Recipe for Hypoxia (O_2)

Playing the Dead Zone game

Jessica A. Kastler

Abstract. Dead zones—areas experiencing low levels of dissolved oxygen—are growing in shallow ocean waters around the world. Research has shown that dead zones form as a result of a specific type of pollution, called nutrient enrichment or eutrophication, and are found in almost every coastal zone where humans have large populations. Concepts related to eutrophication are not complicated individually, but they frequently confuse students. The activity presented in this article is a game designed to help middle and high school students understand the processes that encourage formation of dead zones. Postgame discussions encourage students to consider natural and human causes of dead zone formation, as well as ways in which human contributions to it can be reduced.

Keywords: dead zone, eutrophication, hypoxia, nutrient, phytoplankton, pollution, pycnocline, salinity, stratification

Many teachers provide context for middle and high school science with examples from the environment. Environmental problems are excellent teaching tools because they are multidisciplinary, timely, and relevant to students. In addition, they frequently show the negative effects of human actions on the environment, which introduces opportunities to discuss ways that we, as individuals and members of society, can change our behavior to alleviate some of these problems. However, the complexity of the different processes involved in real-world, multidisciplinary examples can confuse students. This is frequently the case when students first learn about bottom-water oxygen depletion, a condition known as a *dead zone*.

This article presents a game that engages middle and high school students as active players in a continental-shelf environment similar to the area of the Gulf of Mexico where the Mississippi River discharges. The game gives students time to process information with which they may be familiar but not completely comfortable. It requires students to act as one of four major players (i.e., phytoplankton, nutrient, carbon dioxide, or oxygen) in a conceptual model of a river delta–continental shelf ecosystem. This activity takes advantage of kinesthetic and logical learning styles as complements to the more frequently addressed visual and verbal learning styles. After several rounds of the game using different starting conditions, students make progress toward a more complete understanding of the roles of the four major players in photosynthesis and bacterial respiration. Students can also predict the effects of nutrient enrichment and layered water bodies, which will lead them to a better understanding of the environmental and human processes that contribute to hypoxia.

This activity addresses multiple national science education standards (NSES), including content standards for physical, life, and Earth and space sciences (National Research Council [NRC] 1996). The relevant standards for the high school level, which are stated more specifically than the corresponding middle school standards, are listed in Appendix A. The greater specificity in the statement of high school standards reflects older students' advances in

---

JESSICA A. KASTLER *is a research associate at the Gulf Coast Research Laboratory and an educator for the Marine Education Center, both at the University of Southern Mississippi. She facilitates K–12 students', teachers', and scientists' learning about coastal ecology, watersheds, sedimentary environments, and effective dissemination of marine science research. E-mail: jessica.kastler@usm.edu*

both accumulated content knowledge and cognitive abilities. However, almost all middle school students with whom I have worked were capable of understanding the processes described in this article.

The physical science standard is addressed through the concept that differences between the physical properties of river water and seawater prevent the two bodies of water from mixing, thus limiting oxygen reintroduction. The biological standard is addressed as students consider how nutrient pollution fertilizes phytoplankton photosynthesis. Complete understanding requires consideration of how these processes occur coincidentally on the continental shelf. Therefore, a study of hypoxia addresses the NSES requirement that teachers provide unifying concepts and processes to make sense of science concepts categorized by subject area. In other words, this lesson on hypoxia provides context for basic concepts that students are learning, such as photosynthesis and the physical properties of water.

This lesson addresses multiple essential principles of ocean literacy and is an excellent way to teach essential principle 6: "The oceans and humans are inextricably interconnected" (see Appendix B; National Geographic Society et al. 2006). In exploring this specific case of human interaction with the ocean, it also addresses one more NSES: science in personal and social perspectives. The best follow-ups to this game exploring causes of hypoxia are to discuss the natural and human-enhanced occurrences of the phenomenon and to brainstorm realistic ways for humans to reduce their effects on the ocean.

Background

Hypoxia is a situation that occurs when dissolved oxygen (O_2) concentrations in a water body fall below 2 milligrams per liter of water, or 2 mg/L. (The related term *anoxia* refers to a more extreme condition in which the dissolved oxygen concentration has fallen to 0 mg/L.) Hypoxic waters are known as *dead zones*, because fish and aquatic invertebrates require dissolved oxygen to breathe and, therefore, cannot live in hypoxic water. Dead zones occur in water bodies as an extreme result of *eutrophication*, a process that results in enrichment of the nutrients nitrogen and phosphorus, which are needed for plant growth.

Dead zones can occur naturally. For example, estuaries have always been highly productive for plants and algae because they receive nutrient-rich drainage from land. However, pollution from humans is increasing eutrophication beyond natural levels. Types of pollution that contribute to eutrophication include commercial fertilizers, municipal and septic tank overflow, high-concentration animal feeding operations, and atmospheric deposition.

