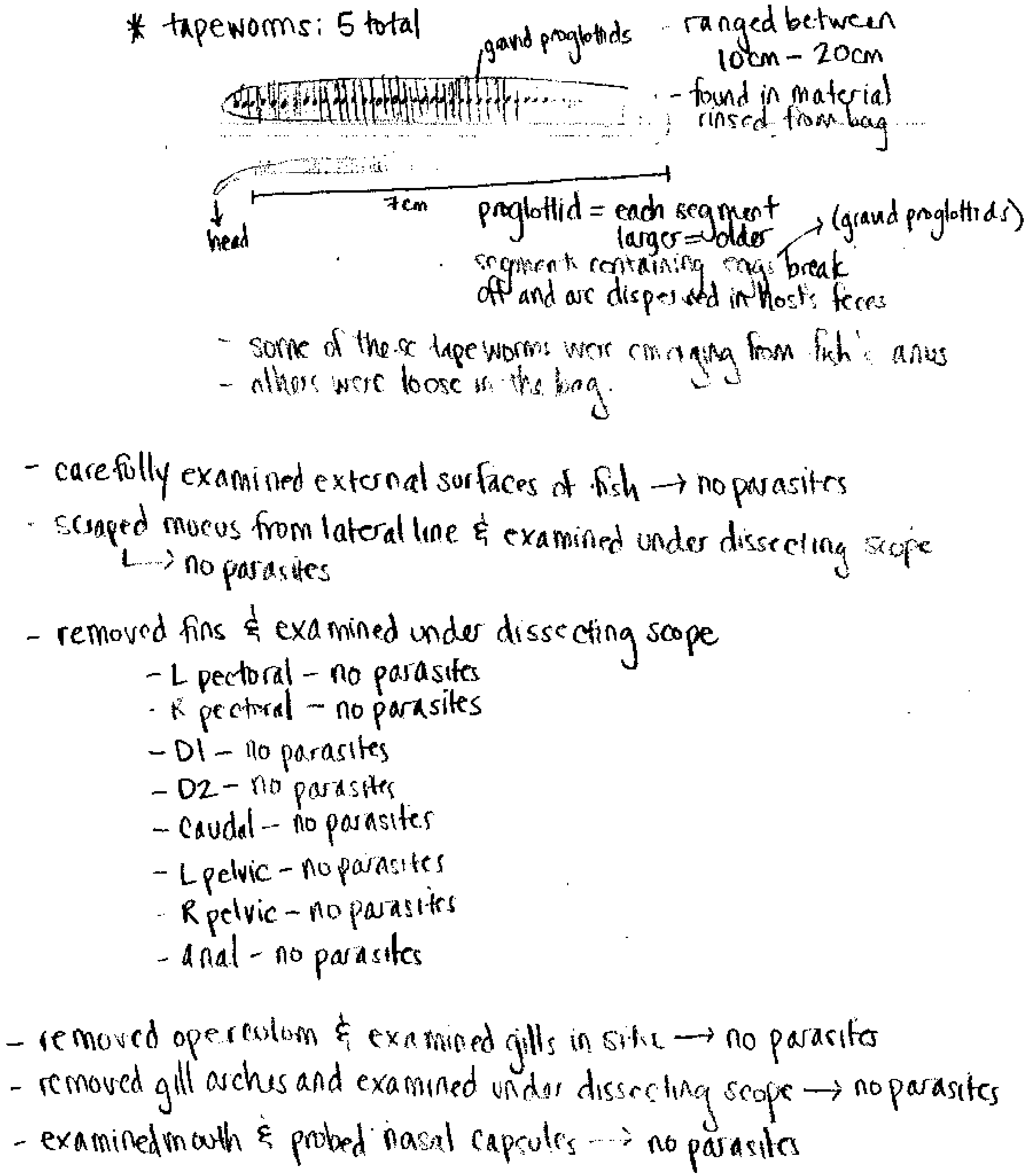
Host Parameters: HL = 15 cm
SL = 34 cm
TL = 46 cm
sex = F (gonad full of eggs)
age = unknown (otoliths & scales not examined)

Ectoparasite Assay:

- dumped contents of bag used to store fish into watch glass
- rinsed bag & dumped rinse into watch glass
- examined with naked eye & under dissecting scope

* nematodes: 8 total
- ranged between 1.5cm – 5cm
- found in material rinsed from bag

Figure 7. Example lab notebook page showing general information and ectoparasite assay. Image credit: Chelsea Wood.



