CourseSource

Lesson

Marsh Madness: Using Video Games and a Case Study to Explore Food Webs and Ecosystem Services in Carpinteria Salt Marsh Reserve

Aislyn A. Keyes[1,2°†*], Laura E. Dee[1†], Jacob T. Wright[3°], Kendi F. Davies[1†], Stephanie K. Polutchko[1†], Mariana Bastias[1††], and Lisa Corwin[1†]

[1]Department of Ecology and Evolutionary Biology, University of Colorado Boulder

[2]Bigelow Laboratory for Ocean Sciences

[3]Recurse Center

[°]A.A. Keyes and J.T. Wright designed the video game with input from L.E. Dee. J.T. Wright executed all aspects of coding and development for the video game.

[†]A.A. Keyes, L.E. Dee, and L. Corwin developed the initial lesson plan with extensive feedback from K.F. Davies and S.K. Polutchko. A.A. Keyes, L.E. Dee, L. Corwin, K.F. Davies, and S.K. Polutchko wrote the manuscript.

[††]M. Bastias translated all the lesson plan materials and video game into Spanish.

Abstract

As the complexity and interconnectedness of our world increases, we are continually expected to be capable of complex, non-linear thinking in order to successfully tackle and solve the challenges we face in the 21st century. Tackling these challenges requires "systems thinking," in which problem solving must consider interconnected components within a whole to solve complex problems. However, high school and undergraduate training often focus on linear cause-and-effect relationships, failing to help students develop a systems approach to problem solving. Food web ecology lends itself well to developing systems thinking skills, as species depend on one another for resources, form complex systems, and provide benefits to society, known as ecosystem services. We developed a case study based on Carpinteria Salt Marsh Reserve that incorporates both active- and game-based learning to teach students about socio-ecological systems and food web ecology and to use systems thinking. This case study was designed for two 75-minute class periods and uses a freely available web-based game developed by the authors. The case introduces food web ecology and ecosystems services, and as such, it is helpful if students have basic knowledge of food webs prior to the case. After implementing this case study in an undergraduate introductory ecology course, we found that students often (i) improved their content knowledge regarding food webs and ecosystem services, (ii) recognized the importance of species interactions and direct/indirect threats for ecosystem services, and (iii) considered multiple types of information to make decisions.

Citation: Keyes AA, Dee LE, Wright JT, Davies KF, Polutchko SK, Bastias M, Corwin L. 2024. Marsh Madness: Using Video Games and a Case Study to Explore Food Webs and Ecosystem Services in Carpinteria Salt Marsh Reserve. CourseSource 11. https://doi.org/10.24918/cs.2024.5

Editor: Nathan Emery, University of California, Santa Barbara

Received: 3/30/2023; **Accepted:** 11/29/2023; **Published:** 3/12/2024

Conflict of Interest and Funding Statement: A.A. Keyes acknowledges funding from the University of Colorado Office of Outreach and Engagement, the National Science Foundation Division of Ocean Sciences INTERN Supplemental Funding (NSF OCE 2226531), and P.E.O. L.E. Dee acknowledges funding from the National Science Foundation Division of Ocean Sciences (NSF OCE 2049360). None of the authors have a financial, personal, or professional conflict of interest related to this work.

*__Correspondence to:__ Email: akeyes@bigelow.org

Learning Goals

This case study is designed to improve students' "systems thinking" which is a multidimensional skill and consists of integrated knowledge of systems concepts and ability to use networks in making decisions. Below we indicate which learning goals contribute to systems thinking with the abbreviation (ST) at the end of the associated goals.

Students will:

1. model ecological networks that depict species and their interactions, and how these types of networks are useful tools in ecology and conservation (ST).
2. evaluate the importance of species interactions by predicting how an ecosystem will respond to threats (ST) and modeling potential responses.
3. analyze the role of species interactions in ecosystem services (ST).

From the Ecology Learning Framework:

A. How are living systems interconnected and interacting?
B. How do systems change over time?
C. How do humans depend on ecosystems for their health and well-being?

Learning Objectives

Students will be able to:

1. describe how threats impact food webs.
2. predict the direct and indirect socio-ecological impacts of threats.
3. develop hypotheses to test why food webs might respond differently to disturbances.
4. use multiple types of information and consider increasingly complex information to make management decisions (ST).

INTRODUCTION

Today's problems are increasingly complex, calling upon scientists and policy makers to consider multiple perspectives and sources of information to make decisions. Generally, the skill associated with integrating multiple information sources when making decisions is called "systems thinking," which is highly valued when it comes to solving 21st century challenges (*e.g.,* the biodiversity and climate crises; 1, 2). Systems thinking is often characterized as "considering all the parts" and "integrating information" to make decisions (2). In ecology, systems thinking requires consideration of how a set of variables (*e.g.,* species in an ecosystem) are interconnected and dependent on one another (*e.g.,* species interactions in nature; 2–5). We view systems thinking processes as: (i) recognizing distinct pieces of information in a system and describing their position and role, (ii) predicting how a single "part" of a system might impact other "parts" of a system under different conditions, and (iii) using multiple types of information about the parts of a system to make informed management decisions that maximize benefits both to ecosystem function and people who interact with it.

Despite the importance of systems thinking, it is often not adequately integrated into curricula (6). However, two tools can help fill this gap: case studies and game-based learning. The case study approach to teaching engages students in exploring a question or problem from a real-word scenario in a narrative format (5). Typically, group-work-focused cases require that students collaborate to solve complex problems, pushing students to move beyond simple recall to perform analysis, evaluation, and application (5, 7). Additionally, as cases unfold, they often become more complicated, reflective of real-world situations and systems, which pushes students to consider more information and greater levels of complexity in their decision making (*i.e.,* pushing them to engage in systems thinking). Prior investigations have demonstrated that there are many benefits from case-based learning that are useful for teaching systems thinking, including improving students' ability to make connections across areas of content, view issues from multiple perspectives, and appreciate the real-world relevance of the problem scenario (8, 9).

The case study described here further pushes students' systems thinking using an interactive web-based game that builds in complexity as students progress. Paired with reflections and discussion, game-based learning can engage students in system thinking in realistic contexts (9–11). This is particularly useful in an ecological context as species are not isolated but instead interact in diverse ways, creating complex biotic and abiotic systems. Ecological systems influence and are affected by social and economic systems, furthering the complexity that students must grapple with when faced with decision making. In this case study, the video game offers students the opportunity to apply the concepts they've learned, challenging the students to combine information about species, their interactions, and threats to those species to make decisions about which species to protect. Integrating games in the classroom can positively impact students' learning outcomes related to problem solving, knowledge acquisition, and motivation (12, 13). When academic content is embedded within a game and students engage with the game successfully, students can apply their knowledge in new ways (12). The video game described herein provides a useful tool for students to practice their systems thinking, apply what they've learned, and develop a deeper appreciation for the challenges associated with managing complex systems.

In this lesson, we develop students' system thinking skills using food webs and ecosystem services. Food webs (*i.e.,* descriptions of who-eats-who in an ecosystem) and the ecosystem services that food webs support represent complex

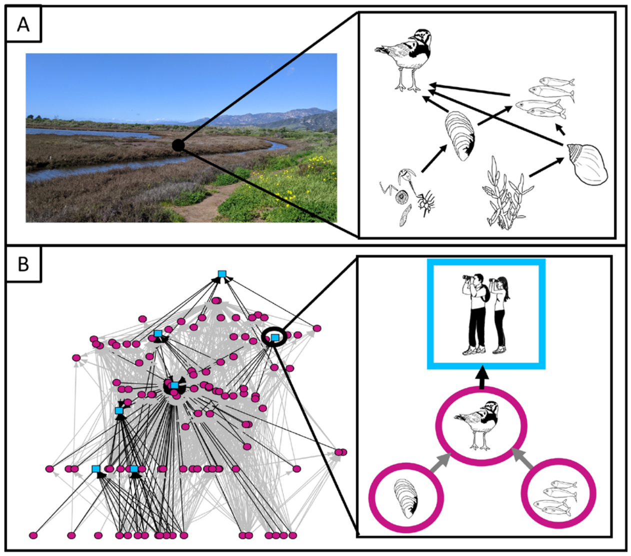

Figure 1. Representing food webs as ecological networks. **(A)** Ecosystems are made up of many interacting species. **(B)** We can represent food webs and services (*e.g.,* birdwatching) as networks. Pink circles and blue squares represent species and services, respectively; grey and black lines represent species eating other species and species providing services, respectively.

socio-ecological systems. These complex systems require that students integrate knowledge of structure and function and apply their knowledge to real-world coastal management problems (1). We use Carpinteria Salt Marsh Reserve (hereafter 'Carpinteria Reserve') for this case study because it is an excellent example of a complex socio-ecological system. First, Carpinteria Reserve is home to over 100 species and over 1,000 trophic interactions, forming a complex ecological system (Figure 1; 14). Second, the salt marsh provides multiple ecosystem services to a diverse group of stakeholders, including the University of California, the city of Carpinteria, CA, USA, homeowner associations, the Southern Pacific Railroad, individuals, private companies, and military bases. Each of these groups interacts with and relies on the salt marsh, adding a layer of social complexity to the system (15). Finally, Carpinteria Reserve is vulnerable to human-driven disturbances; each of these disturbances alters the state of this socio-ecological system, and local stakeholders and land managers are often called upon to make decisions about how to manage these threats (15).

