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Tracy D. Crews

Ocean acidification (OA), the change in ocean chemistry due to increasing concentrations of anthropogenic carbon dioxide in the atmosphere, is an environmental problem that is an active area of scientific research yet remains largely outside of the public's awareness. It is often assumed that if we raise OA awareness, then the public will support and take action to help mitigate the problem. This research project examines this assumption through the lens of educating high school students about OA. The research included three phases: (i) review of existing teaching resources on OA, (ii) development and refinement of a new OA curriculum based on strengths and gaps identified during the review process, and (iii) a longitudinal experiment testing the impacts to knowledge and attitudes of two approaches to teaching about OA.

This study has implications for those engaging in OA outreach and education efforts specifically, and for environmental education campaigns in general. During this study, we found that at least 90 teaching resources focused on OA are already available. These resources provide teachers with multiple approaches to teaching about OA, yet do not adequately address the multiple impacts of OA nor teach students about ways to help address the problem. We developed our own curriculum that underwent four rounds of revisions before appearing in the form presented here. Our experiment found that our teaching intervention increased knowledge but that attitudinal changes, when present, did not persist over time. Despite this lack of attitude change, student attitudes were generally sufficient to support mitigation actions.

Effects of Teaching Household Actions to Address Ocean Acidification on Student Knowledge and Attitudes

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Brian D. Erickson

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APPROVED:

Major Professor, representing Marine Resource Management

Dean of the College of Earth, Ocean, and Atmospheric Sciences

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Brian Erickson, Author

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CHAPTER 1: INTRODUCTION

Imagine I told you there was an environmental problem that you have probably never heard about whose scope and gravity were only truly realized by scientists in the past decade. Since then, thousands of scientific papers have been published detailing the problem and the threat it might pose to coral reefs, rocky intertidal zones, polar seas, and other marine ecosystems. This issue might threaten the food supply of hundreds of millions of people around the globe and has already changed the basic operations of some ocean-related businesses.

What if I told you we knew what caused the problem and that it was primarily a result of our own actions? That we have understood the basic chemistry of the problem for decades even if we remain uncertain of how the impacts will play out in the complex and dynamic real world. Would you want to know more about this mysterious environmental problem?

And what if I told you we have a good understanding of actions that could reduce the problem in the long-term so that our children and their children won't have to deal with an ever-worsening situation? That we know of numerous choices and behaviors that could directly and indirectly address the cause of the problem, and, while new discoveries and inventions could certainly help, we already have the technology we need to enact many of these solutions.

What would it take to motivate you to want to help fix this problem? Information? Fear? Hope? Peer pressure? Financial incentives? Would your intentions to help be thwarted by the demands and routines of daily life? In the end, do you think you would prioritize taking action to avoid this serious but uncertain, abstract future problem over the short-term costs and effort that might be involved in trying to fix it? And do you think other people in your city, state, or country would do the same?

This research project examines aspects of a common, often implicit, assumption: that knowledge of environmental problems will lead individuals to take action to fix those problems. It does this through the lens of educating students about ocean acidification.

PUBLIC AWARENESS OF OCEAN ACIDIFICATION

Scientific knowledge of ocean acidification (OA), the change in ocean chemistry due to increasing levels of atmospheric CO_2, is rapidly expanding. Most research on the topic has been published within the past decade. For example, a Web of Science search (May 2018) for "ocean"

AND "acidification" returns 5,461 publications dating back to 1990. The pace of research and publication has quickly accelerated such that 93% of all papers on OA have been published since 2010. In fact, 1 in 5 papers on OA have been published since the start of 2017. Scientists are clearly making efforts to learn more. Yet, with so many new findings, it can be difficult to synthesize what we know and see the bigger picture. In response to this challenge, there have been multiple efforts to summarize the current state of scientific knowledge on OA as well as calls for action at local, regional, and global scales. While these efforts are essential, the message does not seem to be making its way to the public at large.