* tapeworms: 5 total

grand proglottids

- ranged between 10cm - 20cm
- found in material rinsed from bag

head

7cm

proglottid = each segment
larger = older → (grand proglottids)
segments containing eggs break off and are dispersed in host's feces

- some of these tapeworms were emerging from fish's anus
- others were loose in the bag.

- carefully examined external surfaces of fish → no parasites
- scraped mucus from lateral line & examined under dissecting scope
  - → no parasites
- removed fins & examined under dissecting scope
  - L pectoral - no parasites
  - R pectoral - no parasites
  - D1 - no parasites
  - D2 - no parasites
  - caudal - no parasites
  - L pelvic - no parasites
  - R pelvic - no parasites
  - anal - no parasites
- removed operculum & examined gills in situ → no parasites
- removed gill arches and examined under dissecting scope → no parasites
- examined mouth & probed nasal capsules → no parasites

Figure 8. Example lab notebook page showing notes, description of a tapeworm parasite, and ectoparasite assay (i.e., examining fins under a dissecting scope). Image credit: Chelsea Wood.

Parasite Biodiversity: Community Data Analysis

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ABSTRACT

In this exercise, you will engage with real data to answer the question: how do human impacts on ecosystems change the abundance of parasites in wildlife? You will use data to assess whether human impacts on the environment increase or decrease the abundance of parasites in coral reef fish. Specifically, you will determine if fishing increases or decreases parasite abundance in coral reef fishes.

LEARNING OBJECTIVES

By the end of this exercise, students will be able to:

1. Calculate mean parasite abundance across six species of central Pacific reef fish.
2. Plot mean parasite abundance data and summarize patterns.
3. Discuss the results and how these results apply to similar and different ecosystems.

BACKGROUND

Coral reefs are among the most biodiverse ecosystems on the planet, and that biodiversity includes a large number of parasitic species that reside on and in reef-dwelling fishes. Many factors can influence which species of parasite are present in the community and the number of each species within each host fish, including characteristics of the host, parasites, and the wider coral reef environment. As humans modify the environment, particularly by fishing, we change which host species are present and how many individuals of each host species are present in a given area. These changes to the fish community structure alter the interactions between the host species, which can increase or decrease parasite transmission rates. By changing the overall environment in which the hosts and parasites live, humans may impact how long parasites can live outside their hosts, by providing extra nutrients in the water column or by altering the physical environment present for parasites as they search for hosts. Human influence may alter how receptive the hosts are to parasitic infection, as the fish left behind after fishing may be more or less able to defend themselves from infection. As a result of these changes, we expect human influence to shape the community of parasites present. In this exercise, you will use real data from coral reef fishes to determine how fishing pressure around each island can change the parasite community and you will start to examine potential reasons why this might happen.

The data you will use is from a study conducted in the northern part of the Line Islands archipelago (Figure 1). The Line Islands are a group of eleven total islands formed by volcanic activity in the Pacific Ocean, and they get their name from the fact that they sit on the International Date Line. The northern part of the Line Islands includes three unfished islands (Kingman, Palmyra, and Jarvis) and three fished islands (Teraina, Tabuaeran, and Kiritimati). The unfished islands have never been permanently inhabited by humans or intensively fished, and are therefore some of the least human-impacted coral reef systems in the tropical Pacific. Only a few hundred kilometers away from these unfished islands are islands forming part of the Republic of Kiribati, and they experience intensive fishing pressure, which has depleted the abundance of large-bodied fishes. The fishing in the area is artisanal fishing, which is fishing undertaken at a community or household level using low technology