We used cyclical curriculum development (*i.e.,* where lessons are designed, tested, evaluated, and revised) across two pilot studies. The results reported in this publication are from the third iteration of this lesson. This lesson includes active learning, game-based learning with a web-based video game, and real scientific practices, such as ecological network analysis. We assessed student outcomes related to systems thinking. Many students demonstrated improvement in (i) content knowledge regarding food webs and ecosystem services, (ii) ability to describe the importance of species interactions and direct/indirect threats for ecosystem services, and (iii) ability to consider multiple types of information to make decisions.

Intended Audience

We designed this lesson for broad range introductory ecology or biology courses at any large research university. It can also be used in smaller liberal arts and community college classrooms, and advanced high school science classrooms. We tested multiple versions of this lesson in the Principles of Ecology course at the University of Colorado, Boulder where students ranged in undergraduate education level (*i.e.,* first year to senior class standing). One instructor and 3–4 undergraduate learning assistants were sufficient instructional staff for a class size of 60–100 students. One high school teacher tested this lesson in a high school environmental science class of 15 students without learning assistants.

Required Learning Time

The final version of this case study is two 75-minute sessions, with minimal work expected outside of the classroom.

Prerequisite Student Knowledge

Students should have skills in using a web browser and a collaborative slide program such as Google Docs or PowerPoint. Students should have **basic knowledge** of what a species is and that species have basic biological needs (*e.g.,* species require food to acquire energy); they should also be able to describe what an ecosystem is. This case study is meant to serve as an introduction to food web ecology and species interactions, concepts of direct and indirect threats to species embedded in complex ecosystems, and ecosystem services.

Students should also have familiarity with foundational science practices such as such as creating a hypothesis, developing and using models, and analyzing and interpreting data.

Prerequisite Teacher Knowledge

Instructors should be familiar with: model-based instruction and its utility (16), food webs and community structure, and should articulate the difference between direct and indirect effects, and how these relate to the impacts of threats. Instructors should have a basic knowledge of ecosystem services, or nature's contributions to people. Instructors may want to read (17) for an overview of ecosystem services. We provided instructors with a key to the case study and a glossary of key terms (Supporting File S1). We include an 'Introduction to Key Concepts' slideshow in our Food Web Game that also serves as a helpful review of the necessary concepts for this lesson. Instructors could read (18) to see the research that inspired this case study. Lastly, this case study is about a salt marsh ecosystem in Santa Barbara, CA, USA. While instructors do not need to know everything about this location, it would be good to review the Carpinteria Salt Marsh Reserve website.

The instructor should familiarize themselves with the mechanics of the following pedagogies: think-pair-share, multiple hands multiple-voices, assigning reporters for small groups, using varied active-learning strategies, asking open-ended questions and actively avoiding judging responses (19), and game-based learning (10–12, 20). The above citations are places instructors can visit to learn more about these and adapt them for their specific audience.

SCIENTIFIC TEACHING THEMES

Active Learning

We used short periods of lecture to present new information, broken up by active learning strategies including think- and draw-pair-shares (implemented with recommendations from

[19, 21]), followed by whole-class discussion and independent and collaborative student-centered breakout activities. Our student-centered breakout activities for each new concept allowed students to engage with the case, apply systems thinking, and improve their understanding of concepts. These activities filled the majority of class time and included (i) a jigsaw activity in which individuals learn pieces of information about different threats to Carpinteria Reserve, before briefly reporting what they learned in a group discussion, (ii) concept mapping in which students connected key concepts from the case study to each other and (iii) problem solving using an interactive video game in which students manipulated food webs by "protecting" species from removal and simulated disturbances to the system.

Assessment

We assessed how well students achieved the learning objectives with in-class formative assignments (Supporting File S2; 22). Across three in-class activities, students demonstrated their ability to use systems thinking to make predictions, develop hypotheses, and make decisions. These assessments were graded for completion, and students were provided feedback in real-time by the instructor reviewing the correct answers during class time with opportunities for students to reflect (19, 22).

We developed pre- and post-assessments to assess learning gains summatively (22). The pre- and post-assessments are identical (Supporting File S3). Students completed these assessments outside of class before the first 75-minute period and after the second 75-minute period. The pre- and post-assessments are designed to be used by future instructors to assess gains. If summative assessment is needed, the post-assessment scores can be used to assess if individual students met the learning goals for the case.

Inclusive Teaching

We provided ample time for students to complete assignments. We included multiple instances of the 21 strategies (19) for inclusive teaching, including wait time, allowing students time to write, think-pair-share, multiple hands multiple-voices, assigning reporters for small groups, using varied active-learning strategies, asking open-ended questions and actively avoiding judging responses. Each of these strategies promotes classroom participation and equity (19). For example, providing students with ample time to think through questions, write or draw their thoughts, and share with a neighbor gives students a longer time to process information and contribute to the class, thereby increasing equity in who participates and inclusivity of different students' ideas. Without these strategies, a small fraction of students are likely to participate most of the time (19). We also collected assessment evidence from every student and actively used it to inform revisions and make suggestions for future modifications (19, 22). We encouraged collaboration between peers and provided all the materials in advance (22).

LESSON PLAN

This case study is broken up into four main sections (Table 1):

I. Introduction to food webs and the Carpinteria Reserve,
II. Threats to salt marshes,
III. Introduction to ecosystem services at Carpinteria Reserve,
IV. Preserving complex systems amidst threats.

All data reported and analyzed in this lesson plan are from the Fall 2022 semester. This lesson plan is designed for two 75-minute class periods but can be used in shorter or longer class periods. You can watch how we taught this case study to a lecture-style classroom using the two lecture capture videos: Day 1 video and Day 2 video.

Instructors can also teach this case study in three 50-minute class periods or two 90-minute class periods. If you are teaching this case study in three 50-minute class periods, we suggest the following timeline:

- Pre-Case Study Homework: Students should watch video 1 and complete the questions in the Student Activity Packet and complete the pre-assessment.
- Day 1: Students should complete Section I completely and start Section II. By the end of Day 1, students should have completed the 'Threats to salt marsh ecosystems jigsaw'.
- Pre-Day 2 Homework: Students should watch video 2 and complete the questions in the Student Activity Packet.
- Day 2: Students should start Day 2 by completing the CSMR threats systems mapping activity in Section II and finish the day by completing the CSMR ecosystem services system mapping (end of Section III).
- Day 3: Students should complete Section IV and the Check Your Learning (ii).
- Post-Case Study Homework: Students should complete the post-assessment.

If you are teaching this case study in two 90-minute class periods, we suggest a timeline that parallels the two 75-minute class period format, allotting extra time for each activity. We recommend this option for high school classrooms.

Instructor Preparation

We recommend that instructors review all the lesson materials provided here (Supporting Files S1–S7) and the detailed timeline of this lesson (Table 1). Instructors should: (i) ensure students have access to the Student Activity Packet (one per student), (ii) prepare the pre- and post-assessments in your desired format, and (iii) assign students the pre-assessment and the first homework assignment. This case is designed to be taught in-person or remotely. Students can complete all assessments, assignments, and in-class activities digitally. If feasible, instructors should ensure students have access to laptops. The video game is built to be played on a computer (including Google Chromebooks) and will not work on a tablet.

Instructors should review the following materials if they are unfamiliar with any of the topics covered in this case study: (i) 'Introduction to Key Concepts slideshow', (ii) Carpinteria Salt Marsh Reserve website, (iii) Introduction to food webs as ecological networks video, (iv) Introduction to ecosystem services video, and (v) the Instructor Resources (Supporting File 1). For more in-depth background on the research that underscores this case study, instructors should read (18). Instructors should also play around with the Food Web Game prior to Section IV to better understand the mechanics and concepts.

We provided answer keys for the pre/post assessment and all in-class activities in Supporting File S1.

Pre-Assessment

We used pre- and post-assessments to assess student learning for this case study. These assessments aim to measure students' content knowledge regarding indirect effects in food webs, as well as their ability to predict direct and indirect impacts of threats on food webs and ecosystem services.

Instructors can choose to only assign the post-assessment after the case study if they wish to grade students on correctness and do not wish to assess gains. We assigned the pre-assessment to be completed outside of class before section I. You could have students complete this assessment in class if you have time.

Homework: Introduction to Food Webs As Ecological Networks Video and Questions

Prior to Section I, we assigned a short homework assignment where students watched a brief video and answered questions. This video reviews food webs and introduces students to more complex food webs that can be visualized and studied as networks. The video is accompanied by two questions that can be found in the Student Activity Packet (pages 2 and 3, Supporting File S2). For our class, we used PlayPosit, which could be linked to our online class hub. However, the videos can be accessed on figshare.

Section I: Introduction to Food Webs and Carpinteria Reserve

Mini Lecture, Slides 1–6: Introduction to Case Study and Carpinteria Reserve

Use slides 1–6 from the PowerPoint provided (Supporting File S4) to introduce students to the case study. Start the case study with a draw-pair-share to engage students in the topics. Students should reflect on and sketch a food chain or food web they have either observed or been a part of recently. Encourage students to think outside the box. Students should draw their food chain (there is space to sketch on page 4 of Supporting File S2) and share it with their neighbor before a few people share out with the entire class. This brief activity helps get students excited about and ready for the content of the class period (22).

Next, describe how the case study is based on research from the University of Colorado and uses real data that is used to manage the complex socio-ecological system at Carpinteria Reserve (14). Slides 3–6 help place students in the system by broadly describing salt marsh ecosystems and the Carpinteria Reserve. Instructors should show *The Carpinteria Salt Marsh Reserve* video included in the notes for slide 5 (with written permission from director, Dr. Andrew Brooks).

