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INQUIRY & INVESTIGATION

Demonstrating the Effects of Ocean Acidification on Marine Organisms to Support Climate Change Understanding

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Abstract

Ocean acidification, a product of CO_2 absorption by the world's oceans, is largely driven by the anthropogenic combustion of fossil fuels and has already lowered the pH of marine ecosystems. Organisms with calcium carbonate shells and skeletons are especially susceptible to increasing environmental acidity due to reduction in the saturation state of $CaCO_3$ that accompanies ocean acidification. Creating a connection between human-mediated changes to our environment and the effect it will have on biota is crucial to establishing an understanding of the potential effects of global climate change. We outline two low-cost laboratory experiments that eloquently mimic the biochemical process of ocean acidification on two time-scales, providing educators with hands-on, hypothesis-driven experiments that can easily be conducted in middle and high school biology or environmental science courses.

Key Words: *Ocean acidification; global climate change; science curriculum; inquiry-based learning; experiential learning.*

Introduction

The youth of today are most likely to suffer the negative effects of global climate change. In order for the citizens of tomorrow to alter the present trajectory of our changing environment, they must bring global economies to task by imploring our leaders to implement sustainable management practices and make informed policy choices regarding the health of our planet. It's vital to begin to create a connection between students' general awareness of this problem and the actual consequences facing our natural world. Research has shown that understanding what global climate change *is* doesn't necessarily lead to understanding the *consequences* of it (Boyes & Stanisstreet, 1993). Our perceptions of these issues often lack an experiential component – if we can't "see" the negative effects of climate change, it is more difficult to understand what the impacts are. As advances are made in understanding how students learn and the impact of societal change in the 21st century, it is necessary to reexamine science programs (Bybee, 2012). The activities presented here are a step in the transition to a 21st-century approach to curriculum and instruction that builds students' awareness through authentic science experience. These activities can be utilized to support teachers with transitioning to the type of teaching and learning outlined in the *Next Generation Science Standards* (NGSS Lead States, 2013). Additionally, teachers can use these investigations along with supplemental readings to integrate Common Core State Standards for Science and Technical Literacy.

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Ocean Acidification: What Is It & Who Does It Affect?

Currently, the marine environment is undergoing a state of rapid change because of human activity (Meehl et al., 2007) as drastic increases in atmospheric concentrations of CO_2 are absorbed by the world's oceans (Sabine et al., 2004). Between 1751 and 1994, surface ocean pH is estimated to have decreased from 8.25 to 8.14 (Jacobson, 2005), representing a ~30% increase in hydrogen ion concentrations. A reduction in oceanic pH heavily influences marine organisms that produce shells and skeletons through the process of calcification, which involves the precipitation of dissolved ions into $CaCO_3$, referred to as calcium carbonate (Fabry et al., 2008). Through the process of biomineralization, calcium carbonate is deposited within marine calcifying organisms and provides a physical structure for soft tissue to adhere to, in much the same way that bones provide structure for vertebrate organisms. When CO_2 is absorbed by the ocean, resulting in decreased pH, the saturation state of $CaCO_3$ is reduced, driving the dissolution of calcium carbonate within marine calcifiers, weakening the "bones" of these animals (Figure 1; for a review, see Fabry et al., 2008). Already, experimental work has found that ocean acidification negatively affects many species of marine calcifiers in all ecoregions, including coccolithophores, corals, foraminifera, echinoderms, crustaceans, and molluscs (National Research Council, 2011). Furthermore, the World Health Organization has stated that global climate change has already led to "5 million cases of illness and more

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than 150,000 deaths every year" (Patz et al., 2005), underscoring the need to broaden public awareness regarding the consequences of global climate change.

Discussions about global climate change in the classroom setting are often limited to effects on plants and animals. However, global climate change can also bring about conversations regarding how human-driven changes to our environment are affecting indigenous communities globally and locally. The threat that global climate change poses to many indigenous communities worldwide is particularly perilous, because traditional economies, cultures, and livelihoods are intrinsically and holistically linked to healthy marine ecosystems (Green et al., 2009). In the United States, Native communities have already begun to create and teach climate change–related curricula using traditional ecological knowledge as a framework for highlighting the importance of climate change education (Hugo et al., 2013). Therefore, climate change–related education influences not only the perceptions of the general public but also the health of indigenous people and preservation of indigenous ways of life (Green et al., 2009).