In the 1960s, people living in the densely inhabited watershed of Lake Erie began to notice the effects of pollution on the lake, primarily the excessive growth of algae that washed up on beaches and depleted oxygen needed by other organisms. Researchers found that phosphorus derived from municipal sewage and detergent sources was the principal nutrient contributing to eutrophication in the lake. In the 1970s, this discovery led to a ban on detergents containing phosphorus.

Since the 1980s, eutrophication has been observed regularly in coastal areas, from small estuarine bays to the continental shelf off the shores of Louisiana, Texas, Mississippi, and Alabama. A 2004 survey found that 65% of the United States estuaries assessed were at least moderately eutrophic (Bricker et al. 2007). Worldwide, dead zones have been documented in more than 400 marine systems, affecting an area larger than 245,000 km^2 (Diaz and Rosenberg 2008). The hypoxic area in the northern Gulf of Mexico is the second largest occurrence and has been linked to nitrogen runoff from the watershed of the Mississippi River, which covers 41% of the continental United States (Rabalais, Turner, and Scavia 2002). Although field research by Rabalais has documented the dead zone's annual summer occurrence since 1985, the fossil record preserved in sediments shows that this area of hypoxia is new since the mid-20th century (Sen Gupta, Turner, and Rabalais 1996).

Hypoxia requires a specific set of environmental conditions to become established. In general, there must be a high concentration of nutrients, which stimulate photosynthetic production of a large amount of organic material. There must also be limited oxygen production in the area where the organic materials' respiration is depleting oxygen concentrations.

Hypoxia can occur in any water body when both of these conditions are met, from freshwater lakes subject to phosphorus enrichment to brackish, nitrogen-enriched estuaries. In this article, I explore the area of the continental shelf where the Mississippi River enters the Gulf of Mexico. Specifically, my exploration involves the following question: What happens in the Gulf of Mexico each year to ensure the presence of both conditions and establish the situation known as Gulf of Mexico hypoxia, or the Dead Zone? The article also includes a brief summary of adjustments teachers may make to apply this game to a local hypoxic water body.

Physical Setting: Stratification

Stratification is the layering of water bodies that have different densities in a way that impedes their mixing. In the coastal Gulf of Mexico, the two water bodies are continental shelf water and Mississippi River water. Continental shelf water is deeper, so temperatures do not fluctuate as much as those of river water. For example, during spring warming and throughout the summer, continental shelf water is colder and, therefore, denser than river water. Continental shelf water also contains salt, which further raises its density in comparison to river water. Continental shelf water has a maximum salinity of 35 parts per thousand (ppt), whereas river water has a salinity of 0 ppt.

The result of these differences is that a layer of warm, fresh, lightweight water discharged from the Mississippi River lies on top of the cooler, more saline, denser shelf water. The two layers tend not to mix, and their physical separation is marked by a surface across which density changes abruptly, known as a *pycnocline*. Animals can swim through the pycnocline, and particles with higher density than the river water (sediment and organic materials, including fecal pellets and dead phytoplankton) will fall through the pycnocline to the continental shelf water. However, the pycnocline prevents dissolved gases, including oxygen and carbon dioxide, from diffusing between the river and continental shelf water bodies. Stratification is a natural process that occurs on the continental shelf everywhere that a major river enters the ocean. Where the Mississippi River discharges to the Gulf of Mexico, the stratification persists through the summer.

Biological Setting: Nutrient Enrichment

The food web in aquatic ecosystems starts with phytoplankton harnessing energy from the sun through photosynthesis. *Phytoplankton* refers to small, plantlike, photosynthetic organisms that cannot move far on their own and typically drift with water bodies. They have a variety of mechanisms to keep them buoyant because they cannot photosynthesize below the depth to which sunlight penetrates. In the Gulf of Mexico, the predominant type of phytoplankton is a kind of algae with a silicon shell, known as a *diatom*.

In the presence of sunlight, diatoms photosynthesize to produce simple sugars from carbon dioxide and water. The diatoms store the energy they need for reproduction in these sugars. Because photosynthesis cannot occur in the absence of sunlight, most phytoplankton production occurs in the upper river-water body. Dead diatoms, their crustacean consumers (i.e., *copepods*), and copepod fecal pellets fall to the lower continental shelf–water body. There, bacterial decomposition consumes oxygen, which is used to break down the organic material.

During the process of photosynthesis, phytoplankton incorporate substances called *nutrients* that are essential to the organism's life. Organisms need nitrogen to make proteins and phosphorus for metabolic processes. Depending on the species, phytoplankton require nutrients to be available in various concentrations. The nutrient that runs out first limits the rate of phytoplankton growth. In the 1970s, scientists learned that phosphorus was usually the nutrient limiting photosynthesis in freshwater lakes. Therefore, adding phosphorus-containing soaps via wastewater increased phytoplankton growth. In marine environments such as the Gulf of Mexico, nitrogen—rather than phosphorus—is usually the nutrient that limits photosynthesis.