Breakout: Building the Carpinteria Salt Marsh Reserve Food Web

This activity is meant to help students think about and visualize complexity in trophic interactions, and to build their understanding of the complex system using concepts they are familiar with.

This breakout activity is Step 1 in the CSMR System Mapping (Supporting File S5) activity (page 5, Supporting File S2). By the end of the case study, students will have created a system map of the Carpinteria Reserve system that includes the food web

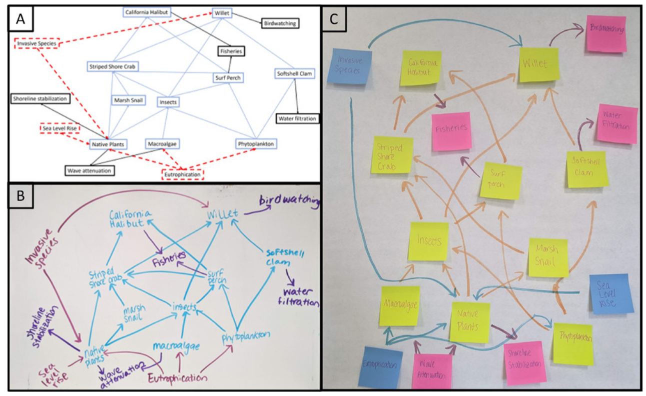

Figure 2. The CSMR System Map Activity can be completed in different ways. Students can build their system map **(A)** digitally in PowerPoint, **(B)** on a whiteboard with dry erase markers, or **(C)** with sticky notes, markers, and big paper.

(*i.e.,* a subset of the species and their trophic interactions), the threats to the food web and the ecosystem services provided by the food web. Step 1 focuses on building the food web only.

For Step 1, have students form groups of 3 and open the CSMR System Mapping PowerPoint (Supporting File S5; also linked in section I of Supporting File S2) on their computer (one per group is sufficient). In-depth directions are provided on slide one; students should use the organism descriptions on slide 3 to build the food web. On slide 4, students will rearrange the text boxes and connect them with arrows that point from resource to consumer to create a food web. After students complete their food webs, bring the class back together for a brief, 2-question discussion and review. If students feel comfortable, they can share their food webs with those around them before starting a class discussion.

Questions to pose to students during class discussion:

- How did you organize the species in your food web?
- Did you notice any patterns in the food web?

In our class, students completed this activity in a PowerPoint presentation, but you could also do this on paper or Google Slides (*e.g.,* Figure 2).

Section II: Threats to Salt Marsh Ecosystems

Mini Lecture, Slides 8–14: Direct and Indirect Threats

Use a think-pair-share (slide 8, Supporting File S4) to start Part II and gauge your students' background knowledge about threats to ecosystems. If anyone feels confident about their definition of direct and indirect effects, invite them to share with the class. Then, with this information, review direct and indirect effects and threats using slides 9–12 (Supporting File S4). We have included drawings on slides 9–12 (completed by Keyes) and examples relevant to the study system. You can prime the students for the next activity by revisiting their food web system from Section I (slide 14, Supporting File S4).

Questions to pose either for discussion as a group or with a neighbor:

- Revisiting our food web from earlier, which species was the most connected?
- What might happen if that species was lost?

Breakout: Threats to Salt Marsh Ecosystems Jigsaw

This activity is meant to help students apply their knowledge about direct and indirect threats to the case study system. They learn about threats by reading and teaching each other.

In this jigsaw activity, individual students will each learn about a different topic before sharing it with their group (pages 6–9, Supporting File S2). Again, break students into groups of three (it is beneficial if these are the same groups from the first breakout activity). Each student will select one of three threats to the reserve (*i.e.,* eutrophication, sea level rise, and invasive species) such that at least one person covers each threat. Students should read the short passage about their threat and then answer questions 1–4 on their own (activity starts on page 6 of Supporting File S2). After students complete questions 1–5 independently, have them share what they learned with their group before completing question 6 together.

Discussion questions:

- What types of species are impacted by each threat? Do some threats only impact species that are low or high in the food web?
- Are certain types of species impacted by multiple threats?
- How many species does each threat directly impact?
- Do you think that some threats will have a greater **indirect** impact than direct?
- What is the reserve doing to address these threats? Did you find that any solutions overlap with each other across threats?

Have students stay in their groups for the discussion, since they will be working together for the next breakout activity.

Breakout: Threats System Mapping

This activity is meant to continue building and applying students' knowledge of the case study system and concepts covered in class by engaging them in systems thinking to identify connections between threats and their impact on the food web.

This breakout activity is Step 2 in the CSMR System Mapping (page 10, Supporting File S5) activity. For Step 2, have the students re-open the CSMR System Mapping PowerPoint that they created in Section I on their computer (one per group is sufficient) or return to their paper system maps. Students should use the threat descriptions on slide 5 and their new knowledge from the jigsaw activity to add the threats to the food web on slide 4 (in-depth directions are provided on slide 1). Students should copy and paste the three red text boxes from slide 5 onto slide 4, then connect them with arrows to the species that they **directly** impact. Arrows should point from the threat to the species that it directly impacts. Remind students that the threat text boxes and arrows should be in a different color than the species and trophic interactions.

After students have added the threats to their map bring the class back together for a discussion or check in with the small groups. You can have students share out how it went and address any confusion and/or you can share the key with students on slide 17 (Supporting File S4).

Think-Pair-Share (Slide 18)

After completing Step 2 in the CSMR System Mapping, you can do a think-pair-share (Obj. 3):

- When considering indirect impacts in each of the food webs, what did you notice about how the effect of a threat spreads throughout an ecosystem?
- How might the impact of threats differ based on the food web complexity of that ecosystem?

Check Your Learning (i)

After completing Section II, students should complete their first "Recommendation for management" (pages 11–13, Supporting File S2). This assessment is completed twice over the course of the case study, once after Section II and once after Section IV. By having the students complete the assessment twice, you can assess whether their thinking changes after acquiring new information and applying their knowledge in different ways. We had students complete this assessment at the end of the first 75-minute class period, but it could also be assigned outside of class.

In this assessment, students are provided with a simplified version (*i.e.,* a fraction of the species and interactions) of the Carpinteria Reserve food web that includes species name, type (*e.g.,* bird, fish, crustacean, etc.), and biomass (based on data from [14]). Students must select two species from this food web to protect. Phytoplankton is included in this food web but is not an option for species to protect because they are not likely to be lost from the ecosystem. Students then list which factors they considered when identifying a species to protect and provide a detailed justification for their choice. Students were not provided with a pre-defined list of factors to consider and were instead encouraged to draw on information from Sections I and II of the case study. Based on our experience teaching this case study, we have modified the format of this assessment to be easier for instructors to assess learning.

Students who do not finish by the end of class must finish it outside of class before class 2. We graded this assessment based on completion as there is no wrong answer. We used qualitative codes (see *Teaching Discussion*; Supporting File S6) to analyze how student thinking changed, if at all, from class 1 to class 2.

Homework: Introduction to Ecosystem Services Video and Questions

Prior to Section III, we assigned a short homework assignment where students watched a brief video and answered questions. This video introduces students to ecosystem services, or nature's contributions to society. The video is accompanied by two questions that can be found on page 14 of the Student Activity Packet (Supporting File S2). We assigned this to be completed outside of class before Section III, but you could have students complete this in class if you have time.

Section III: Introduction to Ecosystem Services at Carpinteria Reserve

When taught in two 75-minute sessions, Section III is the start of class session 2.

Mini Lecture, Slides 20–23: Introduction to Ecosystem Services at the Reserve

Start Section III with a think-pair-share (slide 20, Supporting File S4) to engage students in the topics of the class period:

> Ecosystem services are the benefits that nature provides to people. These ecosystem services are provided by species and ecological communities. There are many types of ecosystem services, from food production to pretty views and carbon storage. With your neighbor, reflect on 1–2 benefits that you have gotten from nature. Discuss specifically how the organisms or ecosystems provide those benefits.

Slides 21–23 introduce students to the specific ecosystem services at the Carpinteria Reserve. First, students are asked to brainstorm which ecosystems services are important at CSMR, based on their knowledge of the food web and a map of the 1996 management plan for Carpinteria Reserve (included with permission from director, Dr. Andrew Brooks). Then they are introduced to the most common ecosystem services in the system, which are referenced later in Section IV.

Breakout: Ecosystem Services at the Carpinteria Reserve

This activity is meant to continue building and applying students' knowledge of the case study system and concepts covered in class by engaging them in systems thinking to identify connections between ecosystem services and their dependence on species in the food web.

This breakout activity is the final step (Step 3) in the CSMR System Mapping (Supporting File S5) activity. For Step 3, students open their CSMR System Mapping PowerPoint on their computer (one per group is sufficient). Students should add the ecosystem services to their system map on slide 4 using the descriptions of five ecosystem services on slide 6 (in-depth directions are provided on slides 1 and 6). Students should copy/paste the three black text boxes from slide 6 onto slide 4, then use arrows to connect the ecosystem service to the species that provides the ecosystem service (known as ecosystem service providers; 17). Arrows should point from the species to the ecosystem service. Remind students that the ecosystem service text boxes and arrows should be in a different color than the species, threats, trophic interactions, and direct threat impacts from Steps 1 and 2. After completing this Step 3, students should take a screenshot of their system map and add it to page 15 of their Student Activity Packet (Supporting File S2).