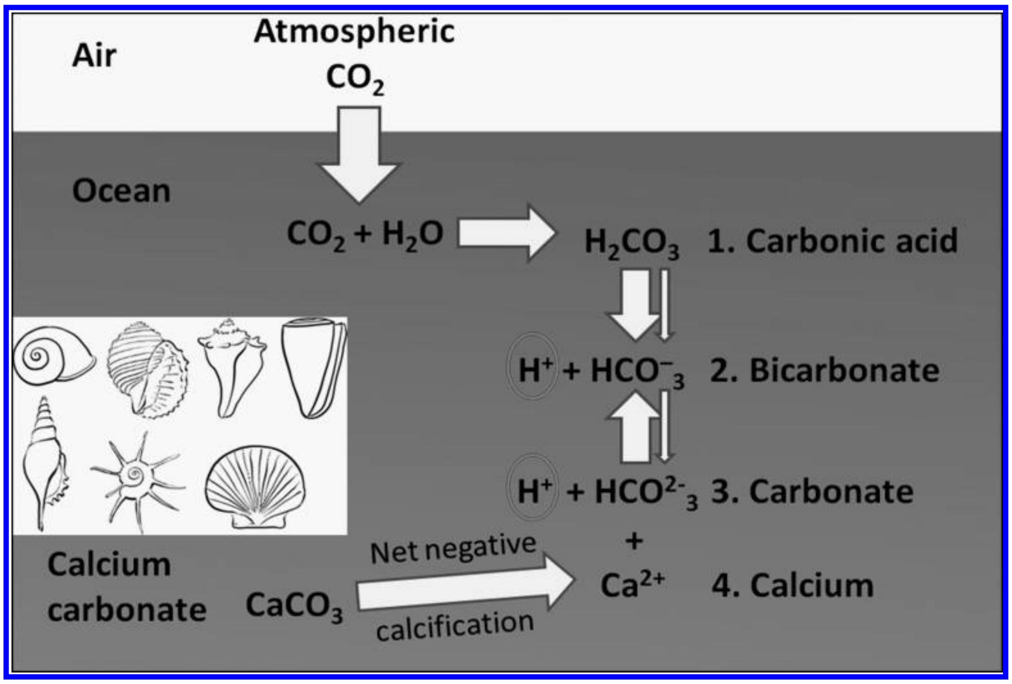

Figure 1. Calcification reaction in seawater. An increase in hydrogen (H+) ions alters the equilibrium reaction, leading to a shift toward bicarbonate. This is because the excess hydrogen ions combine with carbonate to form bicarbonate. Carbonic acid is less stable than bicarbonate in seawater, so that reaction is also shifted toward bicarbonate.

For example, in the Pacific Northwest of the United States, shellfish are critically important to Native American tribes. These animals are collected for both commercial and ceremonial or subsistence purposes (http://nwifc.org/about-us/shellfish/). The Northwest Indian Fisheries Commission states that

> Bivalve shellfish have provided sustenance to Pacific Northwest Tribes for thousands of years and figure prominently in tribal spiritual beliefs. Symbolic of the cultural significance of shellfish is the phrase, *ta'aWshi xa'iits'os*, from the native Quinault language meaning "clam hungry."

From an economic standpoint, ocean acidification can devastate local-scale economies. Researchers from Oregon State University directly linked increases in ocean acidification to the decline of oyster seed production at Whiskey Creek Shellfish Hatchery. They found that as ocean acidification increased, growth was reduced and mortality increased (Barton et al., 2012), reducing the economic viability of this aquaculture product. Furthermore, the aquaculture of oysters on the west coast of the United States generates ~100 million dollars in gross sales annually and is an important component of local commerce for small coastal economies.

Project-Based Curriculum Using the 5E Model

This article presents two in-class activities that demonstrate the process of ocean acidification and its consequences to marine life through the Biological Sciences Curriculum Study (BSCS) 5E model (Engage, Explore, Explain, Elaborate, and Evaluate). These activities place students in the role of active researchers investigating the effect of ocean acidification on marine calcifiers. This approach to teaching and learning is recommend by Llewellyn (2005): "In inquiry-based learning, the emphasis is placed on the student as an active investigator." Through these activities, students take an active role in their learning by using scientific practices and crosscutting concepts to discover disciplinary core ideas. These activities provide curriculum for teachers looking for material that aligns to the *Next Generation Science Standards* for grades 7–9 (Table 1).

