Investigating Aquatic Dead Zones

A series of activities designed to explore a mystery of the deep

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We are increasingly aware of our changing coastal oceans and how they impact our lives—from rapidly eroding shorelines to harmful algae blooms, expanding dead zones, and declining fisheries. Although we read about these and other trends in news articles, their causes and consequences are poorly understood by the general public. Scientific research has produced logical explanations for many of these trends, but clear understanding of the science behind these dynamic processes does not always translate to the broader community.

This article features two engaging high school activities that include current scientific information, data, and authentic case studies. The activities address the physical, biological, and chemical processes in aquatic systems that are associated with oxygen-depleted areas, or "dead zones," in aquatic systems. Students can explore these dead zones through both hands-on investigations and interdisciplinary, critical-thinking exercises. These activities were designed by a research scientist, graduate students, a teacher, and an undergraduate student as part of the Center for Ocean Sciences Education Excellence (COSEE) Coastal Trends

Scientist–Educator Partnerships (see "On the web") and were tested in both middle and high school classrooms.

Understanding dead zones

Dead zones are regions in fresh and marine aquatic environments in which dissolved oxygen concentrations drop to extremely low levels. This condition of oxygen deficiency, known as *hypoxia*, results from a combination of biological, chemical, and physical conditions. In the absence of sufficient oxygen, most nonmicrobial organisms (e.g., fish, worms, and plants) must migrate to more oxygenated areas, or they will suffer physiological stress or even death (Diaz and Rosenberg 1995). Many bacteria, however, can thrive in this region, or "dead zone," by feeding on the abundant food produced in the overlying waters; a few invertebrate species can temporarily withstand the negative effects of low oxygen. Dead zones currently occur, or have occurred, in many aquatic ecosystems around the world, including Lake Erie, the Northern Gulf of Mexico, the Chesapeake Bay, the Black Sea, and Tokyo Bay (Diaz and Rosenberg 2008; Kemp et al. 2009).

Although dead zones develop naturally in many ecosystems, some have expanded and new ones have formed over the last 50 years. This expansion is usually a result of increased land–water loads of key pollutants (e.g., organic matter and inorganic nutrients) derived from human activities such as population growth and associated sewage discharges, expanded use of fertilizers, and increased release of nutrients into the atmosphere from the burning of fossil fuels and animal agriculture. Because dead zones can negatively affect aquatic ecosystems in broad (many organisms suffer) and pronounced (many are killed) ways, efforts to remediate these zones have increased in recent years (Kemp et al. 2009)—many of which have focused on changing human activities on land and in the water.

Scientific efforts to understand dead zones require the cooperation and collaboration of experts from many different disciplines. As a result, this topic is well suited for a range of science classes, including biology, physics, chemistry, ecology, and environmental science. In this article, we present a series of small-group activities and investigations that use readily available materials to explore the various causes of dead zones. All of the activities require some degree of teacher supervision and are best performed in the suggested sequence. From these activities, students gain both scientific training and a greater appreciation for an important socioeconomic problem.

Biology and dead zones

Phytoplankton are free-living, microscopic plants that inhabit all water bodies—they are responsible for the green color of most lakes, ponds, and coastal waters. Like all plants, phytoplankton require light and a series of dissolved

FIGURE 1

Biology and dead zones.

Objective

Students will understand the biological processes associated with dead zones and how human activities affect the severity of dead zones. Students will also learn to collect, plot, and analyze data, and use scientific equipment.

Materials

- three clear 2 L soda bottles or mason jars per student group
- scissors
- plastic wrap
- large rubber bands
- dissolved oxygen sensor
- tape (to label bottles)
- pond, lake, stream, or estuary water (**Safety note:** Water should be obtained from a safe source by the teacher.) CAUTION
- tap water
- sunlit windowsill
- commercial fertilizer (**Note:** Use a fertilizer that contains only nitrate, ammonia, and phosphate [potash is acceptable] and avoid urea.)
- a dark place to set bottles

Procedure

Teacher: Divide students into groups of three or four and have each group bring in three bottles or jars; review the concepts of photosynthesis, respiration, and decomposition with the students.