The process of cellular respiration reverses photosynthesis, using oxygen to break down sugars and release stored energy for metabolism. All organisms respire, including phytoplankton. Respiration occurs whether or not light is present, so it continues throughout the day. The process of cellular respiration in living phytoplankton occurs in surface waters where photosynthesis and atmospheric diffusion ordinarily incorporate adequate oxygen. It is not considered in this game. This activity only considers live animal respiration and bacterial decomposition of dead organic material (including phytoplankton), which are the dominant processes that consume oxygen below the pycnocline.

In areas where nutrients are enriched, phytoplankton photosynthesis causes rapid production of organic material, known as algal blooms. Photosynthetic production and atmospheric diffusion generally maintain dissolved oxygen concentrations in the surface layer of river water. However, oxygen can be depleted in the bottom layer of continental shelf water when large amounts of bloom-generated organic material settle through the pycnocline and decompose. Animals living below the pycnocline do not have access to the dissolved oxygen they need. To survive, they must either swim away from the hypoxic area or wait until oxygen is replenished. Animals that are not mobile may die.

Short episodes of hypoxic bottom water are not unusual in continental shelf areas, particularly in the offshore areas of large watersheds like that of the Mississippi River. However, the offshore area into which the Mississippi River flows maintains a large and persistent body of hypoxic water for several months each summer. The large quantities of organic material stored there consume oxygen as it is added.

Hypoxia in the Gulf of Mexico typically continues until a hurricane or cold front causes a strong wind to disrupt the pycnocline and mix atmospheric oxygen into the lower, continental shelf body of water. However, hypoxia usually recurs when the new oxygen is consumed during the decomposition of the organic material stored in sediment. Hypoxia does not dissipate for the year until repeated cold fronts in the fall mix oxygen into bottom waters while also cooling the surface water and reducing the density differences that lead to stratification of the water.

Materials

- Large area where students can walk around comfortably (indoors or outdoors); this space will act as the continental shelf. Consider the space ahead of time, and decide where each of the following should be located within it:

sun, river discharge, air–water interface (i.e, up), sediment–water interface (i.e., down).

- Labels (optional): one per standard page of paper, for the sun, river discharge, air–water interface, and sediment–water interface
- Player role cards (see Appendix C); for a 20-student class: 8 P-N, 16 CO_2-O_2, 1 fish, and 1 worm
- Rope as long as the playing area
- Printout, chalkboard, or whiteboard diagram of hypoxia (see Figure 1)
- Summary chart (see Appendix D)

Procedure

Introduction

Although setup of the playing area is not required, you must find an appropriate place to play the game before starting the lesson. The space must be large enough for students to stand and walk around each other without crowding. The playing area (in plain view) will act as the continental shelf in cross-section. You should decide which horizontal direction will be up (air–water interface and sun), down (sediment–water interface), and the ocean margin (Mississippi River discharge). When the pycnocline is added in round 2, place the rope across the playing area so it is parallel to the air–water and sediment–water interfaces.

On the chalkboard, whiteboard, or overhead projector, draw the continental shelf in cross-section (see Figure 1). Introduce or review the features shown (the sun, river discharge to the ocean, shallow continental shelf water, and the pycnocline). Review the biological processes that occur there (photosynthesis, respiration, and death and decomposition). Encourage students to define and describe these processes and their controlling factors, including the amount of sunlight and the availability of compounds required for the reaction. Listen for signs of confusion, and address any misconceptions during preparation for the game. If your students are already comfortable with the concepts, consider presenting a brief (4-min) visualization of hypoxia in the Gulf of Mexico (National Oceanic and Atmospheric Administration Environmental Visualization Laboratory 2009).

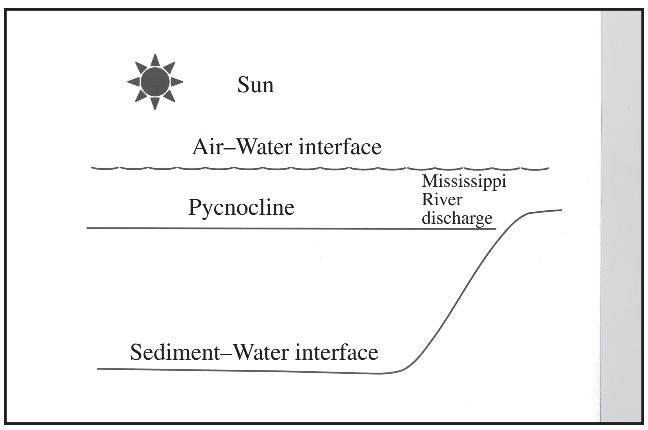

FIGURE 1. Diagram of stratifield continental shelf.

