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The Bio Bay Game: Three-Dimensional Learning of Biomagnification

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Abstract

Pressing concerns about sustainability and the state of the environment amplify the need to teach students about the connections between ecosystem health, toxicology, and human health. Additionally, the Next Generation Science Standards call for three-dimensional science learning, which integrates disciplinary core ideas, scientific practices, and crosscutting concepts. The Bio Bay Game is a way to teach students about the biomagnification of toxicants across trophic levels while engaging them in three-dimensional learning. In the game, the class models the biomagnification of mercury in a simple aquatic food chain as they play the roles of anchovies, tuna, and humans. While playing, the class generates data, which they analyze after the game to graphically visualize the buildup of toxicants. Students also read and discuss two articles that draw connections to a real-world case. The activity ends with students applying their understanding to evaluate the game as a model of biomagnification. Throughout the activity, students practice modeling and data analysis and engage with the crosscutting concepts of patterns and cause and effect to develop an understanding of core ideas about the connections between humans and the environment.

Keywords

Biomagnification; toxicants; environment; health; interactive game; high school biology; three-dimensional learning; data analysis; modeling; NGSS

Introduction

Human health and ecosystem health are fundamental considerations of sustainability (National Research Council [NRC], 2011). Risks associated with exposure to harmful

chemicals or toxicants that are released into the environment pose a serious concern. As our society and world face increasing challenges associated with sustainability, there is a need to educate students about the interrelated issues of human health, toxicology, and the environment.

Connections between humans and the environment are also core ideas in the *Next Generation Science Standards* (NGSS Lead States, 2013) and *A Framework for K–12 Science Education* (NRC, 2012), two documents that are driving current science-education reform. These documents call for science instruction to integrate disciplinary core ideas (DCIs) with scientific practices and crosscutting concepts to promote student learning in science. This approach to integrating these three dimensions of science learning, called *three-dimensional learning*, leads to “the kind of thinking and understanding that science education should foster” (NRC, 2014, p. 1).

To address the need for three-dimensional learning materials that integrate core understandings of sustainability, Project NEURON developed “Bio Bay,” a board game to teach about biomagnification of toxicants. The game and surrounding curriculum, with additional activities that make real-world connections, promote students’ integration of the core ideas, scientific practices, and crosscutting concepts. The three-dimensional learning approach and supporting curriculum set Bio Bay apart from similar activities about biomagnification and trophic levels.

A central feature of Bio Bay is that while playing the game, students generate data that they analyze and interpret in order to construct their own understanding of biomagnification of toxicants. This data analysis, which includes the consideration of toxicant concentration at each trophic level, allows students to develop a deeper understanding of the phenomenon. Here, we highlight these unique aspects as we describe the game and associated lesson materials, how it engages students in three-dimensional learning, and its use in authentic classroom settings.

The Bio Bay Game & Curriculum

Bio Bay is the central activity in a lesson that is part of a larger curriculum unit developed by Project NEURON, “What changes our minds? Toxicants, exposure, and the environment” (<http://neuron.illinois.edu>). This unit, designed for middle and high school students, highlights the role of environment in exposure to chemicals and the neurophysiological effects of toxicants on organisms. It begins with two lessons that ask students to think broadly about “What changes our minds?” and to consider the definitions of the terms *drug* and *toxicant*. Lesson 3 features Bio Bay and addresses the driving question “How does the environment magnify our exposure to toxicants?” In Lesson 4, students learn about the ways in which they are exposed to toxicants in their daily lives and measure exposure by quantifying BPA (bisphenol A), a toxicant found in common plastics and products. In Lesson 5, students examine how a common aquatic algacide can affect *Daphnia* populations and the effects on the larger ecosystem. Lesson 6 goes to the cellular level to describe how toxicants can disrupt normal cell functions, specifically in neurons. To conclude the unit, in Lesson 7, students are asked the question “If it’s harmful, why do we

use it?” As a class, students consider different viewpoints of a real-life debate on whether BPA should be regulated.