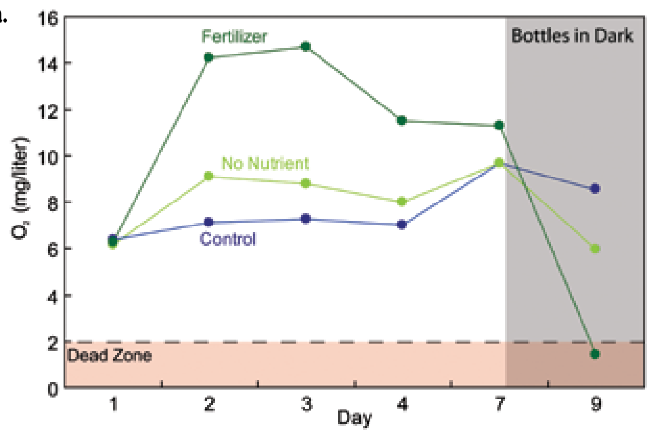
Students:

1. If using 2 L bottles, cut the top off of each bottle (where it tapers) and remove plastic or paper covering. (**Safety note:** Use care with sharp objects such as scissors.) CAUTION
2. Fill one bottle with tap water and let sit overnight. Label the bottle "Control."
3. Fill the remaining two bottles with water from a pond, lake, or other body of water. (**Safety note:** Water should be obtained from a safe source by the teacher.) CAUTION
4. Add 100 mg of fertilizer to one of the bottles from Step 3 (if using 2 L bottles—if not, adjust amount accordingly). Mix thoroughly to dissolve. Label this bottle "Fertilizer." Label the remaining bottle from Step 3 as "No nutrient." Place both bottles in a sunlit window for five to seven days. Record daily ob-

servations of the bottles, including sight and smell descriptions and an oxygen-concentration reading (in mg/L) using the digital lab probe. (**Safety note:** Make sure your teacher is available to supervise when you use the oxygen probe.) CAUTION The best time of day to record oxygen readings is in the afternoon when the growing algae reach peak net photosynthesis. The idea is to simulate an algal bloom, or eutrophication, in which excess phytoplankton grow in response to excess nutrient input. (**Teacher note:** As the microscopic algae grow, observe increased oxygen levels due to photosynthesis. Eventually you will be able to see algae growing. You should observe significantly more algae in the fertilized bottle, and significantly higher oxygen levels.)

5. Plot the dissolved oxygen reading each day using a spreadsheet or by hand, as in Figure 1a.

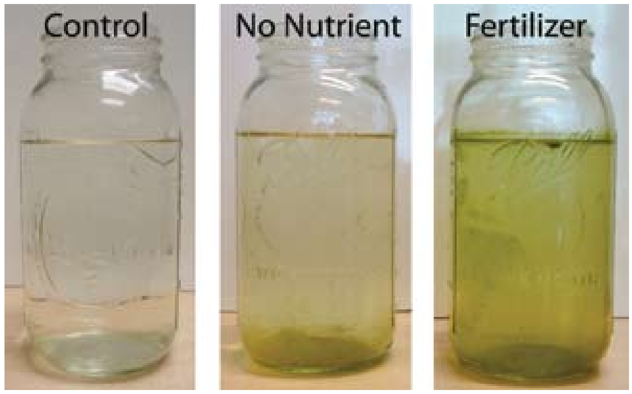
a.



A time series of dissolved oxygen concentrations in the Control bottle, No nutrient bottle, and Fertilizer bottle during and after the bottles were exposed to light.

6. After five to seven days (or when an algal bloom has grown in the fertilizer bottle), remove the bottle from the sunlight and cover with plastic wrap (if a 2 L bottle) or the mason jar cap. Secure the plastic wrap with a rubber band and leave the jar in a dark place. This is meant to simulate what happens when phytoplankton in a coastal system die, sink to the bottom, and decompose—consuming oxygen. Continue to record data each day. (**Teacher note:** Oxygen levels should fall to a dead zone [less than 2 mg/L or 2 parts per million] as algae die and start to decompose [Figure 1b].)

b.