Tell students that the lesson requires them to think of the playing area as a continental shelf environment on its side. Orient them to the location of different features on the playing area, each of which corresponds to one of the elements labeled in Figure 1. If you have labels for the different directions in the playing area, place them now. Each student will play a role in the process of photosynthesis, respiration, or decomposition. The game is played in rounds, each of which has different physical conditions and includes a different number of each kind of player. Each round ends when players can find no other players with whom to interact.

The object of this game is for each player to participate in the processes of photosynthesis and respiration for as long as possible. To do this, players must find the other players they need to act out these roles. Winning is not an individual achievement; rather, it results from the team effort of players acting out their roles. If there is at least one O_2 player and no dead phytoplankton left when a round ends, the whole group, or ecosystem, wins.

Distribute role cards to four students, who will act out each of the following roles: phytoplankton (P), nutrient (N), carbon dioxide (CO_2), and oxygen (O_2). See Appendix C for role cards that describe the rules each role follows. Distribute role cards to four more students and request that each of these students read one role aloud, starting with P. As the reader describes the action and possible transformation of the role, the player of that role acts them out, using other players as props to complete actions. Assist as necessary, vocally or physically guiding students through the movements to complete their parts.

Finish the introduction by guiding a short discussion to clarify important points. Point out roles that transform from one to another: CO_2 to O_2 and P to N. In the ecosystem, these transformations occur in a continuous cycle as long as other necessary players and factors are available. CO_2 becomes O_2 and N becomes P through photosynthesis in the presence of sunlight. P becomes N and O_2 becomes CO_2 through decomposition after P's death. Decomposition is equivalent to the respiration of bacteria that consume the organic material of the dead P. The game is a simplified but fundamentally correct conceptualization of the cycling of processes and the limitations placed on these processes by the presence or absence of different players, particularly N and O_2.

Setup

Hand out role cards assigning roles to students in numbers that satisfy the initial conditions described in that round's rules. Make sure each student understands how to act out his or her assigned role and that each player places the player card so that others can see the initial face showing the assigned role.

Place students on the appropriate playing area for their roles (N, P, CO_2) and the initial conditions (O_2). The N players line up where the river discharges to the gulf because N's source is land drainage. The P players are in the upper water body, close to the air–water interface, because P needs sun to photosynthesize. The CO_2 players are distributed evenly around the whole playing area because, although the atmosphere is the source of CO_2, CO_2 is abundant throughout the ocean. The O_2 is placed according to the initial conditions described for each round.

Play Each Round

Direct the students to start playing their roles. Release N players slowly, allowing the first to get across the playing area before releasing the second. When each round ends, ask students to count how many players of each role are left and to record their data on a summary chart (see Appendix D). Discuss the results of each round to make sure students understand what happened and why.

Round Rules

1. Round 1 represents a healthy ecosystem with mixed water and limited nutrients. In its initial condition, $O_2 > P + N$. There must be at least one more O_2 player than the sum of the P and N players. (A 20-student class would include two P, two N, eight O_2, and eight CO_2.) Begin playing. Once the students get used to making the transfers appropriate to their role, call time. No dead P remains to be oxidized. The ecosystem wins. Make sure students recognize that there is no pycnocline, and discuss how this affects the ecosystem. For example, if the P players move quickly enough, they can maintain a transfer of material from inorganic (N) to organic (P) forms and back again indefinitely.

2. Round 2 represents a healthy ecosystem with stratified water and limited nutrients. Place the rope across the playing area to represent the pycnocline. In the ecosystem's initial condition, $O_2 > P + N$. The proportions of players do not change from round 1, but the O_2 must now be below the pycnocline. Before beginning to play, remind students to read their cards to find out how their characters act with respect to the pycnocline. When play is over, discuss the results. The game makes no provision for N below the pycnocline to be returned to the surface. Therefore, the game will end quickly. All P is decomposed to N, with O_2 remaining. This is a healthy ecosystem; once again, the ecosystem wins.

3. Round 3 illustrates a hypoxic ecosystem with stratified water and excess nutrients. In its initial condition, $O_2 < P + N$ below the pycnocline. (A 20-student class would include two P, six N, six O_2, and six CO_2.) Introduce this round by telling the students that people are adding more fertilizers in the watershed, and begin playing. The round will end soon after the final N player is released. Discuss these results. As long as new N is discharged, P can use it to make new P and release O_2, but the O_2 remains above the pycnocline. When the P dies, it falls and must be oxidized by the O_2 below the pycnocline. In the absence of mixing that would get more O_2 into bottom waters, P's decomposition depletes the O_2 and leaves the area hypoxic. The ecosystem loses. Ask students why it matters if there is no O_2 in the ecosystem. What happens to animals in hypoxic waters?