Logan (2010) noted that at the time, there were no surveys of public awareness of OA. Multiple surveys of public understanding have taken place since (e.g., Buckley et al., 2017; Danielson & Tanner, 2015; Frisch, Mathis, Kettle, & Trainor, 2015; Gelcich et al., 2014; Schuldt, Mccomas, & Byrne, 2016), with several reaching the overall conclusion that the public generally has very limited knowledge of the topic. For example, The Ocean Project (2012) found very low public awareness of OA, but that concern greatly increased after a brief explanation of the issue. Similarly, online surveys of the British public found that only 20% of respondents had heard of OA and that reported knowledge was very low for those who had heard of it (Capstick, Pidgeon, Corner, Spence, & Pearson, 2016; Corner, Capstick, & Pidgeon, 2014). They also found that being presented with information about OA increased concern; however, few participants considered OA a risk over the next 50 years. Epperly, Swearingen, & Dalaba (2016) found that OA and hypoxia tied with wave energy development as the least understood ocean issue amongst Oregon coast visitors.

This disparity in knowledge between scientists and non-scientists suggests an intuitive solution: raise awareness and the public will see that OA is a big problem. Once they are sufficiently concerned, they are bound to demand action. Indeed, the Ocean Research & Resources Advisory Panel's Ocean Acidification Task Force (2011) summarized this mindset when they wrote, "Ultimately, any efforts to address the impacts of [OA] hinge on our ability to establish OA as an immediate concern to the general public"(p.10).

GOALS OF EDUCATION AND OUTREACH

Some researchers and educators may engage in outreach and education for the sole purpose of raising scientific literacy and awareness. However, many others focus on outreach and education in hopes that these efforts will raise support for and engagement in efforts to address the causes and impacts of OA. As the Washington State Blue Ribbon Panel on Ocean Acidification (2012) explains, "[outreach and education] can empower citizens and businesses to help develop and implement solutions"(p.xviii). Similarly, Strong et al. (2014) suggest, "public literacy of OA can increase the demand for science-based decision making and can accelerate regional responses to OA impacts."

KNOWLEDGE TO ACTION?

We know from our own experiences that awareness is only one of many barriers to taking environmentally friendly action. For example, we know that driving cars and flying in planes releases carbon dioxide and that this CO_2 contributes to climate change and OA. Yet, we still fly and drive because it is fast, convenient, and sometimes the only option. We might dislike disposable plastic bottles but use them anyway when we forget our reusable one at home.

Research has confirmed what we know from our own experiences, that lack of knowledge is an inadequate explanation for lack of public concern or action (Evans & Durant, 1995; Fauville, Säljö, & Dupont, 2013; Kahneman, 2011; Kelly, Cooley, & Klinger, 2014; Stern, 2000). In fact, summarizing several studies in conservation psychology, Gardner & Stern (2002) conclude that education alone can change knowledge, attitudes, and beliefs, but often has little to no impact on behaviors, especially when there are external barriers to action. McKenzie-Mohr (2011) explains it a different way when he writes, “The diversity of barriers which exist for any sustainable activity means that information campaigns alone will rarely bring about behavior change” (p.8). Thus, knowledge is only a prerequisite to action (Washington Marine Resource Advisory Council, 2017), or as Kelly et al. (2014) note,

> "knowing what changes societies must make (and the costs associated with making those changes) still does not result in timely action to remediate the causes of these problems. In short, even fairly sophisticated knowledge does not result in action." (p.592)

Fauville et al. (2013) state this more directly when writing,

> "Using information as an attempt to increase public awareness of OA, to change individual behavior (e.g., reduce individual direct and indirect CO_2 emissions) and to increase political engagement and acceptance of the needed policy instruments is not enough” (p.1864).

THEORIES OF ENVIRONMENTALLY-RESPONSIBLE BEHAVIOR

If knowledge alone does not lead to action, what makes some people who worry about an issue act to reduce the threat while others who also worry about the same issue do little or nothing about it? Three theories of action, Value-Belief-Norm theory (Stern 2000), the Theory of Psychological Coping (Lazarus & Folkman, 1984), and the Extended Parallel Process Model (Witte, 1994), while different in their details, all include the same key concept. Actions are determined, at least in part, by two things: whether you view a situation as a threat to something you care about and whether you believe you can do something to improve the situation (see Figure 1.1). As Lazarus & Folkman explain, if we think we have control over a threat that is facing us, we will engage in danger control, meaning we will try to fix the problem. In contrast, if we don't think we can control the threat, we will respond with fear control, seeking to reduce our feelings through responses such as denying, ignoring, or dismissing the threat. When applied to OA, these theories suggest that if we perceive OA as a threat and if we feel we can do something to fix it, then we will likely engage in problem-focused behaviors. In contrast, if we think OA is a problem but we do not think there is anything we can do about it, then we are likely to ignore it, deny it, or downplay its possible consequences. Similarly, if we do not perceive OA as a threat, we will not take action to fix it.