In Lesson 3, the focus of this article, students play the Bio Bay Game to learn how mercury, a neurotoxin, can affect aquatic ecosystems and human health through *biomagnification*. Biomagnification is the process by which a substance increases in concentration (per unit of biomass) at higher trophic levels. Organisms regularly consume substances that may be considered toxic, but most of these toxicants can be broken down or expelled from the body. However, some toxicants, like mercury, are stored within fatty tissues and accumulate within individual organisms – a process known as *bioaccumulation*. When such organisms are eaten, the toxicants are passed on to the consumer. Biomagnification describes how consumers at higher trophic levels have increasingly higher concentrations of toxicants compared to consumers at lower trophic levels. Exposure to toxicants can have serious health consequences for these high-level consumers, including humans. Thus, biomagnification is a relevant issue to a society that depends on accurate, fundamental understandings of ecosystems and ecology.

Bio Bay allows a class to model the scientific phenomenon of biomagnification through a game and supporting curriculum materials that engage students in three-dimensional learning. Students learn disciplinary core ideas related to ecology while playing the roles of organisms in an ecosystem to demonstrate how humans can affect, or be affected by, the environment. Students engage in the scientific practices of analyzing data – collected while playing the game – and evaluating the game as a scientific model. Throughout the lesson, students construct and apply knowledge using crosscutting concepts such as cause and effect and patterns. Specific connections to the *Next Generation Science Standards* are outlined in Table 1.

Playing the Game

The Bio Bay Game models the aquatic ecosystem of a fictional Bio Bay with a simple food chain: zooplankton, anchovies, tuna, and humans (represented by a Fishing Boat). The game is designed to be played in groups of five to seven students. Each group of students has a Bio Bay Game board with spaces that are filled with tokens, representing Zooplankton. Two students in every group play as Pacific Bluefin Tuna (*Thunnus orientalis*) and the remaining three to five students play as Anchovies (*Engraulis* spp.). The teacher acts as the lone Fishing Boat for the entire class. To model realistic scales of biomass at different trophic levels, the teacher, or Fishing Boat, represents one human (at 62 kg), every Tuna player represents two tuna (at 60 kg each), and every Anchovy player represents eight thousand anchovies (at 45 g each). The players use a cup labeled with this information to represent their role and to use as a gamepiece while they are playing on the game board. Materials used in playing the game are shown in Figure 1.

For players, the goals of the game are simple: eat as much as possible and avoid being eaten. Every round, the Zooplankton tokens are replenished on the board, and Anchovies and Tuna roll a die to move and collect tokens from the board (Anchovies) or from other players (Tuna). Finally, the Fishing Boat rolls a die to randomly select a color and “catch” all fish

that happen to be on that color. Whenever a fish is caught, the student gives his or her tokens to the other player and respawns as a new fish on the board. The rounds of gameplay are guided by a Quickrules document that delineates each step of the process (Figure 2).

By playing the game, the teacher and students model a portion of a complex aquatic ecosystem. During this process, students lay the groundwork for learning about the impact of anthropogenic changes by first modeling some of the basic interactions, such as predation and transfer of biomass between trophic levels, within the ecosystem being investigated. Engaging in modeling through the game encourages students to observe patterns (a crosscutting concept in the *Next Generation Science Standards*) of organism interactions and the movement of matter through a food chain. Participating in the model also prepares students to grasp concepts of how human actions can disrupt an ecosystem (Table 1: DCIs LS2.C and LS4.D).

After 10 rounds of the game, players representing Anchovies, Tuna, and Fishing Boat count their tokens, and the teacher compiles these data in the electronic Class Data spreadsheet. Students are then informed that some possible toxicants have been found in Bio Bay, and they are tasked as investigators to read and learn about what has happened in other ecosystems before interpreting the data they have collected.

Making Connections to the Real World

In order to better understand what might be happening in Bio Bay, students gather more information about toxicants and their effects on ecosystems by reading and discussing two brief articles: “Mercury in the Environment” and “Cat Dancing Disease.”

“Mercury in the Environment” was adapted from an article by the Utah Department of Environmental Quality (n.d.). The article introduces the concept of biomagnification and explains the process by which mercury is introduced into the environment, undergoes chemical changes, and enters a food chain. Mercury binds to animal tissues and, therefore, increases in concentration at each trophic level. This article gives students insight into how the tokens they have been collecting in the game can actually represent toxicants that each organism passes on to its consumer.