4. Round 4 illustrates a hypoxic ecosystem with stratified water, excess nutrients, and animals present. In its initial condition, $O_2 < P + N + \text{fish} + \text{worm}$ below the pycnocline. (A 20-student class would include two P, four N, six O_2, six CO_2, one fish, and one worm.) When you introduce the two new players, the fish and worm, ask students to describe the behavior they would expect of each new role, following the format of the other role descriptions. Select students to play the fish and worm and ask each to read the role card aloud. Make sure the fish and worm are showing their "alive" faces. Start the game by releasing the first N. After two N have been released, interrupt play by asking the students to stop in place, and then ask students to consider how the ecosystem is functioning with this limited nutrient load. They should recognize that all is well and that anything dead has decomposed. Release the remaining N one at a time, slowly. When the round is over, discuss the results. Without O_2, dead P may remain. When O_2 is depleted, the fish swims to the surface water, but the worm dies. In hypoxic areas, fish usually have time to swim out of the area, but organisms that cannot move away die.

Summarize Results

Complete the summary chart with students. Some important take-home messages from the game include (1) awareness of each player's role in the ecosystem, (2) understanding that the game (and therefore the ecosystem) can continue as long as the water column is mixed and nutrients are low, (3) recognition that stratification isolates the bottom water body from additional oxygen, and (4) realization that inadequate oxygen requires animals to move or die. Important messages that are not addressed directly in the game but should be discussed between rounds include (1) that winds from hurricanes and cold fronts can introduce dissolved oxygen into bottom waters and (2) that hypoxia may return if stored organic material consumes all the introduced dissolved oxygen.

Develop and Test Hypotheses

Even after the class has moved through a healthy system and observed the effects of adding stratification, excess nutrients, and animals, it may not be obvious from this exercise that either stratification or a limited quantity of nutrients may be added beyond normal levels without immediately causing hypoxia. Students can explore these issues in rounds 5 and 6.

5. Round 5 represents mixed water with excess nutrients. Use this round of the game to explore the number of nutrients that can be added in a mixed system before hypoxia occurs. Put students in teams, making sure that all roles are represented on each team. Assign the students to predict the maximum number of N players that could be added to a stratified system with one P, six O_2, and six CO_2 if at least one O_2 must remain at the end of the round. Each team makes and records a prediction, writing it in a sentence that describes the students' reasons for making this prediction. As a class, review the teams' hypotheses. Note similarities and differences, and have students explain their reasoning. Then allow teams to take turns running the game as a model to check their predictions. One team at a time, in order of increasing nutrients, should set up the game to check their model. Team members may play roles themselves or assign classmates to play roles, but at least one person on the team must remain the leader to make sure all players are properly placed for the initial condition and to release N to the continental shelf. After you check the placement of players for each initial condition, allow the team leader to release N. Watch the play to find out if decomposition will consume all the O_2. It becomes clear that O_2 remains after players have repeated transformations more than once after all N are released. At this point, stop the round and allow the next group to test its hypothesis. Discuss the results. As students may have predicted, hypoxia will never be a problem when there are more O_2 than N plus P (maximum N = 4). Through discussion, apply this reasoning from the game to real life, where hypoxia will not become a problem if wind, diffusion, and photosynthesis introduce sufficient dissolved oxygen to ecosystems.

6. Round 6 represents stratified water with excess nutrients. Repeat the hypothesis-making step of round 5, with new conditions. Have students predict the maximum N that could be added without causing hypoxia in a stratified system starting with one P, seven O_2, and seven CO_2, if four O_2 and four CO_2 are in bottom water. You may allow the teams to test their hypotheses by putting the class to work in the game. It is possible that the teams will not need to test all their hypotheses because the class will make the generalization about the relationship between O_2, N, and P. In this case, fewer nutrients may be added (maximum N = 2).

The final discussion should summarize the results of rounds 5 and 6, leading to the take-home message that this ecosystem is resilient and can process some excess nutrients, but it will not function normally if nutrient loading leads to the production of so much organic material that its decomposition depletes oxygen. This conclusion may lead to further discussions of the effects of hypoxia on humans, the potential loss of fisheries resources, and steps that humans living in the watershed can take to reduce nutrient loading.

Assess Student Learning

Student assessment occurs throughout playing time. You can tell by observation of the game if any student is confused about what he or she should be doing. You can also call on individual students to describe the relationship between actions in the game and actual processes occurring in the marine environment. It is important not to move to the next round until students are able to play their roles appropriately and articulate the processes that their roles model. A more formal assessment, such as a homework assignment or test, should require students to describe specific processes on the ecosystem cross-section (see Figure 1); accurately predict the occurrence of hypoxia under given circumstances; or discuss interactions of the key players N, P, CO_2, and O_2.