Photos of the bottles at the end of the investigation.
PHOTOS COURTESY OF CASSIE GURBISZ

Hints

- This investigation is best suited for non-winter months, when sunlight, phytoplankton biomass, and temperature are at high levels.
- Reagent grade nitrate (e.g., sodium nitrate) and phosphate (e.g., sodium phosphate) can be purchased or obtained from a chemistry lab and used instead of fertilizer. The percentage of the mass of these compounds should be 15% nitrate and 23% phosphate to prepare the appropriate 100 mg addition to the 2 L bottles.
- Take oxygen readings at the same time each day—ideally in the afternoon, as this is the peak of daily phytoplankton oxygen production.
- You may need to leave the bottles in the sun for a few more days if you do not observe a marked difference between bottles—especially if you experience several cloudy days during the investigation.

Student questions

- What trend did you observe in oxygen readings for each bottle throughout its time in the sunlight (i.e., did the readings increase, decrease, stay the same)?
- Why did this trend occur?
- Explain the different colors and oxygen levels in each bottle after a week of growth.
- What happened to oxygen concentrations when you placed your bottles in the dark? Why?
- How do you think a fish would react if you placed it in the dead zone bottle?
- How might the presence of a large dead zone affect the marine food web?

compounds to synthesize complex organic molecules from inorganic carbon and water. In most aquatic ecosystems, nitrogen and phosphorus are the most important nutrients for regulating phytoplankton growth. For this reason, the addition of these nutrients to water bodies often results in the production of large blooms of phytoplankton through a process called *eutrophication* (Nixon 1998). When this occurs, and the availability of some nutrients becomes restricted, the phytoplankton die and sink into deeper waters. Here they are decomposed by bacteria in a process that consumes oxygen—driving dissolved oxygen levels down.

Since World War II, both the availability of inexpensive fertilizer and the growing human population have led to large increases in the transport of nitrogen and phosphorus from land to adjacent waters through many pathways. First, larger populations have resulted in more nutrient-rich wastewater from sewage treatment plants flowing directly into water bodies. Second, the expanded coverage of agricultural lands and higher applications of fertilizer have increased the amount of nutrients washing off of these lands into streams, lakes, and estuaries. Finally, the nitrogen that results from animal manure and the burning of fossil fuels in power plants and automobiles enters water bodies through atmospheric deposition. These trends are further aggravated by the loss of forests and wetlands—which naturally retain or filter nutrients—to

FIGURE 2

Physics and dead zones.

Objective

Students will understand the physical processes associated with dead zones, focusing on the concepts of density and stratification. Students will also be challenged to think critically about a simple demonstration, and hypothesize about various outcomes of the demonstration.

Materials

- water
- salt
- scales
- food coloring
- 10 ml graduated cylinders
- medicine droppers or pipettes
- paper cups

Procedure

1. Add 1 g of salt to 5 ml of cold water. Mix thoroughly in a cup to dissolve salt. Add one drop of food coloring (photo; cool, salty water).
2. Pour into a 10 ml graduated cylinder.
3. Add 5 ml of warm water to another cup. Add one drop of a different colored food coloring (photo; warm, freshwater).
4. Using a medicine dropper or pipette, add fresh, warm water to the graduated cylinder containing the cold, salty water (the two waters should not mix).
5. Check that the graduated cylinder with separated water masses looks similar to the photo.
6. Pick a partner and brainstorm different ways that you can mix the water to simulate earthquakes, tornados, hurricanes, and the cooling of surface waters in winter.
7. Try to simulate one of your ideas by mixing the water.

Hints

- You can try separate density-layering scenarios using one type of water (e.g., warm, freshwater) and compare how this is similar or different to the combined scenario.
- You can experiment with tools, such as ice cubes or straws, to aid mixing.

Student questions

- On a hot summer day in a deep body of water, where is the warm water, and where is the cold water?
- Which is denser: hot water or cold water? Salty water or freshwater?
- Why did the two layers of water not mix?
- How does oxygen get into water?
- How might stratification contribute to the dead zone?
- Why does a dead zone typically occur in deep water?