We graded this activity based on the number of elements (*i.e.,* species, threats, and ecosystem services) and connections (*i.e.,* trophic interactions, direct threat impacts, and species providing ecosystem services) that students included. If students included all species, threats, and ecosystem services and identified 70% of the connections, they received full credit. If they did not include all the elements and identified less than 70% of the connections, they received partial credit. Alternatively, students could review their peers' work and compare/contrast their maps. We included the key on slide 25 (Supporting File S4).

Section IV: Preserving Complex Systems Amidst Threats

Mini Lecture, Slides 26–28: Introduction to the Food Web Game

You will now introduce the Food Web Game (Figure 3) to students. This game is inspired by actual research (*e.g.,* 17) and uses the same Carpinteria Reserve food web data (14) referenced throughout the case study. The slides provide an overview of the goal of the game and how to play it. A more detailed explanation is included in the game tutorial.

Breakout: Playing the Food Web Game

The Salt Marsh version of this game has seven levels, which are increasingly complex and therefore more challenging. Each level of the game uses the same food web data but group species in different ways. The overall goal of the game is to maintain ecosystem services. Students are given a different objective (*e.g.,* maintain the recreational fisheries) and a different disturbance threatens the food web at each level. This threat will **directly** impact some species (*i.e.,* cause the species to be removed from the food web), and other species will be **indirectly** impacted (*i.e.,* if a species loses its food source, it will be removed from the food web). At each level, students must decide which species to protect to achieve the objective.

After introducing the game, students should play independently or in pairs. They should also answer the reflection questions on pages 16–17 of their Student Activity Packet (Supporting File S2) while completing levels 1–4.

Remind students that ecologists use similar models to understand and predict what will happen when a species is protected or lost from an ecosystem, and that this game is a valuable tool for science communication. This breakout activity provides students with the opportunity to apply everything that they have learned from the case study. It also prompts students to grapple with complexity (*i.e.,* engage in increasingly challenging systems thinking) by gradually introducing additional system impacts and factors. This activity encourages students to reflect on the challenges of making decisions about complex systems with varying levels of information. Further, this game is an excellent tool to discuss tradeoffs with students, an important aspect of conservation. For instance, you can win some levels by maintaining ecosystem services but losing most of the species in the food web, exemplifying the challenge of achieving multiple objectives.

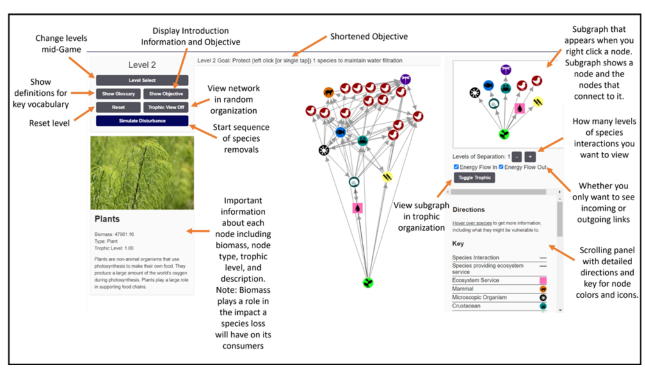

Figure 3. Overview of game functions. This screenshot of the main game screen describes each of the buttons needed to successfully play a level, as well as an overview of the different types of information available to students.

Food Web Game Discussion

After students have had the opportunity to play the game and answer the questions, bring them together, or check in with them individually, for a discussion of how it went.

Pose the following questions to your students (slide 30, Supporting File S4):

- Did anything strike you as strange as you were playing the game?
- What types of information did you consider for each level, how did you decide what to prioritize and what information was useful?
- Did the increasing complexity change your approach?

Some potential responses to these questions (and good things to point out to your students include):

Potential response: You can still win the level even if you lose most of the species in the food web.

Teaching point: This highlights tradeoffs! In conservation, you often must make choices that benefit some species and harms others. Sometimes, you can have win-win scenarios when protecting one species for an ecosystem service also helps others (23). Other times, you need to decide whether the service is more important to maintain than certain species.

Potential response: You can win some levels by protecting the raccoon, but we recognize that raccoons don't need protection.

Teaching point: This is a perfect example of how models (like the Food Web Game) are abstractions of reality and that while this is a useful tool for engaging with complex systems, it does not capture everything that is happening. Models are helpful, but imperfect.

Mini Lecture, Slide 31: Managing the Carpinteria Reserve

After playing the game, many students will be curious about how complex systems like the Carpinteria Reserve are managed. We spoke with the reserve's director, Dr. Andrew Brooks, to get more insight into this. Use slide 31 to describe some of the ways that real managers at the reserve use the same data that the students used in the game to manage the reserve.

Check Your Learning (ii)

After completing Section IV, students should complete their second "Recommendation for management" (pages 18–20, Supporting File S2). This assessment is identical to the first "Check your learning (i): Recommendation for management" but includes two additional reflection questions.

We graded this assessment based on completion, as there is no wrong answer. We used qualitative codes (see *Teaching Discussion*; Supporting File S6) to analyze how students' thinking changed from class 1 to class 2, with the expectation that students might more frequently mention what was covered in the second-class period. This allowed us to develop a more nuanced understanding of how students were thinking for the purpose of this publication. To streamline this process, we have updated the Check your Learning assessment in the Student Activity Packet.

Post-Assessment

We assigned the post-assessment as homework. The post-assessment is the same as the pre-assessment and can either be linked to the pre-assessment to assess learning gains or be assigned on its own to assess student knowledge.

Extension Activities

There are several extension activities that instructors could pair with this case study. First, since this lesson plan requires that students only complete levels 1–4 of the Food Web Game, instructors could build in time for students to work on the higher levels (levels 5–7) which are much more challenging. Second, in an upper-level class, instructors may have students read and discuss the paper (18) for the research that inspired this case study. Third, instructors could have students interact with and explore the data files used in the Food Web Game (14, 24) to learn more about the structure of network data. Finally, the code that supports the Food Web Game is available on GitHub and can be downloaded to teach students about game development and computer science.

TEACHING DISCUSSION

In this case study, we used active- and game-based learning to teach students about food webs and ecosystems services while helping them to develop systems thinking skills. We found that upon completion of this case study, students (i) improved their content knowledge regarding food webs and ecosystem services (Figures 4 and 5, Table 2), (ii) were better able to recognize the importance of species interactions and direct/indirect threats for ecosystem services (Figure 6, Table 3), and (iii) could consider multiple types of information to make decisions using systems thinking (Figures 6 and 7, Table 3). Notably, the case study and game-based design of this lesson contributed to these outcomes by immersing students in a narrative that aligns with the course content, allowing students to build skills and knowledge, and transferring them as the levels progressively get more challenging (20). Below we organize this teaching discussion according to three components: pre-post assessments, in-class assessments (*i.e.,* Check Your Learning), and finally in-class activities. Within each of these we discuss the main findings regarding students' learning and overall experience during the case study.

Pre- and Post-Assessments

The pre- and post- assessments consisted of four questions. The first two questions asked students about content while question three and four focused on systems thinking skills (*e.g.,* predicting the direct and indirect impacts of a threat). We analyzed the pre- and post-assessments using chi-squared and paired t tests (Table 2). We analyzed the two sections separately (n = 30 in section A; n = 36 in section B) because the sections varied in classroom environment (in one section, students were seated in groups at round tables and in the other section, students were seated in a lecture format), and times of day (one morning and one afternoon section).

We found that overall, students improved their content knowledge regarding indirect effects to food webs and ecosystem services (Learning Goals 1–3; Society Goal A; Obj.

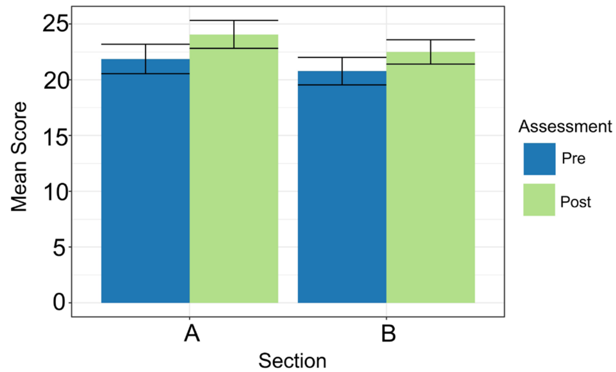

Figure 4. Pre and post assessment scores. Generally, students scored higher on the post-assessment than on the pre-assessment, though there was a ceiling effect.

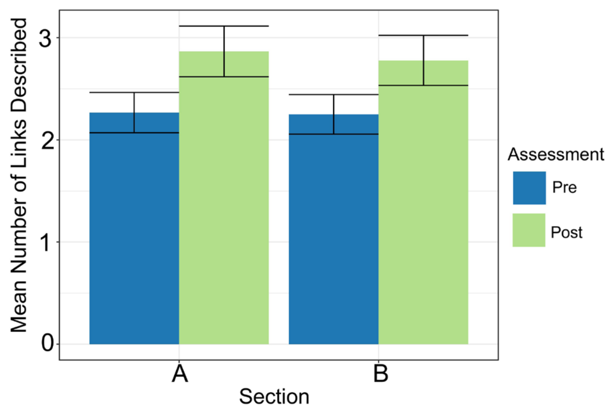

Figure 5. Mean number of links that students described in Question 4. Bars show the mean number of connections that students described. Error bars show the standard error. The maximum number of connections described was 5 on Day 1 and 7 on Day 2.