○ Experiment 1: Chalk-Acid Activity

This experiment is intended to model how increased atmospheric CO_2 results in an acidic ocean environment, which can affect an animal's calcium carbonate structure. Chalk is made of limestone, a byproduct of the gradual accumulation of minute calcium carbonate plates shed from coccolithophores over evolutionary time and models the "marine organism" in this experiment. To represent the "acidic ocean," a number of household items can be used, including lemon juice, carbonated water, or vinegar. These solutions vary slightly in their relative acidity, and all can be used to compare the differing effects that variations in pH can have on the dissolution of the chalk. The activity can be broken into 2 days: the first for an introduction and exploration, and the second for explanation and extension.

This scope and sequence of the lesson places these activities toward the end of an ecology unit as part of an activity exploring chemical cycles, particularly the carbon cycle. The activity can begin by engaging students with a question about dissolved CO_2 in solution. Students are asked what makes soda bubbly. They can then observe and compare

Table 1. ***Next Generation Science Standards*** **addressed in activities.**

Science & Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
• Asking questions and defining problems. • Developing and using models. • Planning and carrying out investigations. • Analyzing and interpreting data. • Using mathematics and computational thinking. • Constructing explanations and designing solutions. • Engaging in argument from evidence. • Obtaining, evaluating, and communicating information.	• LS2.B: Cycles of Matter and Energy Transfer in Ecosystems. • ESS3.C: Human Impacts on Earth Systems. • ESS3.D: Global Climate Change. • ETS1.B: Developing Possible Solutions.	• Identifying patterns. • Cause and effect: Mechanism and explanation. • Scale, proportion, and quantity. • Systems and system models. • Energy and matter: Flows, cycles, and conservation. • Structure and function. • Stability and change.

Table 2. Record pH and mass of chalk (g).

Solution no.	Initial Solution pH	Initial Chalk Mass	Chalk Mass (5 min/pH sol.)		Chalk Mass (10 min/pH sol.)		Chalk Mass (15 min/pH sol.)		Chalk Mass (20 min/pH sol.)	
1. Lemon juice										
2. Soda water										
3. Water										

carbonated water with noncarbonated water. In addition to the bubbles, students will discover that pH differs between carbonated and noncarbonated water. Students are then asked how increased CO_2 in the atmosphere might affect the ocean. Once students have formulated their questions, they can be shown a brief video clip explaining the connection between anthropogenic increases in atmospheric CO_2 and ocean acidity (https://www.youtube.com/watch?v=mFlOgNrfSdo). This leads to the essential question, "How might increased ocean acidity affect marine calcifiers?" Students can then begin their exploration of this topic through a guided investigation.

Engage

Students begin by brainstorming three organisms that live in the ocean that have a calcium carbonate shell or exoskeleton. They then use chalk to model their chosen marine calcifiers and the effects that the different solutions will have on their model organism. Students will need to generate a hypothesis statement in which they state which solution (1, 2, or 3) will cause the greatest degree of change in the chalk and why. The materials available for students to test their hypothesis include the following: beakers, pieces of chalk, lemon juice or vinegar, carbonated water, noncarbonated water, fresh seawater if available, weigh boats, graduated cylinders, forceps, pH probe or pH paper, bottle of rinse water, and scale (g). Students can then carry out a guided investigation.

Explore: Guided Discovery

For this experiment, students should have all the above items laid out on a table. Solutions should be numbered 1, 2, 3, etc. Initial pH measurements of the solutions can be taken and recorded before starting the experiment (Table 2). The chalk should be soaked overnight in water so that its mass is measured from a saturated condition at the start of the experiment. The chalk should then be weighed and the data recorded in the data table. Next, students set a timer for 5 minutes. The timer should be started at the exact time the chalk pieces are dropped into the various solutions. Students can gently stir each solution during the 5 minutes. When the timer beeps, the chalk should be blotted dry with a paper towel and weighed, and the mass recorded in the table. Next the pH of each solution is measured and those values are recorded in the table. Reset the timer for 5 minutes and repeat the above steps 4 times for a total of 5 chalk mass measurements (Initial, 5, 10, 15, and 20 minutes). The final pH values of the solutions are then measured and recorded.