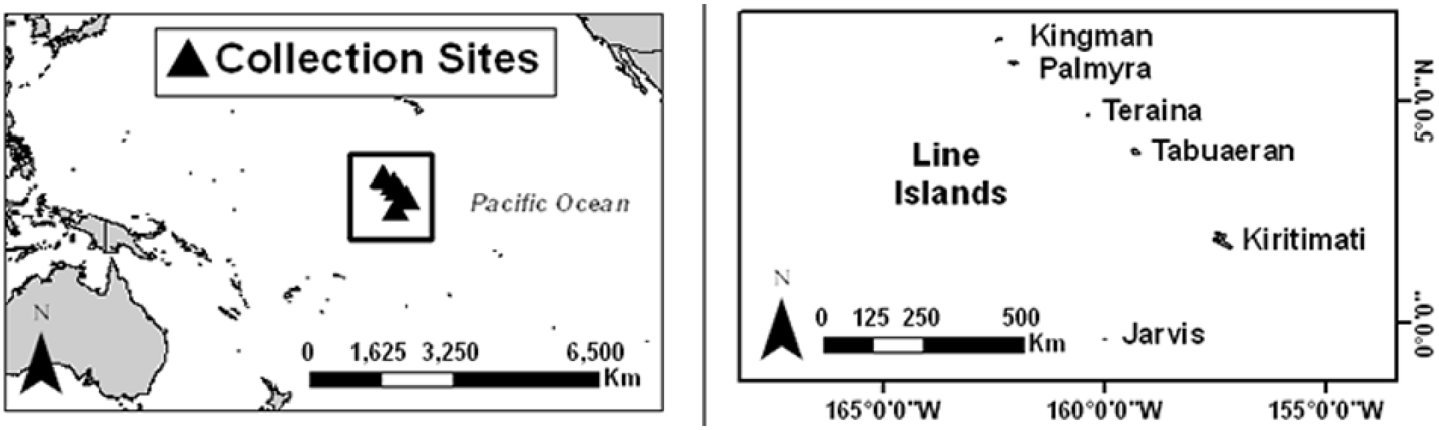


Figure 1. Map of the Northern Line Islands. Image credit: Wood et al. 2014; CC Public Domain.

methods.

We know that fishing can change the number and types of fish present around the islands that are fished. Now we want to know how those changes in host biodiversity (number and type of host fish present) might, in turn, influence what parasites are present and how many of each type of parasite there are. Two possible options include that (1) maybe fishing reduces the number of fish present, reducing the number of possible hosts, and potentially reducing the number of parasites or (2) higher diversity of fish in unfished areas might be linked to higher diversity of parasites.

A group of researchers wanted to know how fishing and human settlement might impact parasite communities. They joined up with a larger group of researchers and travelled all the way to the Line Islands to conduct this study. A total of 821 fishes (Figure 2) were collected by researchers while scuba diving at the six islands in October and November 2010. Fish were caught with a spear, placed in a bag underwater, and brought to the surface. Once the scuba divers were back on the boat, each fish was identified, numbered, and placed into an individual baggie. Fish were then frozen and transported back to the lab in the USA. Each fish was dissected and comprehensively examined to detect, identify, and quantify the abundance of metazoan parasites (parasites within the animal kingdom). Each parasite was classified according to its broad taxonomic group (Figure 3).

For this study, the researchers were specifically interested in the differences between two different types of metazoan parasites: trophically transmitted parasites (i.e., parasites with complex life cycles that must use hosts of multiple species, such as trematodes, cestodes, and nematodes) and directly transmitted parasites (i.e., parasites that can be transmitted among conspecific hosts, such as parasitic crustaceans and monogeneans), in terms of their response to fishing pressure. Of the six major groups of parasites they studied, three were trophically transmitted parasites (trematodes, cestodes, and nematodes) and three were directly transmitted parasites (monogenes, copepods, and isopods). These parasites tend not to be lethal, but they do take energy from their hosts. For example, isopods extract blood and fluids from their host by latching onto their host with piercing mouthparts, and cestodes (also called tapeworms) absorb important nutrients from the digestive system of their host.