1–3; Table 2; Figure 4, p = 0.0001 in section A and 0.05096 in section B). Our observations as instructors lead us to believe that these gains in content knowledge were made because of our introduction of food webs and the reinforcement of these concepts in the subsequent activities. For example, students worked with the same food web in increasingly complex ways to explore and understand the nuances of indirect effects. However, our observations of learning were dampened by a potential ceiling effect: in both sections, most students displayed a high level of content knowledge on the pre-assessment with little room to improve on the post-assessment (Supporting File S10). We believe that the pre- and post-assessments were not sufficiently challenging for university-level ecology students and could be made more challenging for future use. However, as written, the pre- and post-assessments are likely sufficiently challenging for high school students.

We also observed evidence of students' systems thinking improving (Society Goals A–C; Obj. 2, 4) over the course of the case study. Systems thinking involves being able to identify more effects within a system, especially indirect effects. We saw this in question 4, where students were asked to predict what would happen to ecosystem services following the introduction of the European Green Crab (Learning Goals 1–3; Society Goal C; Obj. 3). In addition to scoring student responses based on correctness (Table 4, Figure 5, Supporting File S7), we quantified the number of connections that students made (*e.g.,* between species, between a species and environmental conditions, etc.) when making their predictions. Using a paired t test, we found that generally, students made more connections on their post-assessment than they did on the pre-assessment (Table 4, Figure 5, p = 0.053 in section A and 0.092 in section B). Prior to completing the case study, many of the student responses to question 4 were like the following:

> *"The European Green Crab indirectly will decrease the blue mussel population since it is a food source for crabs. This will affect the pH levels of the water."*

Following the completion of the case study, many of the student responses looked like the following:

> *"The introduction of the European Green Crab will indirectly cause the buildup of toxins and bacteria in the water, impacting water filtration. There will also be a decline in the population of species that seek habitat and energy from the Blue Mussel, and the Blue Mussel fishing industry will suffer as well."*

We interpret these results to mean that students were better able to consider the importance of species interactions in multiple ecosystem services and to make predictions about the direct and indirect socio-ecological impacts of threats after completing the case study (Learning Goals 2, 3; Society Goal C; Obj. 2, 3). In particular, the components of the lesson that built these skills were the system mapping activity, threats to salt marsh ecosystems jigsaw, and the food web game. During the implementation of these activities, students learn about the distinct elements in the system, and make connections with how those elements change based on threats. Each of these activities guides students' understanding and prepares them to apply and test their knowledge using the video game. The video game serves as a useful tool for students to practice the systems thinking skills that they have developed throughout the case study and creates an enjoyable environment for students to self-assess what they've learned. Thus, it is likely that these components of the lesson lead to this.

The pre- and post-assessments highlighted areas of confusion by students, however the origin of these misconceptions was unclear. In question 3, students were asked to predict and justify what would happen to five species following the introduction of the European Green Crab (Obj. 1–3). We found that students struggled with two species in question 3: acorn barnacle and rockweed (Supporting File S7). In class, we did not focus on these species, as they are not found in the Carpinteria Salt Marsh. Instead, students were routinely exposed to salt marsh species throughout the case study, which students did not seem to have challenges with. We recommend that future instructors add small activities (*e.g.,* think-pair-share) that challenge students to extend their knowledge to a different system. To improve these outcomes in the future, we recommend that instructors practice a similar exercise in class, where students can practice their justifications with their peers and the class to further develop these skills.

In-Class Assessments

We designed the in-class assessments (*i.e.,* Check Your Learning [i] and [ii]) to understand if students were incorporating new knowledge into their decision making about which species to protect. These assessments consisted of

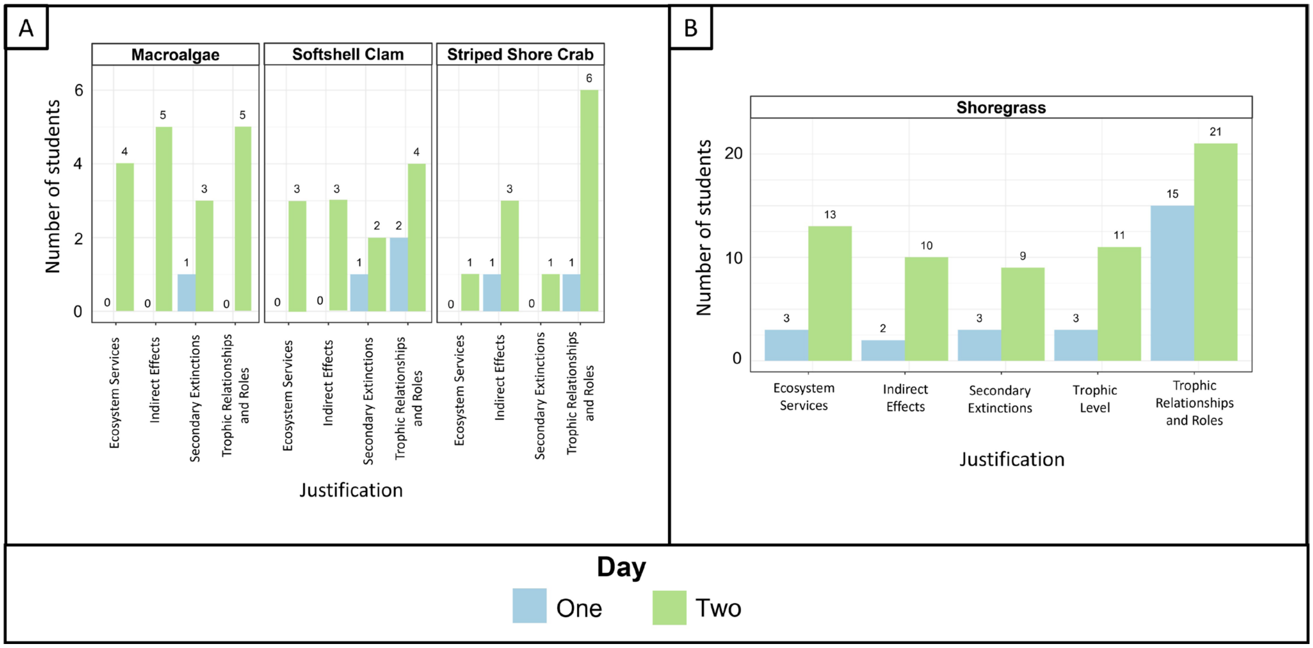

Figure 6. Justification for select protected species. **(A)** In section A, there was a substantial increase in the number of students that protected Macroalgae, the Softshell Clam, and the Striped Shore Crab. There was also a substantial increase in consideration for this subset of justification categories. **(B)** In section B, there was a substantial increase in the number of students that protected Shoregrass. There was also a substantial increase in consideration for this subset of justification categories.

three questions: students had to decide which species to protect, list all the factors they considered, and provide a detailed justification for their decision. To assess how students' thinking changed from Day 1 to Day 2, we coded student justifications for protecting species. First, we reviewed student responses to identify common reasoning behind justifications and then we created categories that reflected the responses. Then, we coded each short answer based on these categories (Supporting File S6).

We found that students shifted which species they protected on Day 1 versus Day 2 (Figure 8) largely due to incorporating concepts taught during the case study into their systems thinking framework (Obj. 4). Most commonly, the concepts that influenced shifts in species protection were (i) knowledge of how a species' position in the food web would affect the food web upon their removal (including knowledge of indirect effects and secondary extinctions) or (ii) knowledge of the

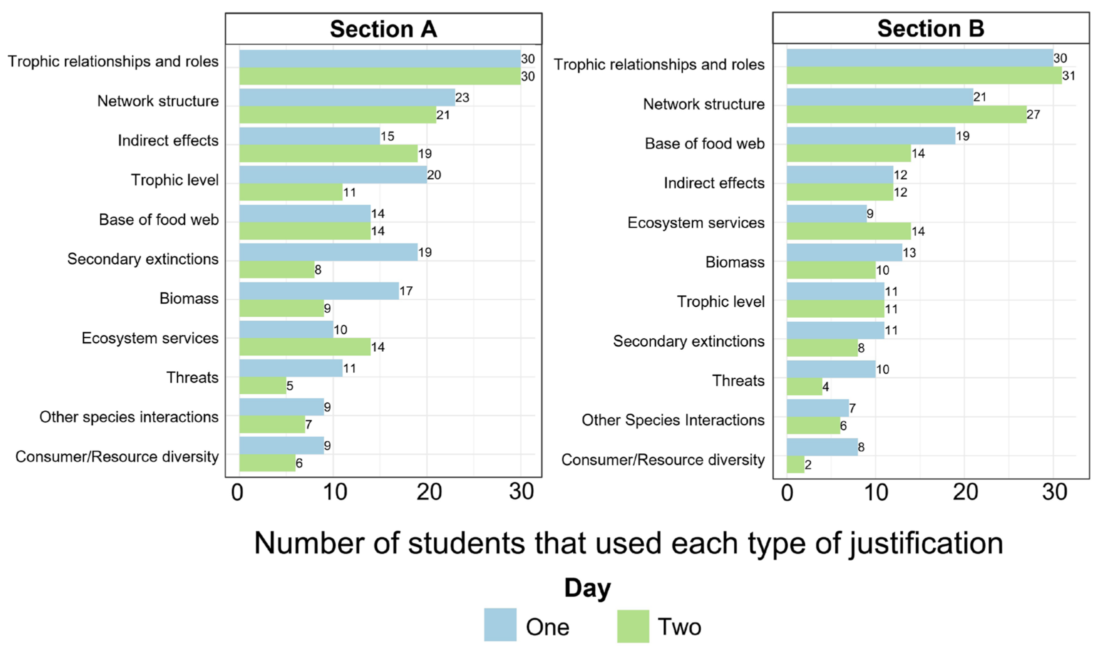

Figure 7. Number of students that used each type of justification. Bars show the number of students that used a given type of justification to protect species in sections A and B. The color shows which day students used each type of justification. Justification types were determined after reviewing students' responses. We categorized their responses by coding them according to the categories that best aligned with their short answers.