Students present their datasets by organizing them in labeled and titled graphs. Students can make two graphs showing their results – one showing change in chalk mass over time and one showing change in pH for each solution. For the analysis and conclusion portion, students will show that they have a thorough understanding of the concept of the experiment and the results obtained. They will address the question "What is the significance of the findings?" Students will compare expected results with actual results, analyze experimental error, explain how the methods could be improved, and build a claim of significance based on the results. Students then can explain the results in terms of the purpose and support their claim with evidence from other similar experiments/studies (i.e., seeding the ocean with iron). This is a great way to allow students to extend or elaborate on their learning as well as evaluate the investigation and the impact of increased atmospheric CO_2 on marine ecosystems.

Explain: Inquiry to Understanding

After completing this experiment, students will be able to see the dissolution of the chalk over time while it is immersed in an acidic solution and can quantitatively characterize the change in mass as well. Because chalk is actually derived from marine organism fossils, students can logically associate the use of chalk to represent marine calcifiers in this experiment. These activities represent the blending of research with teaching. This transforms the traditional classroom into one based on professional science practices. McLaughin (2010) contends that this blend helps students open their eyes and make connections to nature while stressing the importance of conservation.

Elaborate

Additionally, with the educational scaffolding presented above, students can practice critical thinking by being asked how changes to the ocean might affect communities that derive a subsistence living from it. This can help illustrate the economic and social impacts that global climate change has on human communities, not just on animals. This current issue makes science relevant, which is particularly important for students traditionally underserved in science education and underrepresented in STEM fields. Teachers can ask, "Who around the world rely on catching their own food?" and "Who might these people be?" This opens up the discussion to include how global climate change can have an effect on cultural communities, specifically those indigenous groups that rely on healthy ocean ecosystems for subsistence survival. A short video describing the cultural connection to the ocean can be used to reinforce this idea (https://www.youtube.com/watch?v=uZexlPneYDI).

Evaluate

Students can demonstrate their understanding of ocean acidification by designing, evaluating, and refining a solution for reducing the impacts of human activities on the environment and biodiversity (NGSS Lead States, 2013). Students can read and discuss other climate change–related issues that are predicted to occur, for example sea-level rise. Based on what the students have learned from the above activity, the question can be posed, "How might sea-level rise affect indigenous communities?" The main goal of such questions is to highlight the fact that global climate change affects not only animals and economies, but indigenous cultures as well.

Table 3. Weekly record of shell mass (g).

Shell no.	Week 0	Week 1	Week 2	Week 3
1	18.29	14.74	12.33	12.33
2	14.74	10.35	9.50	8.93
3	10.06	4.68	1.84	1.70
4	42.95	34.44	34.30	2.72
5	56.98	52.16	44.65	44.08
6	4.96	13.89	11.06	8.65
7	3.54	1.13	0.71	0.14
8	9.92	8.36	7.23	7.09
9	136.79	87.60	60.10	58.12
10	39.83	29.20	29.06	23.53
11	17.58	6.66	6.52	2.83
12	4.96	2.27	0.99	0.85
13	32.74	26.08	25.94	19.28
14	13.47	10.06	9.21	9.07
15	16.44	14.12	13.78	13.32
16	30.62	22.82	22.25	22.11
17	33.31	24.66	19.70	19.56
18	18.71	16.58	15.45	15.45
19	45.08	35.44	30.33	30.19
20	37.28	31.47	26.93	26.79
Total mass	**588.25**	**446.73**	**381.90**	**326.76**

○ Experiment 2: Shells in an Acidic Ocean

Although this activity is similar to the one described above, the duration is much longer, as it is conducted over several weeks rather than in an hour. It is a more realistic representation of the effects of ocean acidification because it utilizes actual calcium carbonate shells from marine calcifiers instead of industrially produced chalk. Again, the "acidic ocean" in this experiment can be created from several household items, including vinegar, carbonated water, or another acidic compound. The duration of this experiment can be augmented, but a minimum of 3 weeks is necessary to visually see the changes in size, mass, and morphology of the shells.