Species: *Acanthurus nigricans*
Common name: whitecheek surgeonfish
Family: Acanthuridae (surgeonfishes)
Distribution: Indo-Pacific
Diet: herbivore, eat filamentous algae

Species: *Ctenochaetis marginatus*
Common name: blue-spotted bristletooth
Family: Acanthuridae (surgeonfishes)
Distribution: Indo-Pacific
Diet: detritivore

Species: *Cephalopholis urodeta*
Common name: darkfin hind
Family: Serranidae (sea basses)
Distribution: Indo-Pacific
Diet: predator, small fishes & crustaceans

Species: *Paracirrhites arcatus*
Common name: arc-eye hawkfish
Family: Cirrhitidae (hawkfishes)
Distribution: Indo-Pacific
Diet: benthic predator

Species: *Pseudanthias bartlettorum*
Common name: Bartlett's anthias
Family: Serranidae (sea basses)
Distribution: Pacific
Diet: zooplanktivore, feeds on plankton

Species: *Stegastes aureus*
Common name: golden gregory
Family: Pomacentridae (damselfishes)
Distribution: Pacific
Diet: herbivore

Figure 2. Fish hosts collected from the Northern Line Islands, present in the dataset provided, and descriptions of their characteristics. Image credits (L-R): *A. nigricans*, D. Ross Robertson/Smithsonian Institution (public domain); *C. marginatus*, NOAA Photo Library (CC BY 2.0); *C. urodeta*, Rickard Zerpe (CC BY 2.0); *P. arcatus*, Richard Ling (CC BY-SA 2.0); *S. aureus*, NOAA Photo Library (CC BY 2.0).

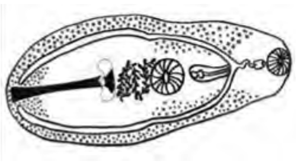
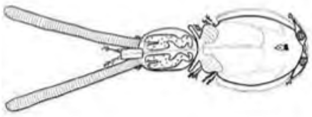
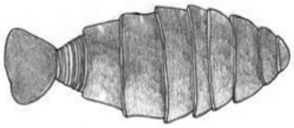
 Trematode Parasitic flatworms Complex life cycle, trophic transmission	 Monogene Ectoparasitic flatworms Direct life cycle	 Copepod Parasitic crustaceans Direct life cycle
 Isopod/Gnathiid Parasitic crustaceans Direct life cycle, Gnathiids are protelean parasites	 Cestode Tapeworms Most have complex life cycles with trophic transmission	 Nematode Roundworms All in this study have complex life cycles

Figure 3. General classes of parasites found associated with the fish hosts. Image credit: Danielle Claar.

PROCEDURE

Now you'll be provided the data collected from the above research project. First you'll explore the data, then you'll calculate the mean abundance and the standard error of the mean for the abundance of each parasite within each host, on both fished and unfished islands. You'll finish by plotting the results and considering the potential drivers of the patterns you find by responding to questions.

Explore The Data

1. Open the .csv or .xls file named "ParasiteBiodiversity_DATA" in Excel or other spreadsheet software (available from ncep.amnh.org).

DATA QUESTION ONE: How many rows does the file have? How many columns?

2. Below are the descriptions of the column headers and the associated data. There are questions embedded within to encourage you to get familiar with the data. Consider sorting or filtering data to help answering the questions, but if sorting, be sure to select all columns and all rows before sorting to ensure you do not scramble the dataset.
    - fish_sp : Fish species. The species of host are:
        - aca_nig: *Acanthurus nigrans* (137 fish; 2 parasite taxa)
        - cep_uro: *Cephalopholis urodeta* (162 fish; 4 parasite taxa)
        - cte_mar: *Ctenochaetus marginatus* (141 fish; 4 parasite taxa)
        - par_arc: *Paracirrhites arcatus* (129 fish; 2 parasite taxa)
        - pse_bar: *Pseudanthias bartlettorum* (109 fish; 2 parasite taxa)
        - ste_aur: *Stegastes aureus* (see Data Question 2)

DATA QUESTION TWO: How many *Stegastes aureus* fish were collected? How many different parasite taxa were found in/on this species?