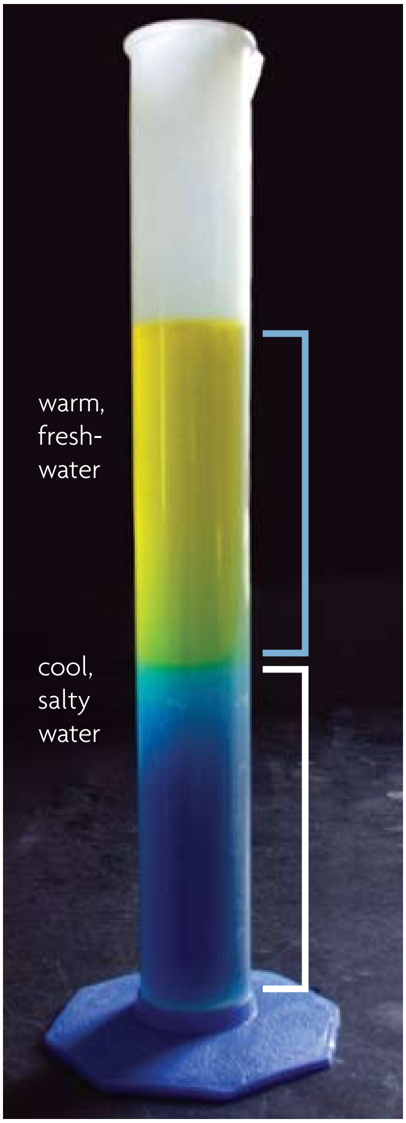


Image of graduated cylinder containing water masses of differing densities.

PHOTO COURTESY OF CASSIE GURBISZ

make room for farmlands, suburban development, and urban expansion.

The activity in Figure 1 (p. xx) aims to connect the concepts of increased nutrient loading, phytoplankton blooms, and dead-zone formation in an experimental aquatic "ecosystem." This activity can be introduced with lessons on phytoplankton physiology and human impacts on land. In the activity, students place pond, lake, stream, or estuary water in bottles, and add fertilizer to one bottle. They observe excess phytoplankton growth in the fertilized treatment—both visually and through the changes in oxygen due to increased photosynthetic activity. Teachers should discuss with students that oxygen is a product of photosynthesis, so as the algae grow, the amount of oxygen in the jars increases. Students also force the resulting phytoplankton bloom to die by placing the bottles in darkness, where they then observe oxygen depletion caused by decomposing algae. Students compare the fertilized bottle to the unfertilized controls to learn how excess nutrients cause rapid algae growth and, ultimately, dead zones.

Physics and dead zones

The density of a material is defined as its mass in a specific volume. Density is often expressed in kilograms per cubic meter (kg/m^3). The density of pure water at 4°C approaches 1,000 kg/m^3 (or 1 g/cm^3). Warm water is less dense than cold water, and adding salt to water increases its density; this is because mass is added to the water without a substantial change in volume. Water that has more mass per unit volume—thus exhibiting a higher density—will sink beneath warm, freshwater of a lower density. Therefore, warm, freshwater will rest above cold, salty water.

Stratification is the vertical separation of two water masses with differing densities. One important consequence of stratification is that the two vertically distinct water masses often do not mix with each other—so the transfer of dissolved gases, such as oxygen, between these layers of differing densities is restricted. Because dead zones often form in deeper waters where photosynthesis does not occur, the only source of oxygen is that which is mixed from surface waters into bottom waters across a density boundary.

In lakes, temperature is the primary cause of density differences; the boundary between the warm surface waters and cool bottom waters is called a *thermocline.* The thermocline is generally strongest (most developed) during the summer, when air temperatures effectively warm surface waters.

In estuaries, salt level (or salinity) is the primary cause of density differences, and freshwater sits above saltier deep waters. The boundary between these two layers is called a *halocline,* and is strongest when freshwater inflow is strongest—effectively reducing the salinity of the surface water. The density boundary is also strong during warm summer months, although temperature plays a minor role in the stratification of estuaries.

Weather patterns can also affect stratification. The physical energy from winds and tides enhances gas exchange between the atmosphere and surface waters and mixes surface waters with bottom waters. As a result, oxygen in the air diffuses into water and is mixed into bottom waters—replenishing oxygen that was consumed by decaying algal blooms. During periods with little wind, oxygen movement into bottom waters is restricted, and dead zones can become larger. During warm periods, the quantity of oxygen that water can hold (its solubility) is reduced, and warm surface waters therefore have less oxygen to mix into deep water. Warmer temperatures also speed up the biological processes that consume oxygen in deep waters, so oxygen movement into bottom waters must be faster to keep dead zones from growing.