The article “Cat Dancing Disease” was adapted from an article by Douglas Allchin (n.d.). The reading is a true case-study of extreme mercury poisoning in a small Japanese town by Minamata Bay due to mismanagement by a local chemical factory. Through the brief narrative, students are introduced to the negative health effects of mercury toxicity and begin to see how the food chain modeled in the game can be a vehicle for toxicants.

By reading, discussing, and answering questions about these two articles, students gain essential science content knowledge about human impacts on the environment and the phenomenon of biomagnification. The readings communicate the important consequences of human activity by describing toxic pollution of waterways and the resulting disruption of aquatic ecosystems. Students gain insight about complex patterns of cause and effect, particularly how a nonobvious cause, such as mercury in an ecosystem, can have far-reaching, domino-like effects on multiple organisms across trophic levels (Grotzer, 2003).

Analyzing & Interpreting Data

Next, students apply their knowledge of mercury in ecosystems to analyze and interpret the data they generated as a class through the game. Students begin by reconsidering the role of the tokens in this model of biomagnification. Drawing on what they learned from the readings, students realize that the zooplankton units were tainted with mercury and that the tokens indicate the units of toxicant that entered the food chain. With this in mind, the class analyzes graphs generated in the Class Data spreadsheet (Figure 3).

The Class Data spreadsheet is an Excel file that serves as a useful tool for teachers to guide discussion and differentiate instruction. Teachers can easily enter the class data into the file, and the graphs are automatically generated. The graphs can then be used by the teacher to structure data analysis and class discussion. Alternatively, students can use the file independently in small groups to enter and analyze class data. Additionally, if the mathematical background of the students is sufficient, the teacher may have students use the built-in formulas to construct the graphs themselves instead of generating the graphs automatically.

The analysis of each graph is accompanied by guiding questions that support students to think critically about their data and use the graphs to describe scientific phenomena. First, students examine the total numbers of toxicants at each trophic level, which are the total counts of all the tokens at each level (Figure 3: Graph A). Students are supported to observe patterns in the data and draw connections to the biological concepts through the following questions:

- Why are the quantities of toxicants relatively the same at each trophic level in this model?
- If the toxicant was degrading rapidly, what trend would you expect across trophic levels?
- How does this graph show bioaccumulation?

These questions scaffold students' thinking about bioaccumulation. Because the toxicants are incorporated into animal tissues, they do not leave the body. Over time, toxicants entering the ecosystem at the lowest trophic levels are present even at the highest trophic levels. If the toxicant degraded rapidly, little or no toxicants would be present at the highest trophic levels. Therefore, Graph A indicates that bioaccumulation is occurring because the toxicants are present at the highest trophic level, humans (Figure 3).

In the next step of data analysis, students consider the total biomass at each trophic level (Figure 3: Graph B). The total biomass is calculated as the following (using Tuna as an example):

$$\begin{aligned}\text{Total biomass at trophic level (kg)} &= P \times T \times w \\ P &= \text{number of students playing as Tuna} \\ T &= \text{number of tuna represented by each Tuna player} \\ w &= \text{weight per tuna (kg)}\end{aligned}$$

To assist them with interpretation, students answer the following questions about the graph:

- What patterns do you notice about biomass across trophic levels?
- What do you think causes these patterns?

Graph B shows that as the trophic level increases, the total biomass at each trophic level decreases. This phenomenon is commonly referred to as the “ecological pyramid” (also trophic pyramid or energy pyramid). Simply, the pattern illustrates the fact that there are typically more producers in an ecosystem than primary consumers or secondary consumers.

Depending on the level of students’ understanding, the explanation can be left at this, or some teachers may also use this as an opportunity to address the mechanisms of *why* this phenomenon occurs. When energy is transferred from one trophic level to the next trophic level, energy is lost from the system at each step. Consumers use approximately 10% of the energy to build new biomass; the rest of the energy is used in metabolic processes. Thus, although it is not the main focus of the activity, Graph B can address extended learning goals, particularly in connection to the DCI “Cycles of matter and energy transfer in ecosystems” (LS2.B).