- fish_id: Unique fish ID.

DATA QUESTION THREE: How many unique, individual fish were collected in total?

- island: Island where the fish was caught. The islands are:
    - Jarvis
    - Kingman
    - Kiritimati
    - Palmyra
    - Tabuaeran
    - Teraina

- fishing_status: Either "Fished" or "Unfished"

- depth: Depth in feet where the fish was caught.

DATA QUESTION FOUR: What was the deepest collection point? What was the shallowest?

- habitat: Habitat where the fish was caught. Either: "backreef," "forereef," or "patchreef"

- total_length: The total length of the fish in mm

- fork_length: The fork length of the fish in mm

- standard_length: The standard length of the fish in mm

DATA QUESTION FIVE: Find the shortest fish (by standard length) that was caught. How long is it in mm? What species of fish is it? Did it have any parasites?

- parasite: Which parasite is being counted. They are:

Stephanostomum:	*Stephanostomum* sp. Trematodes with trophic transmission
FinMetacercariae:	Fin metacercariae. Trematode larvae from the fish's fins with trophic transmission
Grandiunguid:	Grandiunguid sp. Copepod with direct transmission.
Neobenedenia:	*Neobenedenia* sp. Monogenean with direct transmission
LarvalNematode:	Nematode larvae with trophic transmission
Tetraphyllidean:	Tetraphyllidean sp. Cestodes with trophic transmission
GillMetacercariae:	Gill metacercariae. Trematode larvae from the fish's gills with trophic transmission
Microscaphiid:	Microscaphiid sp. Trematodes with trophic transmission
Lepeophtheirinae:	Lepeophtheirinae sp. Copepods with direct transmission
Hatschekia:	*Hatschekia* sp. Copepods with direct transmission
Ancyrocephalid:	Ancyrocephalid sp. Monogenean with direct transmission

- parasite_class: Classification of the parasite into the groups shown in Figure 3.
  cest: cestodes
  cope: copepods
  mono: monogeneans
  nema: nematodes
  trem: trematodes

- transmission: Transmission type. Either: "trophic" or "direct"

- count: The number of each parasite within that specific fish.

DATA QUESTION SIX: What does each row correspond to? Explain why there are multiple rows with the same unique fish ID.

3. In the next section, you'll be calculating the mean abundance and the standard error of the mean for the abundance of each parasite within each host, on both fished and unfished islands.

DATA QUESTION SEVEN: Which data columns do you think will be most important for these calculations? Which columns will most likely not be used?

Data Analysis & Visualization

1. Make a table of the mean ± standard error of the abundance of each parasite for each parasite taxon/fish species combination. Include rows for "Unfished," and "Fished" islands. For each parasite, you should note underneath it whether it is directly transmitted or trophically transmitted. You should make one table for each fish species.

   Example:

Table 1. *Acanthurus nigricans* mean parasite abundance ± standard error for unfished islands and fished islands.

	Gill Metacercariae	**Neobenedenia**
Transmission	Trophic	Direct
Unfished	6.28 ± 1.37	
Fished		

- Mean abundance ($\bar{x}$) is the average number of parasites per fish. It can be calculated by taking the sum of all the individual observations (x_i) and dividing by the number of observations (*n*). In Excel, you can type the command "=average()" and then select the cells you'd like to see the average of.