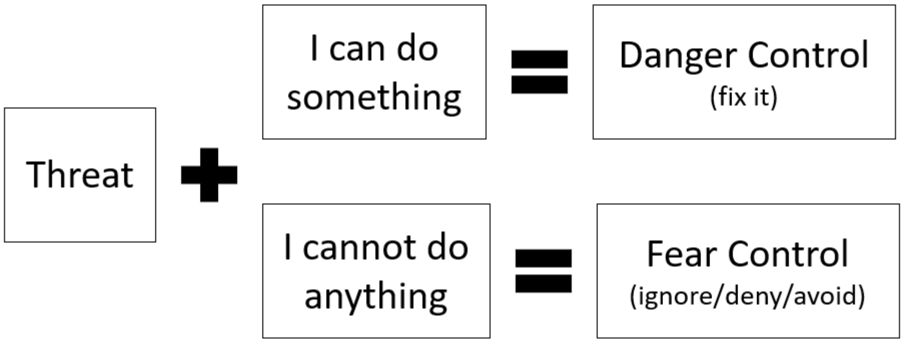

Figure 1.1 – Combined theory of action.

OCEAN ACIDIFICATION CURRICULA

Educators and scientists have responded to the need for instructional resources on OA. Indeed, at least 90 resources are freely available on the internet (see CHAPTER 2: for a detailed review of existing ocean acidification curriculum). These teaching ideas are essential in helping teachers, many of whom are also just learning of OA themselves, teach their students about the issue. However, many of these materials are scientifically outdated, few spend time addressing the range of possible impacts of OA, only a third discuss solutions at all, and few give more than passing mention of actions that might address the problem. Even when solutions are mentioned, it is not always clear how they relate back to OA's causes or impacts.

STUDY PURPOSE

This project seeks to increase student understanding of OA science through the creation, piloting, teaching, and distribution of a four-lesson high school curriculum module. We tried to design a curriculum that would inspire students to want to take action on OA. Then, we tested this curriculum in an experiment to see if talking about solutions, household energy saving actions in this case, changed students’ attitudes about OA. The ultimate question guiding this work is, does focusing on solutions make students more inclined to take action on OA?

STUDY DESIGN

This project included three key phases: resource review, curriculum development and revision, and a two-group non-randomized experiment. While detailed methods are provided in subsequent chapters, a brief overview is described here.

A review of existing curriculum was conducted via web search with two goals in mind: to understand how OA is currently taught and to identify the strengths and weaknesses in existing curricula. The results of this review, along with information from coursework, interviews with OA researchers, and a literature review, led to the identification of goals for a new curriculum. The curriculum and survey instrument used in the experiment were pilot tested with a group of twenty high school students attending a marine science summer camp at Hatfield Marine Science Center in Newport, Oregon. Following this pilot, the curriculum was revised and presented to a focus group of science educators for additional feedback. The curriculum was revised for a third time in preparation for the experiment, which included 10 high school science classes in Lincoln County School District, Oregon. In the experiment (see Figure 1.2), all students received three days of instruction on OA. Then, on the final day, the students in the control group conducted a traditional lab experiment on OA while the treatment group participated in a lesson that discussed household actions to reduce CO_2 emissions and thus combat the primary cause of OA. The