Finally, students construct Graph C by dividing the units of toxicant (tokens) by the total biomass at each trophic level to calculate toxicant concentrations (Figure 3). This critical step allows students to visualize the increase of toxicant concentrations at higher trophic levels, or biomagnification. Students discuss:

- Why should we consider toxicant concentration, instead of just examining toxicant per individual?
- What kind of relationship does this graph show of toxicant concentration across trophic levels?
- How does this graph show biomagnification?
- What is the difference between bioaccumulation and biomagnification?
What are the connections between these concepts?

Students consider the toxicant concentration (toxicant units per mass) because the organisms at each trophic level are different sizes. A human or a tuna is much larger than an individual anchovy. But because there is less biomass *overall* at the highest trophic level, the accumulated toxicants have very high concentrations. Therefore, Graph C shows an exponential increase in toxicant concentrations across trophic levels, and this relationship is the very definition of “biomagnification.” Students also benefit by comparing Graph A and Graph C to discuss the differences and connections between bioaccumulation and biomagnification.

Evaluating the Model

In science, it is important to evaluate a model by discussing its accuracy as a representation of the natural system being investigated (NRC, 2012). Therefore, after students analyze the

data, they apply their understanding of the science to discuss and evaluate the game as a model of biomagnification. They discuss specific questions, such as:

- Can this game be used as a model? If so, how?
- How is this game useful as a model?
- What are the limitations of this model?
- Do bioaccumulation and biomagnification apply to terrestrial ecosystems?
- How can you lower your risk for exposure to mercury?

These questions help students put the game into the context of real-world ecosystems and the impact on society. The game is useful as a model in multiple ways: it generates data that can be analyzed; it can be used to explain the phenomenon of biomagnification; and it can be used to explain how, if humans eat at lower trophic levels, they can lower their risk of exposure to mercury.

In addition to the strengths, students also explicitly discuss the limitations of the game as a model of scientific phenomena. Limitations include how, in reality, ecosystems have food *webs* with mixed trophic levels, biomagnification occurs over larger time scales, and biomagnification is affected by temperature and other chemicals. The discussion can also include how biomagnification occurs in terrestrial ecosystems – for example, the pesticide DDT that harmed bird eggs, made famous by Rachel Carson’s *Silent Spring*.

In this final component of the activity, evaluating Bio Bay as a model, students draw on the different DCIs, practices, and crosscutting concepts with which they have been engaging throughout the lesson. In order to evaluate the model, students apply their understanding of the core ideas of ecosystem dynamics and human impact through pollution. They also draw on their analysis of the data to understand the role of modeling scientific phenomena. Students integrate crosscutting concepts as they use patterns and causes and effects to think critically about the game as a model.

Feedback from the Classroom

We report here on use of the Bio Bay activity by teachers who attended a summer professional development institute. The feedback we discuss comes from five teachers’ classroom enactments, collected through classroom observations and two in-depth individual teacher interviews. We found that teachers typically used the Bio Bay activity in introductory-level high school biology classes. While two teachers used the game as part of the whole “What changes our minds?” curriculum unit, the remaining teachers integrated just the Bio Bay activity into their existing ecology unit. In all cases, the game was used to make connections to concepts in the DCIs described earlier (LS2.C: Ecosystem Dynamics, Functioning, and Resilience; and LS4.D: Biodiversity and Humans) and to the practices of modeling and data analysis. One teacher extended the activity to address concepts of energy flow and matter cycling between trophic levels (LS2.B: Cycles of Matter and Energy Transfer in Ecosystems).

All teachers used two or three days of instruction to implement the Bio Bay activity. The teachers interviewed suggested two methods of implementation. One teacher's suggestion was to implement the activity over three days – introducing the game and conducting a practice round at the end of the first day, reserving the second day for gameplay and data collection, and using the third day for readings and data analysis. Another teacher recommended playing over two days – spending a day and a half learning the rules, playing the game, and completing the readings; and finishing the second day with the data analysis. In the latter scenario, the teacher suggested taking photos of the game boards at the end of the first day in order to quickly set up the game again the second day.