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$$

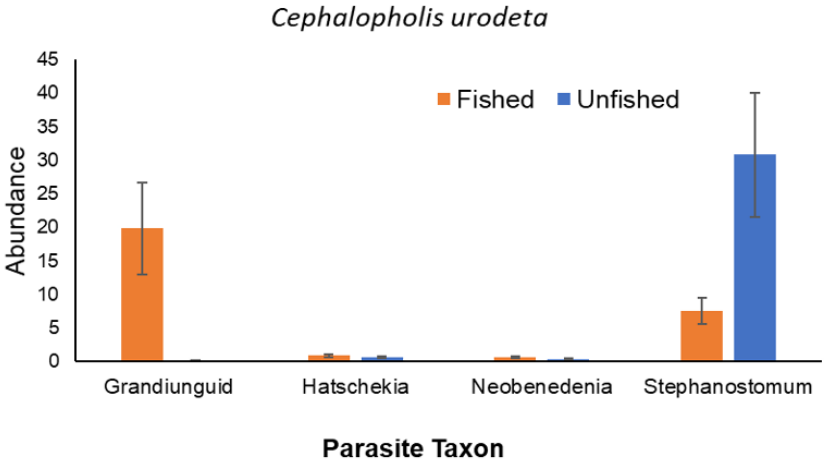
- Standard error allows us to estimate the accuracy of our mean value. To calculate standard error, you first need to calculate the variance and standard deviation. First, you calculate the difference between the mean ($\bar{x}$) and each individual observation (x_i) and square that number. You then sum these squared differences and divide that by the number of samples minus one to get the variance. The standard deviation is the square root of the variance. The standard error is the standard deviation divided by the square root of the number of samples. In Excel, you can type the command "=stdev()/sqrt(count())" and within each (), select the cells you'd like to see the standard error of.

  Standard error = (standard deviation)/square root (sample size).

$$\frac{\sqrt{\frac{\sum_{i=1}^{n}(\bar{x} - x_i)^2}{n-1}}}{\sqrt{n}}$$

2. Plot mean ± standard error for each parasite taxon/fish species combination in both fished and unfished islands. To make a bar chart in Excel, you can select the cells with the data you'd like to plot. You then click insert along the top ribbon, followed by 2D column within the chart area. You can add your calculated error by clicking the "Chart Elements" button on the right of the chart (it looks like a plus sign). From there, click "custom" and select the values you'd like to appear as error bars. If you're unsure how to make the plots, Microsoft Office has an excellent help section which can guide you in the right direction, or you can search the internet for tutorials on making plots in your preferred spreadsheet software application.

Example:



*At the end of the session, you should have tables and charts for each fish species, as well as answers to the data questions.

DISCUSSION AND CRITICAL THINKING QUESTIONS

Answer the following questions based on the data you have generated.

1. Describe how fishing changes the mean parasite abundance. Give some examples from your results.
2. In the charts you made, you noted whether parasites were trophically transmitted (cycle through many hosts who eat each other) or directly transmitted (passed through the environment with fewer hosts). Looking at your summary data and the charts you've produced, does the impact of fishing differ between directly and trophically transmitted parasites? Do you notice any trends? Why do you think that you are seeing these patterns?
3. Did all host species have similar numbers of parasite taxa and abundances present? If there are differences, what about the hosts or parasites could cause them (consider reviewing Figure 2 and 3 in Background)? If there are no differences, provide one or two reasons that specific associations between parasites and their hosts may not happen?
4. These fish were collected by scuba divers underwater, brought to the surface, frozen, and then brought back to the lab to be dissected. How could collection methods alter the results? Which of the steps above could change the findings?
5. There were data columns that you did not use for the above calculations. Come up with a question that you could answer with the additional data that was collected. Do you think it's an interesting or helpful question for the researchers to ask? Why or why not?
6. Are there any additional data you would have collected within this study? Could any other stressors or environmental variables be linked to the patterns seen in the parasite communities?
7. These samples were collected in 2010. If these data were collected again today, do you expect the same patterns to be seen or would there be changes? If not, why not and if so, why?

FURTHER EXPLORATION

For more background information about this study and a more in-depth discussion of results, read:

- Wood, C.L., S.A. Sandin, B. Zgliczynski, A.S. Guerra, and F. Micheli. 2014. Fishing drives declines in fish parasite diversity and has variable effects on parasite abundance. Ecology

95(7):1929–1946.

- Wood, C.L., J.K. Baum, S.M.W. Reddy, R. Trebilco, S.A. Sandin, B.J. Zgliczynski, A. Briggs, and F. Micheli. 2015. Productivity and fishing pressure drive variability in fish parasite assemblages of the Line Islands, equatorial Pacific. Ecology 96(5):1383–1398.

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