In this activity, students will directly test the effect of an acidic solution, "ocean acidification," on marine calcifiers. The goal of this activity is to investigate how changes in the external environment affect marine organisms with calcium carbonate shells and skeletons.

Students need to be provided with an assortment of calcium carbonate shells from marine organisms (clam shells, sea snail shells, dead coral, etc.). They will be asked to predict how changes in ocean pH might affect their shells. They can then begin designing an experiment using the following materials: 5-gallon bucket, scale set to grams, aquarium aerator with air stone, 1 gallon of vinegar, and pH meter or litmus strips.

Students need to weigh each shell and record this mass as the initial mass at the beginning of the experiment (Table 3). It is important that students are able to identify each shell visually through the course of this activity; we suggest tracing the outline of each shell in a lab notebook to help identify each shell. Pictures of each shell can be taken at the beginning of this experiment so that students can see morphologically how the shells change over time. In a 5-gallon bucket, students can mix 1 gallon of white vinegar and 1 gallon of tap water, measure the pH, and record it (should be between 4 and 6 pH). Next, they will need to place the aquarium aerator bubbler in the 5-gallon bucket and turn it on. It is important to have continued water/vinegar flow over the shells so that the $CaCO_3$ continues to react with the acid over the duration of the experiment. Students then place the shells in the bucket and visually describe what they see. Some shells will start to "bubble" as shell dissolution immediately starts when the shells are placed in the bucket. The chemical

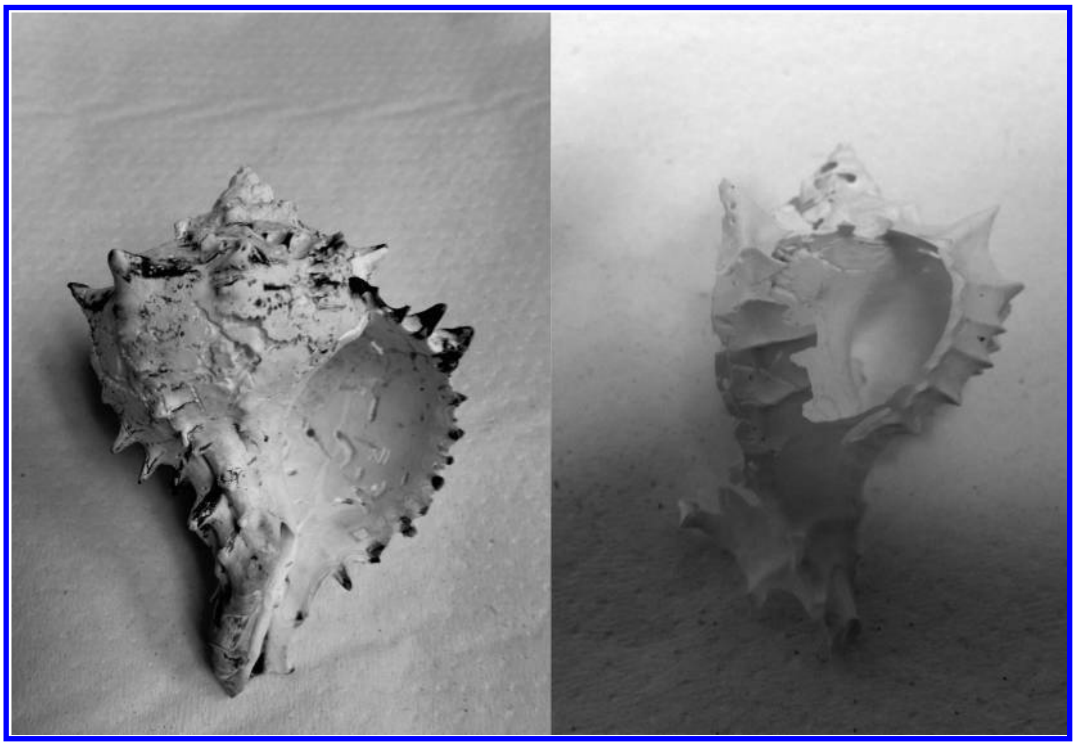

Figure 2. The effect of vinegar/water solution (pH 5) on a gastropod shell over the course of the experiment, 3 weeks. Photo courtesy Kayla Garcia.