Students are able to observe stratification in the activity in Figure 2. They also learn how the stratification of lakes and estuaries contributes to the formation of dead zones. In this activity, students simulate stratification by carefully placing dyed, warm freshwater on top of a cold saltwater solution dyed with a different color. They hypothesize about and test ways that stratified waters can mix. This activity can be introduced with an overview of density, stratification, and climatic effects on aquatic physics.

Extensions and conclusions

A third activity involving biophysical interactions is available online (see "On the web"). In this activity, students analyze real dead-zone distributions over time and space in the Chesapeake Bay and learn how different combinations of nutrient loading and wind energy create larger and smaller dead-zones. This activity should follow the activities in Figures 1 and 2 because it synthesizes the lessons learned from both activities into critical thinking about how dead zones may vary and how this variation relates to real-world questions. These applied questions focus on dead zones' impact on aquatic organisms and ecosystem management problems.

The concepts covered in the activities presented in this article apply to topics in both life and physical science (NRC 1996; see "Addressing the Standards," p. xx). These hands-on activities provide a meaningful context for students in understanding processes that are difficult to directly observe and that relate to their everyday experiences. By exploring the science concepts associated with dead zones in a step-by-step manner, students can progressively unravel the details that underlie this complex and potentially nonintuitive topic. Through research and critical thinking, students gain a deeper understanding of the direct connection between humans and the aquatic environments we influence. This link can be further addressed through discussions

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of how future changes in land use and climate may affect dead zones and by exploring the trade-offs associated with human activities and their consequences.

Further investigations into the science of dead zones can also be accomplished by free-form exploration of web-based resources (see "On the web"). Computer labs can allow personal web searches, or teacher-guided web searches can provide more guided learning. In this way, students are able to address specific questions about dead zones at their own pace.

The activities described in this article should enhance students' understanding of how processes studied in two core scientific disciplines—physics and biology—interact to produce dead zones in aquatic ecosystems. An opportunity is therefore provided to introduce a timely environmental management problem in the classroom and analyze the problem both visually and quantitatively. Students can apply this advanced scientific knowledge to develop an integrated view of how humans and their activities interact with climate changes to degrade natural ecosystems now and in the future. ■

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On the web

Activity information and dead zone tutorial:
- *www1.coseecoastaltrends.net/modules/dead_zones/get_started*
- *www1.coseecoastaltrends.net/modules/dead_zones/access_classroom_resources*

Biophysical interactions activity: *www.nsta.org/highschool/connections.aspx*

COSEE Coastal Trends Modules: *www1.coseecoastaltrends.net/modules*

Dead zone scenario data cards: *www1.coseecoastaltrends.net/modules/dead_zones/access_classroom_resources/what_affects_dead_zones*

Gulf of Mexico Hypoxia Watch: *http://ecowatch.ncddc.noaa.gov/hypoxia*

Lake Erie Dead Zone: *www.epa.gov/lakeerie/eriedeadzone.html*

Maryland Department of Natural Resources and Chesapeake Bay Program: *http://archive.chesapeakebay.net/status/wquality/interpolator/do/gallery.htm*

United States Geological Survey Hypoxia Summary: *http://toxics.usgs.gov/definitions/hypoxia.html*

References

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Kemp, W.M., J.M. Testa, D.J. Conley, D. Gilbert, and J.D. Hagy. 2009. Coastal hypoxia responses to remediation. *Biogeosciences Discussions* 6: 6889–6948.

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Nixon, S.W. 1998. Enriching the sea to death. *Scientific American* 9: 48–53.

Addressing the Standards.

The following National Science Education Standards (NRC 1996) are addressed in these activities:

- Unifying Concepts and Processes (p. 117):
  - Evidence, models, and explanation
  - Constancy, change, and measurement
- Science as Inquiry (p. 173):
  - Abilities necessary to do scientific inquiry
  - Understandings about scientific inquiry
- Physical Science (p. 176):
  - Structure and properties of matter
- Life Science (p. 181):
  - The cell
  - Interdependence of organisms
  - Matter, energy, and organization in living systems
  - Behavior of organisms
- Science in Personal and Social Perspectives (p. 193):
  - Natural resources
  - Environmental quality
  - Natural and human-induced hazards