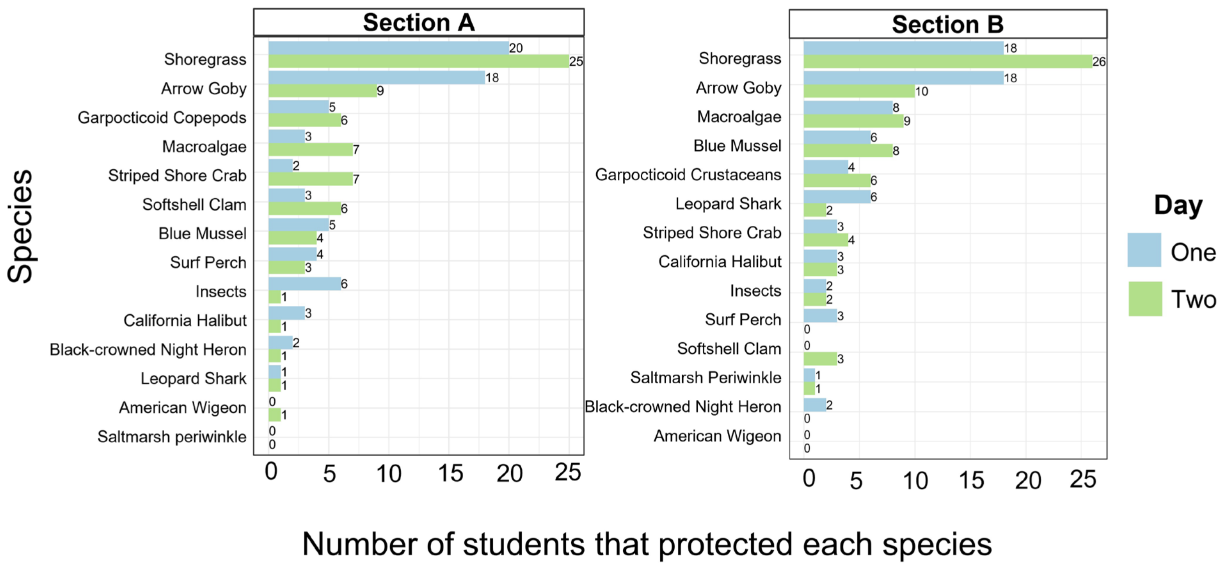

Figure 8. Number of students that protected each species. Bars show the number of students that protected a given species in sections A and B. The color shows which day students selected each species.

ecosystem services the species would provide (Figures 6 and 7). We believe that the video game influenced student gains in this area because the game visualizes the outcomes of students' decisions, allowing them to compare how the protection and/or loss of certain species indirectly impacts other species and ecosystem services. While students can learn about indirect effects without a game, it is a challenging subject to fully comprehend without dynamic visuals, which are a strong suit of game-based learning (12, 20). We noticed that when students were engaged in the game, they were often surprised, frustrated, and more curious when they "lost" a level compared to when they won it. The challenges presented in the game helped students grapple with the complexity of managing real ecosystems and motivated them to try different scenarios.

There is strong evidence that students retain most of the information from the first day of the case to inform decisions during the second iteration of the in-class assignment (Obj. 4). However, one concept, threats, was not frequently utilized by students on the second day (Figure 7). This may be due to the timing of our class discussion. We discussed threats at the end of Day 1, but threats were not revisited on Day 2. Future instructors may consider reminding students of threats to the salt marsh at the start of Day 2. This is somewhat surprising given that the game incorporated threats and that game-based learning literature says that we would expect to see students integrating important concepts in games to their learning (20). However, threats were not the focus of how the students interacted with the game, species removal was. In the game, students are given information about threats, but this information does not remain on the screen after they initiate the level. One way that we could improve the game in the future to better reinforce threats would be to include a brief reminder of the threat similar to how we include a header that briefly describes the objective. Instructors could also further emphasize threats in when describing and introducing ecosystem services on Day 2.

Students did, however, incorporate information presented about ecosystem services on day two into their reasoning, demonstrating their ability to incorporate multiple and new pieces of information into decision making (Table 3; Learning Goals 1–3; Society Goals A–C; Obj. 2, 4). In section A there was a 40% increase and in section B there was a 55% increase in the number of students that considered ecosystem services in their justifications (Figure 7). However, we still see an overall preference for students to discuss food webs (the first day topic) over ecosystem services (the second day topic, Table 5). This may be because this case study reinforced food web concepts more than ecosystem services. For example, the networks displayed in the game, as well as the vast majority of secondary extinctions, are largely comprised of species, with only 1–7 of the nodes depicting ecosystem services on any given level. Thus, the impact of species losses, and the visuals associated with these have less emphasis on ecosystem services based solely on quantity. We believe that this may have influenced the lower consideration for ecosystem services in students' responses. Because many students still did not consider ecosystem services when protecting species (Table 5), instructors may consider further emphasizing ecosystem services and the socio-economic benefits that society receives from protecting species and supporting ecosystems. A limitation of the way we conducted data collection is that we cannot know for sure if students who did not write that they considered ecosystem services or threats actually did not consider them or if they simply did not report on all factors that they considered. Written responses are often limited in this way because students only have a limited time to respond. Our suggested edits to this question would better allow a comprehensive understanding of all the factors students considered.

Overall, we recommend that instructors provide more time to complete the in-class assessment or choose to assign it for homework.

In-Class Activities

This section covers observed student outcomes and student experiences when completing the two of the main break-out activities for the case: CSMR systems mapping and the Food Web Game. We also include suggested improvements based on these observations. For all activities, students reported that directions were easy to follow and were able to quickly engage with each activity with minimal clarification questions. Students appreciated the agency they had, especially in the Threats to salt marshes jigsaw where students selected a threat to become an "expert" on and share their knowledge with their peers.

The CSMR systems mapping activity highlighted challenges students experienced with identifying indirect effects of threats (Obj. 1). In Step 2 of this activity (Threats System Mapping), students faced more of a challenge identifying which species are **directly** impacted by the threats. For example, sea level rise will cause habitat loss for salt marsh specialist species (*i.e.,* endemic fish species or species that are only found in salt marsh ecosystems), and many students will interpret this as a direct threat to those species. However, sea level rise directly affects the plants that provide the habitat. You can reference the first example in slide 12 of the PowerPoint (Supporting File S6) to help make this point for students. Eutrophication can also be tricky for students; eutrophication directly impacts plant species. However, when these plants die off, the decomposition can create low oxygen conditions that can kill fish. This is an indirect threat to fish that follows changing conditions caused by eutrophication. We recommend that instructors walk around the room to see how students are doing with this step and help guide students if they need clarification on the direct and indirect impacts of the threats.

The Food Web Game allowed students to apply the concepts from class and practice systems thinking (Learning Goals 1–3; Society Goals A–C; Obj. 2, 4), especially regarding understanding trade-offs. Using the reflective worksheet, students were able to draw conclusions about how complex socio-ecological systems can be, how conservation decisions can lead to trade-offs, and how scientists and resource managers must balance this complexity when making conservation decisions.

> *"It [the game] made me see how complex the ecosystem really was and better understand that trying to save everything is a challenging endeavor. It's sad to see one region of the food web get knocked out by a disturbance and watch all the unique species in that region disappear, but at the end of the day, there's no solution which leads to the preservation of everything. If you try to protect everything, you end up spreading your resources too thin, and then you solve nothing."*

As is highlighted in the game-based learning literature (11, 12, 20), the emotional responses to the game combined with the integration and application of content increased learning. This is because in game-based learning, students have the opportunity to immediately visualize their thinking, and adapt, building skills and transferring their ideas from level to level (20, 25). The cognitive dissonance introduced when the game does not function as expected gives rise to questions that can help students understand content more deeply. For example, when students win a level—*i.e.,* achieve their objective of maintaining an ecosystem service—but most of the species are lost, students directly experience the complex challenges associated with conservation decision making and are able to recognize multiple solutions (26). Thus, we strongly encourage instructors to draw on students' reflections in the short discussion after playing the game to maximize the takeaways and relevance of the game.

Generally, both because of the game and the discussions afterward, students found the food web game to be the best part of the case study. Many students expressed that the interactive nature of the game allowed them to apply the concepts that they had learned over the course of the case study.

> *"My favorite part of the two-class period was the game because I actually had to think about and apply the concepts that I was learning. Seeing how disturbances can affect a real food web connected the material to the real world which is always something I enjoy. The game gave me a better understanding of how complex the system is."*

Some students may get frustrated as the levels get substantially more challenging and complex. The complexity of the food web can be overwhelming for students as there are many species and interactions in the system. Encourage your students to use the different functions of the game (*e.g.,* subgraph) to digest the network information more easily. Instructors may consider having students pair up or work in small groups to minimize frustration and to encourage collaboration.

Suggestions for Adaptations to Different Courses and Student Populations

Alternative Audiences

We designed this case study for an undergraduate, introductory ecology course. However, the entire case study or individual activities from this case study can be used in a variety of ecology, environmental science, conservation, biology, and network analysis courses at the undergraduate level. For example, instructors could use just the food web game in a conservation class to teach students about trade-offs and win-win scenarios in a more in-depth way than as described here.