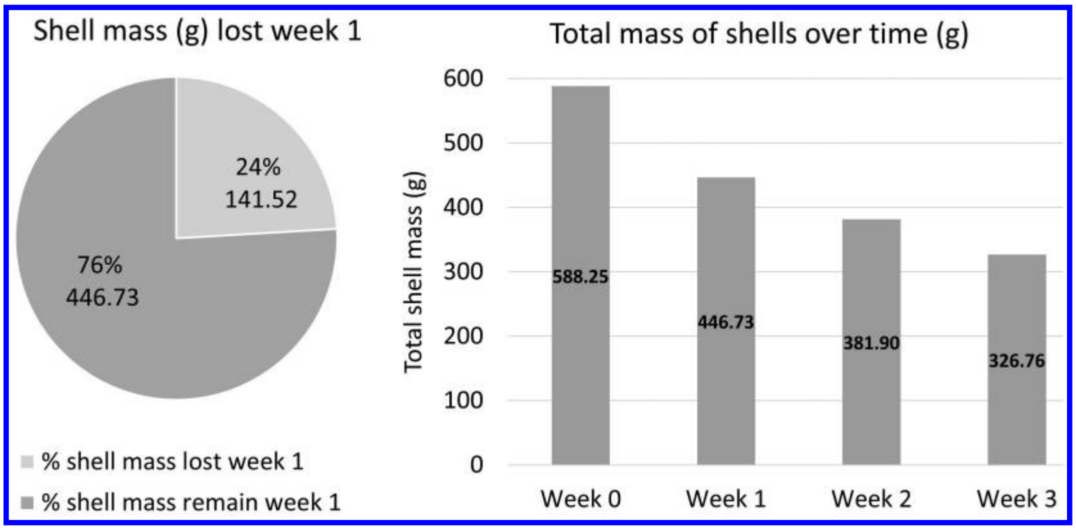

Figure 3. Pie chart illustrating the percent change in mass (g) in 1 week's time and bar chart showing the mass (g) of all shells lost over the course of the 3-week experiment.

equation for the active dissolution of shells is $CaCO_3 \Rightarrow Ca^{2+} + CO_3^{2-}$ (steps 3–4; Figure 1).

After a week of submersion, students can remove the shells from the bucket, hand dry them with a towel, and set them out overnight to dry. After drying for 24 hours, have students weigh each shell and record the mass in grams in their lab notebook (Table 3). They should note any visual changes to the shells; students might notice that they look lighter in color, as if they had been bleached. Ask students whether the size of the shell has changed. Suggest that students take pictures of each shell to visually record how they have changed over time (Figure 2). Before placing the shells back in the bucket, students need to record the pH of the vinegar water. They should be asked, "Did the pH change from the original pH measurement at the start of this experiment?" The pH of the vinegar water has probably changed, so replace it with new vinegar water set at the same concentration that was used at the start of the experiment.

Verify the pH of the replacement solution with a pH probe or pH paper. Put the shells back in the bucket and make sure that the aerator is working properly. Repeat the above steps for at least 3 weeks.

Students can decide for themselves how they would like to visually represent the data. One way of describing the effect of the acidic solution on the shells is to create a pie chart that describes how the shells lost mass over time (Figure 3). Also, a bar chart showing the total mass of all the shells throughout the duration of the experiment can illustrate how the shells lost mass each week (Figure 3).

○ Inquiry to Understanding

Research confirms the need for new models of climate change education (Moser & Dilling, 2004). This activity provides a model that demonstrates how an acidified solution reacts with calcium carbonate biostructures that result in active dissolution of those structures via a chemical reaction (steps 2–4; Figure 1). It is important for students to construct models that explain phenomena (Krajcik & Merritt, 2012). Students who participate in this lab will be able to recognize that ocean acidification is a threat to the global oceans, which can lead to behavioral augmentation that reduces the human impacts of global climate change because students now understand the significance of the problem (Mohai, 1985). In particular, laboratory experience is necessary for understanding science, because verbal and written forms of communication do not adequately translate the scientific process (Singer et al., 2006). The inquiries presented here are an inexpensive, easy-to-understand alternative to simply lecturing about global climate change. Education on this topic has the potential to alter the future course of environmental policy, decision-making, and even the future of our planet.

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