Discussion

My use of the term *game* incorporates several definitions, selected from the 10 provided by Free Online Dictionary. In one sense, a game is an amusing activity in which players compete according to set rules. In a mathematical sense (i.e., game theory), games model a competition, identifying interested parties and providing rules governing all aspects of the competition. These different perspectives on games bring up several issues to consider in facilitating this activity. First, playing games may help students take a relaxed but active approach to learning. Through their involvement as players, students focus on following straightforward rules to explore progress in the game. Each student needs to learn only his or her part, but students learn their own assigned roles well while exploring how interactions with other players control ecosystem functioning in the model continental shelf. Therefore, the pathway to learning is relaxed, perhaps even entertaining, and students engage as interested participants, rather than as outside observers.

Second, there is a competitive element to this game, but students do not compete against each other. Rather, they work together as a community to explore how changing conditions affect the ecosystem. The explanation of each round of play concludes with one of these statements: "The ecosystem wins" or "The ecosystem loses." Some students try to win the game as individuals, which is not possible. However, creative students may enjoy adding their own embellishments by introducing individual competition or other modifications. This is not a problem as long as the behavior does not confuse other students or cause misconceptions. However, recognizing the possibility of such behavior ahead of time allows you to decide at its first expression whether to discourage or allow it.

Third, this game is an accurate but extremely simplified model of the interaction of living organisms with inorganic elements through the inverse processes of photosynthesis and respiration. Try to mention some of the game's limitations in class discussions. (For example, it does not deal with mixing waters; the nightly loss of sunlight; or all the players, such as specific nutrients, in an ecosystem.) Then work with students to help them consider additional factors that might make this model more accurate.

At least in the early rounds, the game is more like a dance, a play, or a demonstration than a competition; as long as each student correctly follows the rules, there should be little variation in the results. A good game engages people intellectually by requiring strategic thinking, decision making, and problem solving. The dead zone game introduces these requirements late because student players need time to learn their individual roles. This is analogous to completing drills in a chess game to learn the moves each piece is allowed before competing against a real player. Strategic thinking can be enhanced in later rounds for a well-prepared group, but there is a limit to the number of N and P that can be introduced in a class of 20–30 students because the concentration of CO_2 and O_2 in healthy, normally functioning ecosystems is so much larger than that of N and P. An interesting possibility would be for advanced students to play the game on their own and then teach the roles to a larger group of younger students, using the younger students to test additional hypotheses. This extension introduces possibilities for enhancing learning for both the younger players, as students, and the advanced players, as teachers.

You can devote several days to this game. If students are confident in their understanding of photosynthesis and have been introduced to aquatic food webs, the whole game could be completed in a single class period. However, some students will benefit from a review of these processes using the role cards. I suggest teaching this activity in sequence with others that introduce specific types of nutrient pollution (e.g., the Enviroscape nonpoint pollution model, available at www.enviroscapes.com/) and illustrate how density changes can reduce mixing of water bodies. It is also a good idea to conduct this activity in association with water quality data collection or manipulation of archived data from hypoxic areas (Lindstedt 2003). Once students are aware of hypoxia's causes, you can emphasize ways of using this information to reduce the occurrence of hypoxia. The Enviroscape watershed model is a particularly good way to show students the benefits of good stewardship in avoiding nutrient pollution.

This article explores hypoxia as it occurs on the continental shelf, where the Mississippi River enters the Gulf of Mexico. However, the game does not need to be set in this specific water body. All roles, role cards, and round rules are appropriate for describing the incidence of hypoxia in any water body subject to seasonal stratification and eutrophication. Teachers may adjust their introduction to students by substituting appropriate types of phytoplankton that are likely to bloom; naming the local nutrient most likely to contribute to eutrophication (in general, we expect phosphorus to limit freshwater systems and nitrogen to limit marine systems); describing the appropriate season and mechanisms contributing to stratification (in the absence of salinity, freshwater stratification is almost entirely temperature driven); and referring to the pycnocline, which describes a density change, by the more specific term *thermocline*, which relates to a temperature change alone. These changes lead to similar adjustments that must be included in the discussion that occurs throughout the game. For example, although winds associated with cold fronts are likely to assist in mixing freshwater bodies, as they do in the Gulf of Mexico, tropical storms may not play a large regular role in mixing stratified lakes. Consult Internet resources to learn about mechanisms of stratification in other water bodies and how they contribute to oxygen depletion (e.g., Videtich and Crooks 2009). With a basic understanding of the local situation, the hypoxia game can be customized to include many bodies of water, offering a locally resonant example to students wherever eutrophication and stratification cause oxygen depletion.