In an earlier version of this case study, high school students were able to complete all the activities, though it was more challenging. If instructors want to use this in a high school classroom, we suggest that instructors take more time on each activity and review the concepts regularly with the class. High school instructors may consider having students work in small groups so that students can discuss their ideas with each other.

Alternative Formats

Some students may come to your class already having a strong background in food webs. In these instances, you may consider reducing or omitting the lesson sections on fundamental food web concepts, such as the introductory video and mini lecture.

We taught an earlier version of this case study online during COVID-19. This case study can easily be completed in an online format and could be adapted for an asynchronous class. For an asynchronous class, instructors may remove the group-work aspect of the activities and use discussion boards to facilitate conversations about the assignments and topics covered.

SUPPORTING MATERIALS

- S1. Marsh Madness – Instructor Resources
- S2. Marsh Madness – Student Activity Packet
- S3. Marsh Madness – Pre Post Assessment
- S4. Marsh Madness – Case Study Slides
- S5. Marsh Madness – CSMR System Mapping
- S6. Marsh Madness – Rubrics for Data Analysis
- S7. Marsh Madness – Statistical Test Results

ACKNOWLEDGMENTS

We thank Adam Cohen-Leadholm, Dan Larremore, Meghan Hayden, Lucy Van Kleunen, Anna LoPresti, Katie Peterson, Katherine Siegel, and Henry Li for their feedback on the video game and case study. We thank Andrew Brooks for sharing his knowledge and resources about the Carpinteria Salt Marsh Reserve. A.A. Keyes acknowledges funding from the University of Colorado Office of Outreach and Engagement, the National Science Foundation Division of Ocean Sciences INTERN Supplemental Funding (NSF OCE 2226531), and P.E.O. L.E. Dee acknowledges funding from the National Science Foundation Division of Ocean Sciences (NSF OCE 2049360).

According to the University of Colorado Boulder IRB office, this work (Protocol #22-0152) was exempt from IRB review under categories 1 and 2: data were collected in a common educational setting to study curricula and all data were de-identified.

Table 1. Teaching timeline table.

Activity	Description	Estimated Time	Notes
Before First Class			
Pre-assessment	This brief assessment serves to assess students' learning gains before and after this case study. The assessment is the same for the pre- and post-assessment. It can be completed in class or outside of class but it should be completed prior to watching the video and answering the questions. For the 2x75-min format, we had students complete this outside of class.	10 minutes	The pre-assessment can be found in Supporting File S3. We used Google Forms for this activity, which worked well.
Video and questions: Introduction to food webs as ecological networks	This activity serves as an introduction to food webs as ecological networks. The video is brief (5 minutes, 35 seconds), and there are two questions associated with the material. We had students complete this activity in PlayPosit, but students can watch the video on YouTube and pause to answer the questions. For the 2x75-min format, we had students complete this outside of class.	8–10 minutes	Students can access this activity in their packet, provided in Supporting File S2. The video is on figshare and linked in the packet.
Section I: Introduction to Food Webs and Carpinteria Salt Marsh Reserve			
Think-pair-share	Have students sketch a food web or a food chain that they've seen in the last few weeks. They should include at least 5 organisms and indicate who eats who with arrows. When students are done, have them share with their neighbors. Have 1–3 students share their food chains with the class. This can be done in the student packet or digitally. Encourage students to think outside the box with their food chains.	3 minutes	Slides provided in Supporting File S4. Students can access this activity in their packet, provided in Supporting File S2. They can either draw it directly in the workbook if printed out, or on scrap paper if the workbook is digital.
Introduction to Carpinteria and case study (lecture)	5 lecture slides that introduce students to the case study and Carpinteria Salt Marsh Reserve (CSMR). One of these slides include a video with audio (link in PowerPoint notes) to provide students visual context for the case study's system.	~5 minutes	Slides provided in Supporting File S4.
Building the CSMR food web	In groups of 3–4, students will engage with the community and trophic structure of the CSMR. Have one student per group open the CSMR System Mapping PowerPoint (Supporting File S5) and follow the directions to construct a basic food web for CSMR. This is the first step in the slide deck. Make sure that students stop after completing Step 1.	5–10 minutes	Slides provided in Supporting File S4. Students can access this activity in their packet, provided in Supporting File S2. The slide deck can be found in Supporting File S5. Making observations about trophic interactions and then modeling interactions (what students will do on the second slide) are much like what ecologists do when creating food webs.
Section II: Threats to Salt Marshes			
Think-pair-share	Pose the following question to the students: What do you think of when you hear the terms "direct effect" and "indirect effect"? Students should first think/reflect on their own, then pair up and discuss with their neighbor. Finally ask for a few people to share out with the class.	1 minute	Slides provided in Supporting File S4. Students can access this activity in their packet, provided in Supporting File S2.
Threats to food webs (lecture)	Present lecture slides that briefly review direct and indirect effects and threats to food webs.	2–3 minutes	Slides provided in Supporting File S4.

Activity	Description	Estimated Time	Notes
Threats to salt marsh ecosystems jigsaw	In this activity, students will break out into groups of 3–4. Each student will select one of 3 threats (eutrophication, sea level rise, or invasive species) such that each threat is covered by at least 1 person. Students will read the brief description of their threat then answer questions 1–4 on their worksheet on their own. Then, they will share what they learned with their group before completing the final question 5 in the worksheet.	25 minutes	Slides provided in Supporting File S4. Students can access this activity in their packet, provided in Supporting File S2.
CSMR threats system mapping	Have students return to their CSMR System Mapping PowerPoint in their groups and complete Step 2. In Step 2, students will add the three threats to their food web, connecting them to the species they **directly** impact.	5–8 minutes	Slides provided in Supporting File S4. Students can access this activity in their packet, provided in Supporting File S2. The slide deck can be found in Supporting File S5. Some students will be confused by the direct versus indirect impacts.
Think-pair-share	Pose the following questions to the students: 1. When considering indirect impacts in each of the food webs, what did you notice about how the effect of a threat spreads throughout an ecosystem? 2. How might the impact of threats differ based on the food web complexity of that ecosystem? Students should first think/reflect on their own, then pair up and discuss with their neighbor. Finally ask for a few people to share out with the class.	3 minutes	Slides provided in Supporting File S4. Students can access this activity in their packet, provided in Supporting File S2.
Check Your Learning (i)			
Recommendation for management decision	Students will then complete the first of two “Recommendation for management decision” questionnaires. In this activity, students will have to decide which 2 species to protect in a simplified CSMR food web based on different types of information (*i.e.,* the food web structure, species’ interactions, and species’ biomass). They will select the 2 species and provide justification through 2 additional questions. This can be completed in class or at home but should be completed before the next session. For the 2x75-min format, we had students start this at the end of Day 1 and finish outside of class before Day 2.	10–15 minutes	Slides provided in Supporting File S4. Students can access this activity in their packet, provided in Supporting File S2. We used Google Forms for this activity, which worked well.
Before Section III (second class if using lesson as described for 2x75-min class periods)			
Video and questions: Introduction to ecosystem services	This activity serves as an introduction to ecosystem services. The video is brief (4 minutes, 11 seconds), and there are two questions associated with the material. We had students complete this activity in PlayPosit, but students can watch the video on YouTube and pause to answer the questions. For the 2x75-min format, we had students complete this outside of class before Day 2.	5–8 minutes	Students can access this activity in their packet, provided in Supporting File S2. The video is on figshare and linked in the packet.

Activity	Description	Estimated Time	Notes
Section III: Introduction to Ecosystem Services at CSMR			
Think-pair-share	Pose the following questions to the students: 1. Ecosystem services are the benefits that nature provides society. These ecosystem services are provided by species and ecological communities. There are many types of ecosystem services, from food production to pretty views and carbon storage. 2. With your neighbor, reflect on 1–2 benefits that you have gotten from nature. Discuss specifically how the organisms or ecosystems provide those benefits. Be prepared to share your ideas with the class. Students should first think/reflect on their own, then pair up and discuss with their neighbor. Finally ask for a few people to share out with the class.	3 minutes	Slides provided in Supporting File S4. Students can access this activity in their packet, provided in Supporting File S2.
Ecosystem services at CSMR (lecture)	Present 3 lecture slides that provide an overview of the ecosystem services at CSMR. The first slide shows a map of CSMR. Here, ask students to briefly brainstorm what they think the services are based on the map from the 1996 Management Plan. Have students share their ideas with the class.	5 minutes	Slides provided in Supporting File S4.
CSMR Ecosystem Services System Mapping	Have students revisit their CSMR System Mapping PowerPoint one last time and add the 5 ecosystem services that are relevant to the species in the simplified food web. Remind students that definitions and clues as to which species provide each service are in the slide deck for Step 3.	5–8 minutes	Slides provided in Supporting File S4. Students can access this activity in their packet, provided in Supporting File S2. The slide deck can be found in Supporting File S5.
Section IV: Preserving Complex Systems Amidst Threats			
Introduction to the Food web game (lecture)	Present 3 slides that introduce the core concepts of the Food web game.	3 minutes	Slides provided in Supporting File S4.
Food web game	Students will play the food web game and answer the questions on the worksheet. Students can work individually, in pairs, or in small groups. If your internet bandwidth is low, have students work in pairs or groups on one computer. This game works best on laptops and desktops but can be played on a Chromebook. It will not work on tablets or smartphones.	25 minutes	Slides provided in Supporting File S4. Students can access this activity in their packet, provided in Supporting File S2.
Food web game discussion	Pose the following questions to your students: 1. Did anything strike you as strange as you were playing the game? 2. What types of information did you consider for each level, how did you decide what to prioritize and what information was useful? 3. Did the increasing complexity change your approach?	3 minutes	Slides provided in Supporting File S4. Students can access this activity in their packet, provided in Supporting File S2.
Managing CSMR (lecture)	Present 1 lecture slide that provides an overview of how CSMR, a complex system, is **actually** managed in real life.	2 minutes	Slides provided in Supporting File S4.