In one interview, a teacher expressed his initial concern with using games in the classroom. He wondered if students would learn enough to make the time invested worthwhile. However, this teacher remarked that his concern was assuaged during the data-analysis and debriefing portions of the activity, which he described as “absolutely essential in making the game a successful learning tool.” He also found that the construction and discussion of the graphs were useful for both him as a teacher (“I was getting that piece of feedback that I needed to feel comfortable [about my students’ understanding]”) and the students (the handout was “something with which to remind them of [the] activity and its purpose”). Second, through the data analysis and the model evaluation that served as formative assessment tools, he was able to see that students grasped biomagnification of mercury as a real-world phenomenon.

Furthermore, teachers expressed enthusiasm for how the game increased students’ engagement in the data-analysis portion of the activity. The game engaged students of all ability levels, which increased student participation in the discussions that followed. Students were motivated to analyze the data set because they were invested in it, having generated the data themselves. As one teacher described it:

[Students] were finally given a graph that was based on something they had fun with, and I think that actually has a huge amount of power to it, because of that investment piece, that engagement piece ... we actually *want* to make meaning of what we’ve just done.

Conclusion

Bio Bay offers students an opportunity to engage with the complex scientific phenomenon of biomagnification by playing a board game. Teachers who tested the activity have found that it provides students with a meaningful three-dimensional learning experience. By playing the game, making sense of the data, and evaluating the model, students utilize core ideas related to humans and the environment, engage in modeling and data analysis, and draw connections to the crosscutting concepts of patterns and cause and effect.

Activity Materials on the Web

All curriculum materials developed by Project NEURON are freely available at <http://neuron.illinois.edu>.

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Figure 1. Some of the materials needed to play Bio Bay, including the colorful game board, “Quickrules” document (close-up shown in Figure 2), the Color Chart guide for the Fishing Boat, and the Tuna and Anchovy fish tags (lower right) that label students’ cups as they play.

Figure 2.

The “Quickrules” document helps students learn the game and guides gameplay. After setting up the game, tokens are placed on every space on the game board. Then Anchovies, Tuna, and the Fishing Boat take turns (in that order) collecting tokens in each round.

Figure 3.

Examples of graphs generated from data collected by students during the activity. Graph A is a summary of the toxicants (tokens) that were at each trophic level at the end of the game. Graph B is the calculated biomass at each trophic level, based on the weight and number of organisms that players represent. Graph C depicts the resulting biomagnification, the increase of toxicant concentrations at higher trophic levels, with an exponential line for comparison. See text for discussion.

Table 1

Connections of the Bio Bay Game to the *Next Generation Science Standards* (NGSS Lead States, 2013).

Disciplinary Core Ideas	Science Practices	Crosscutting Concepts
<p>LS2.C Ecosystem dynamics, functioning, and resilience “Anthropogenic changes (induced by human activity) in the environment – including habitat destruction, pollution, introduction of invasive species, overexploitation, and climate change – can disrupt an ecosystem and threaten the survival of some species.” (p. 156)</p> <p>LS4.D Biodiversity and humans “Humans depend on the living world for the resources and other benefits provided by biodiversity. But human activity is also having adverse impacts on biodiversity through overpopulation, overexploitation, habitat destruction, pollution, introduction of invasive species, and climate change.” (p. 167)</p>	<p>Analyzing and interpreting data “Analyze data systematically, either to look for salient patterns or to test whether data are consistent with an initial hypothesis.” (p. 62)</p> <p>Developing and using models “Represent and explain phenomena with multiple types of models ... Discuss the limitations and precision of a model as the representation of a system, process, or design and suggest ways in which the model might be improved to better fit available evidence or better reflect a design’s specifications. Refine a model in light of empirical evidence or criticism to improve its quality and explanatory power.” (p. 58)</p>	<p>Cause and effect: Mechanism and explanation “Events have causes, sometimes simple, sometimes multifaceted. A major activity of science is investigating and explaining causal relationships and the mechanisms by which they are mediated. Such mechanisms can then be tested across given contexts and used to predict and explain events in new contexts.” (p. 84)</p> <p>Patterns “Observed patterns of forms and events guide organizing and classification, and they prompt questions about relationships and the factors that influence them.” (p. 84)</p>