Conclusion

The game described here was developed to give students an opportunity to explore the roles and transformations of key participants in a continental shelf ecosystem subject to nutrient enrichment and stratification. Through several rounds, students learn how nutrients, phytoplankton, oxygen, and carbon dioxide interact in the presence of sunlight to photosynthesize and contribute organic material for bacterial respiration. The game reinforces the cycling of basic biological processes in an aquatic system. It also introduces students to two key ingredients that are required to produce bottom-water hypoxia every summer in the Gulf of Mexico where the Mississippi River discharges freshwater and nutrient pollution. The first factor is nutrient enrichment. Hypoxia was not a persistent, annual condition until commercial fertilizer use began in the 1950s in the Midwest, bringing excess nutrients into the Mississippi River. However, hypoxia does not begin until the summer, when maximum density differences between the Mississippi River water body and the continental shelf water body establish stratification of Mississippi River water over continental shelf water. Hypoxia is eliminated annually when seasonal mixing by winds destroys the stratification and returns oxygen to bottom water. Both ingredients, nutrient enrichment and stratification, are required to prepare the recipe for disaster known as hypoxia.

This game illustrates the definitive controls exerted on the environment by interplay between humans, chemistry, and biology. Given a certain amount of information about some of these components, students learn how to predict outcomes. Through play, students explore the interactions of players, the effect of hypoxia on animals, and the capacity of their model ecosystem to process excess nutrients. This puts them in a position similar to that of scientists and managers who are currently working to understand and alleviate the problem of hypoxia wherever it occurs.

References

Bricker, S., B. Longstaff, W. Dennison, A. Jones, K. Boicourt, C. Wicks, and J. Woerner. 2007. *Effects of nutrient enrichment in the nation's estuaries: A decade of change*. NOAA Coastal Ocean Program Decision Analysis Series No. 26. Silver Spring, MD: National Centers for Coastal Ocean Science.

Diaz, R. J., and R. Rosenberg. 2008. Spreading dead zones and consequences for marine ecosystems. *Science* 321 (5891): 926–29.

Free Online Dictionary. "Game." http://www.thefreedictionary.com/game (accessed March 1, 2009).

Lindstedt, D. 2003. On again, off again: Dead zone mapping activity. Louisiana Sea Grant Web site. http://www.lamer.lsu.edu/classroom/deadzone/index.htm (accessed March 1, 2009).

National Geographic Society, National Oceanic and Atmospheric Administration (NOAA), Centers for Ocean Sciences Education Excellence (COSEE), National Marine Sanctuary Foundation, National Marine Educators Association, College of Exploration. 2006. Ocean literacy: The essential principles of ocean sciences grades K–12. http://www.coexploration.org/oceanliteracy/documents/OceanLitChart.pdf (accessed March 1, 2009).

National Oceanic and Atmospheric Administration Environmental Visualization Laboratory (NOAA-EVL). 2009. The dead zone. http://www.nnvl.noaa.gov/MediaDetail.php?MediaID=84&MediaTypeID=2 (accessed March 14, 2009).

National Research Council (NRC). 1996. *National science education standards*. Washington, DC: National Academy Press.

Rabalais, N. N., R. E. Turner, and D. Scavia. 2002. Beyond science into policy: Gulf of Mexico hypoxia and the Mississippi River. *BioScience* 52:129–42.

Sen Gupta, B. K., R. E. Turner, and N. R. Rabalais, 1996. Seasonal oxygen depletion in continental-shelf waters of Louisiana: Historical record of benthic foraminifers. *Geology* 24:227–30.

Videtich, P. E., and E. J. Crooks. 2009. Grand Valley State University: Living with the Great Lakes—Seasonal lake stratification. http://faculty.gvsu.edu/videticp/stratification.htm (accessed April 19, 2009).

Appendix A
National Science Education Standards (NSES), Grades 9–12

NSES 1.1 Unifying concepts and processes: systems, order, and organization
NSES 3.2 Physical sciences: structure and properties of matter
NSES 4.5 Life science: matter, energy, and organization in living systems
NSES 5.1, 2 Earth and space science: energy in the Earth system; geochemical cycles
NSES 7.2–6 Science in personal and social perspectives: natural resources; environmental quality; natural and human-induced hazards; and science and technology in local, national, and global challenges

Source. National Research Council 1996.