Activity	Description	Estimated Time	Notes
Check Your Learning (ii)			
Recommendation for management decision	Students will finally complete the second of two "Recommendation for management decision" questionnaires. In this activity, students will have to decide which 2 species to protect in a simplified CSMR food web based on different types of information (*i.e.,* the food web structure, species' interactions, and species' biomass). They will select the 2 species and provide justification through 2 additional questions. This can be completed in class or at home but should be completed before the next session. For the 2x75-min format, we had students start this at the end of Day 1 and finish outside of class.	10–15 minutes	Slides provided in Supporting File S4. Students can access this activity in their packet, provided in Supporting File S2. We used Google Forms for this activity, which worked well.
After Class			
Post-assessment	This brief assessment serves to assess students' learning gains before and after this case study. The assessment is the same for the pre- and post-assessment. It should be completed after completing Check your Learning (ii). It can be completed in class or outside of class. For the 2x75-min format, we had students complete this outside of class.	10 minutes	The post-assessment can be found in Supporting File S3. We used Google Forms for this activity, which worked well.

Table 2. Pre and post assessment scores. We ran a paired *t* test to assess whether students' assessment scores increased from the pre- to the post-assessment.

Section	*p*	T	Lower 95% Confidence Interval	Upper 95% Confidence Interval	Mean Score (SE) on Pre-Assessment	Mean Score (SE) on Post-Assessment
A	0.0001	-4.0558	-3.285	-1.115	21.867 (4.138)	24.067 (3.908)
B	0.05096	-1.9854	-3.451	0.007	20.778 (4.244)	22.5 (3.772)

Table 3. Justification for protecting species: Chi-squared results. We ran chi-squared tests to see if students' reasoning for protecting species changed from Day 1 to Day 2. For most categories, we did not find that reasoning changed.

Section	Category	X2	*p*	***n*** **students that reported each category on:**	
				Day 1	**Day 2**
A	Base of food web	1.0587	0.3035	14	14
	Trophic level	0.64253	0.4228	20	11
	Ecosystem service	4.1896	0.04067	10	14
	Network structure	0.013992	0.9058	23	21
	Consumer/Resource diversity	0.19388	0.6597	9	6
	Trophic relationships	8.2709e-05	0.9927	30	30
	Indirect effects	2.7624	0.0965	15	19
	Secondary extinctions	2.3261	0.1272	19	8
	Threats	3.9408e-31	1	11	5
	Biomass	0.51953	0.471	17	9
	Other species interactions	0.53968	0.4626	9	7
B	Base of food web	1.0587	0.3035	19	14
	Trophic level	1.3229	0.2501	11	11
	Ecosystem service	3.7523	0.05273	9	14
	Network structure	1.4387	0.2303	21	27
	Consumer/Resource diversity	0.13026	0.7182	8	2
	Trophic relationships	0.18541	0.6668	30	31
	Indirect effects	0.41192	0.521	12	12
	Secondary extinctions	0.15322	0.6955	11	8
	Threats	0.31383	0.5733	10	4
	Biomass	0.020188	0.887	11	12
	Other species interactions	0.17868	0.6725	7	6

Table 4. Students referenced different numbers of connections on Question 4. We ran a paired *t* test to assess whether students referenced more or fewer connections in Question 4 from the pre- to the post-assessment. Most students referenced either the same number of or more connections on the post-assessment.

Section	*p*	T	Lower 95% Confidence Interval	Upper 95% Confidence Interval	*n* students that reported		
					More connections	Less connections	The same number of connections
A	0.0534	-2.014	-1.209	0.009	11	7	12
B	0.0921	-1.732	-1.146	0.091	16	9	11

Table 5. Students weighed food webs more heavily than ecosystem services when protecting species. We ran a chi-squared test to assess whether students weighed maintaining the food web or ecosystem services more when deciding which species to protect on Day 2.

Section	X2	*p*	***n*** **students that were more driven by maintaining:**	
			Food web	**Ecosystem services**
A	7.6087	0.0058	34	10
B	8.0096	0.0047	37	11

REFERENCES

1. York S, Lavi R, Dori YJ, Orgill M. 2019. Applications of systems thinking in STEM education. J Chem Educ 96:2742–2751. doi:10.1021/acs.jchemed.9b00261.
2. Meadows DH. 2008. Thinking in systems: A primer. Chelsea Green Publishing, White River Junction, VT.
3. Ritchie TA. 2017. PhD thesis. Developing and measuring systems thinking skills in students and teachers. University of Florida, Gainesville, FL.
4. Verhoeff RP, Knippels M-CPJ, Gillssen MGR, Boersma KT. 2018. The theoretical nature of systems thinking. Perspectives on systems thinking in biology education. Front Educ 3. doi:10.3389/feduc.2018.00040.
5. Bonney KM. 2015. Case study teaching method improves student performance and perceptions of learning gains. J Microbiol Biol Educ 16:21–28. doi:10.1128/jmbe.v16i1.846.
6. Lee TD, Gail Jones M, Chesnutt K. 2019. Teaching systems thinking in the context of the water cycle. Res Sci Educ 49:137–172. doi:10.1007/s11165-017-9613-7.
7. Herreid CF. 2011. Case study teaching. New Dir Teach Learn 2011:31–40. doi:10.1002/tl.466.
8. Yadav A, Lundeberg M, DeSchryver M, Dirkin K, Schiller NA, Maier K, Herreid CF. 2007. Teaching science with case studies: A national survey of faculty perceptions of the benefits and challenges of using cases. J Coll Sci Teach 37:34–38.
9. Castiblanco Jiméneza IA, Cruz González JP, Ruiz Cruz CR. 2021. Developing systemic thinking through gamification with invention system kits: Case of an aircraft assembly line. Acad Virtualidad 14:23–40. doi:10.18359/ravi.4888.
10. Shah M, Foster A. 2014. Undertaking an ecological approach to advance game-based learning: a case study. J Educ Technol Soc 17:29–41.
11. Kim YJ, Pavlov O. 2019. Game-based structural debriefing: How can teachers design game-based curricula for systems thinking? Inf Learn Sci 120:567–588. doi:10.1108/ILS-05-2019-0039.
12. Perotta C, Featherstone G, Aston H, Houghton E. 2013. Game-based learning: Latest evidence and future directions. NFER Research Programme: Innovation in Education, Slough, England.
13. Sailer M, Homner L. 2020. The gamification of learning: A meta-analysis. Educ Psychol Rev 32:77–112. doi:10.1007/s10648-019-09498-w.
14. Hechinger RF, Lafferty KD, McLaughlin JP, Fredensborg BL, Huspeni TC, Lorda J, Sandhu PK, Shaw JC, Torchin ME, Whitney KL, Kuris AM. 2011. Food webs including parasites, biomass, body sizes, and life stages for three California/Baja California estuaries. Ecology 92:791–791. doi:10.1890/10-1383.1.
15. UCSB Natural Reserve System and the Museum of Systematics and Ecology. n.d. The Management Plan for Carpinteria Salt Marsh Reserve. Carpinteria Salt Marsh Reserve. Retrieved from https://carpinteria.ucnrs.org/foreword.html (accessed 1 March 2024).
16. Svoboda J, Passmore C. 2013. The strategies of modeling in biology education. Sci Educ 22:119–142. doi:10.1007/s11191-011-9425-5.
17. Jones E. 2012. A simple guide to ecosystem services. The University of Aberdeen, Aberdeen, Scotland.
18. Keyes AA, McLaughlin JP, Barner AK, Dee LE. 2021. An ecological network approach to predict ecosystem service vulnerability to species losses. Nat Commun 12:1586. doi:10.1038/s41467-021-21824-x.
19. Tanner KD. 2013. Structure matters: Twenty-one teaching strategies to promote student engagement and cultivate classroom equity. CBE Life Sci Educ 12:322–331. doi:10.1187/cbe.13-06-0115.
20. Bork P. 2012. How video games may enhance students' learning and cognitive development. Int J Technol Knowl Soc 8:43–56. doi:10.18848/1832-3669/CGP/v08i01/56257.
21. Prince M. 2004. Does active learning work? A review of the research. J Eng Educ 93:223–231. doi:10.1002/j.2168-9830.2004.tb00809.x.
22. Sathy V, Hogan KA. 2022. Inclusive teaching: Strategies for promoting equity in the college classroom. West Virginia University Press, Morgantown, WV.
23. Xiao H, Dee LE, Chadès I, Peyrard N, Sabbadin R, Stringer M, McDonald-Madden E. 2018. Win-wins for biodiversity and ecosystem service conservation depend on the trophic levels of the species providing services. J Appl Ecol 55:2160–2170. doi:10.1111/1365-2664.13192.
24. Dee LE, Keyes AA. 2022. Analyzing ecosystem services as part of ecological networks in three salt marsh ecosystems. Ecology 103:e3609. doi:10.1002/ecy.3609.
25. Wong KK. 1996. Video game effect on computer-based learning design. Br J Educ Technol 27:230–232. doi:10.1111/j.1467-8535.1996.tb00690.x.
26. Chuang T-Y, Chen W-F. 2009. Effect of computer-based video games on children: An experimental study. Educ Technol Soc 12:1–10.