Appendix B
Ocean Literacy Essential Principles and Fundamental Concepts

Ocean Literacy Principle 6: The oceans and humans are inextricably interconnected.

a. The ocean affects every human life. It supplies freshwater (most rain comes from the ocean) and nearly all Earth's oxygen. It moderates the Earth's climate, influences our weather, and affects human health.
b. From the ocean we get foods, medicines, and mineral and energy resources. In addition, it provides jobs, supports our nation's economy, serves as a highway for transportation of goods and people, and plays a role in national security.
c. The ocean is a source of inspiration, recreation, rejuvenation, and discovery. It is also an important element in the heritage of many cultures.
d. Much of the world's population lives in coastal areas.
e. Humans affect the ocean in a variety of ways. Laws, regulations, and resource management affect what is taken out and put into the ocean. Human development and activity lead to pollution (point source, non-point source, and noise pollution) and physical modifications (changes to beaches, shores, and rivers). In addition, humans have removed most of the large vertebrates from the ocean.
f. Coastal regions are susceptible to natural hazards (tsunamis, hurricanes, cyclones, sea level change, and storm surges).
g. Everyone is responsible for caring for the ocean. The ocean sustains life on Earth, and humans must live in ways that sustain the ocean. Individual and collective actions are needed to effectively manage ocean resources for all.

Source. National Geographic Society et al. 2006.

Appendix C
Role Cards Used to Assign Each Student a Role as a Game Player

I suggest formatting these cards so that each player symbol uses a full 8.5 × 11 in. piece of paper. Use different colors of paper for different roles. Laminate each page. Put all pages for a specific role onto a piece of cord so that the student can easily flip from one page to another to show where he or she is in transformations. I suggest putting the rules for each player onto a separate and smaller piece of paper, laminating them. and stringing them onto another cord. The role N occurs three times because it is needed with P, FISH, and WORM.

O_2	Our hero! Walk slowly in circles of different sizes. You may go anywhere you want as long as you do not cross the pycnocline. If you are tapped, by a Fish☺, Fish☹, Worm☺, Worm☹, or P☹, you will become a CO_2. Turn your face to let CO_2 show.
CO_2	Walk slowly in circles of different sizes. You may go anywhere you want as long as you do not cross the pycnocline. When a P and N together join you, remain with them long enough to turn your face over to become an O_2.

N	Walk slowly back and forth and up and down across the water body. Do not cross the pycnocline. If you come across a P☺, join it and a CO_2 long enough to turn your card over and become a P☺. If you cannot find a P☺, keep walking.
P ☺	Walk briskly back and forth and up and down across the water body. Spend most of your time near the surface. Do not cross the pycnocline. Whenever you see an N, join it and a CO_2 long enough to for the N to become a P and the CO_2 to become an O_2. Then continue drifting. When you have crossed the water body (across and back, plus down and up), you die and become PK; turn your face to let K show.
P ☹	Fall slowly through the pycnocline. Then stand still. If you can reach an O_2, tap it. You become N; turn your face to let N show.

N	Walk slowly back and forth and up and down across the water body. Do not cross the pycnocline. If you come across a P☺, join it and a CO_2 long enough to turn your card over and become a P☺. If you cannot find a P☺, keep walking.
FISH ☺	Walk slowly anywhere you want in any pattern you want. You must find one (no more than one) O_2 for each two lengths across the water body. When you find an O_2, tap it. Keep swimming. If you cross the water body twice without finding an O_2, you die; turn your face to let ☹ show.
FISH ☹	Stand still. If you can reach an O_2, tap it. You become N; turn your face to let N show.

N	Walk slowly back and forth and up and down across the water body. Do not cross the pycnocline. If you come across a P☺, join it and a CO_2 long enough to turn your card over and become a P☺. If you cannot find a P☺, keep walking.
WORM ☺	Stand in one place. In a smooth action, raise your right arm and lower it, then raise your left arm and lower. Repeat this movement constantly and at a steady rate. You must find one (and no more than one) O_2 during the time you raise your left arm 5 times. When you find an O_2, tap it and finish counting to 5. Then begin again counting and looking for an available O. If you do not tap an O_2 by the time you raise your left arm 5 times, you die; turn your face to let ☹ show.
WORM ☹	Stand still. If you can reach an O_2, tap it. You become an N; turn your face to let N show. Sit down.

Appendix D
Summary Chart

Provide a chart like this one to each student, or complete one for the whole class. I suggest beginning with the chart blank except for the first two lines. That will encourage students to think about what is required to complete every blank.

	Initial Conditions						Final Conditions					
Round	P	N	CO_2	O	F/W	Situation	P	N	CO_2	O	F/W	Result
1	2	2	8	8	0	Mixed, low nutrients					0	Healthy—win
2	2	2	8	8	0	Stratified, low nutrients					0	Healthy—win
3	2	6	6	6	0	Stratified, excess nutrients				0	0	No DO—lose
4	2	4	6	6	2	Stratified, excess nutrients, animals				0		Animals die—lose
5	1		6	6	0	Mixed, excess nutrients				> 0		Win
6	1		7	7	0	Stratified, excess nutrients				> 0		Win