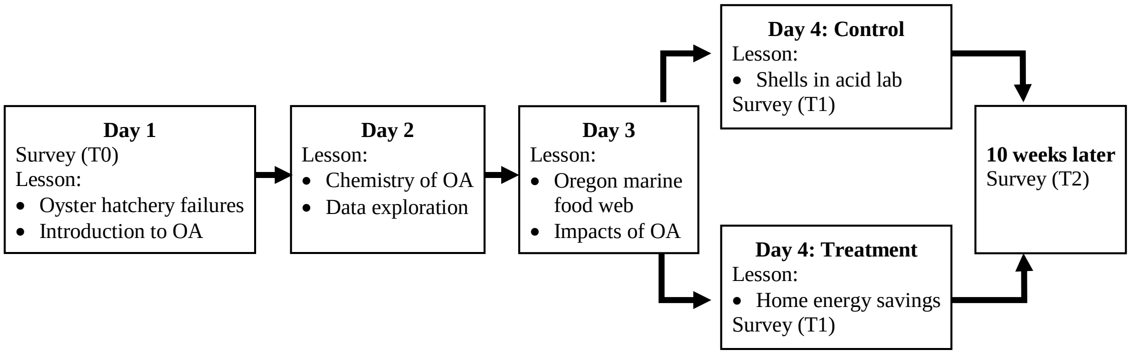

Figure 1.2 – Experimental design.

curriculum was revised one final time following the classroom experiment and is presented here in its final form.

THESIS OUTLINE

This thesis describes the development of a new OA curriculum, which was created after review of existing curricula (Chapter 2). The final curriculum is presented (Appendix A), as well as two manuscripts. The first manuscript (Chapter 3) is designed to help disseminate the new curriculum to high school teachers, while the second manuscript (Chapter 4) describes an experiment that was conducted to examine whether teaching students about ways to address OA changed students' attitudes about the problem. The conclusion (Chapter 5) discusses overall findings, limitations, and future directions.

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CHAPTER 2: CURRICULUM REVIEW

Before developing the ocean acidification (OA) curriculum outlined in chapters 3 and 4 of this thesis, I conducted a needs assessment to understand the existing landscape of freely available, online instructional materials on OA and to assess the merit of those materials.

LOCATING EXISTING CURRICULUM

Multiple steps were taken to find freely available, online instructional materials related to ocean acidification. Online teaching resources were used since teachers often resort to internet sources to find instructional resources and ideas. A keyword search using a search engine (Google) was conducted. To locate curriculum published in academic journals, the online library catalog of Oregon State University was searched. Even though resources in the University’s library are not necessarily freely available to educators, they were included to provide a more comprehensive understanding of the landscape of existing resources. Also, references and links appearing in identified teaching resources were used to find additional resources. Finally, websites of organizations that were likely to provide resources on ocean acidification were searched, including: Better Lesson, Virginia Institute of Marine Science (VIMS Bridge), National Ocean and Atmospheric Administration (NOAA), Center for Microbial Oceanography: Research & Education (C-MORE), Systems Education Experiences (SEE), Oregon Coast Education Program (OCEP) and others.

This search process located over 155 potential instructional materials. Since this project ultimately sought to develop a high school level curriculum on ocean acidification, resources that did not mention "ocean acidification" or were geared towards a college-level audience were excluded from evaluation. Additionally, resources that did not provide ideas on instruction, such as resource hubs (websites that only linked to other teaching resources but did not provide novel content), podcasts, videos, and radio segments, were not evaluated. In total, 90 resources from 59 different organizations were included in the final analysis (see Table 2.1), although one resource, NOAA's Data in the Classroom Ocean Acidification module, was under revision for the duration of this project and thus could not be evaluated.

Table 2.1 - Instructional resources included in the curriculum merit review.
All hyperlinks to available resources begin with http://tinyurl.com, which is followed by the text listed in the table. Grades: E= Elementary, K-5; M= Middle, 6-8; H= High, 9-12; G= General audience. L# = "lesson number." Bolded resource titles indicate our 12 favorite resources.

Organization	Resource Title	Summary	Date	Grade	Days	TinyUrl
Aquarium of the Bay	HS Chemistry Teacher Resource Guide	L1: Discuss pH and test pH of solutions. L2 lecture on ocean acidification equations. L3 use a carbon calculator to determine carbon footprint; CO_2 in water demo using dry ice. L4 is a student designed experiment of (egg)shells in acid. Good discussion guidance; no timing provided. No overarching set of instructions about the collection of lessons; unclear if they are meant to be taught in sequence or are supposed to be stand alone.	–	H	7-9	/ydaopym8
Around the Americas	Coral, Carbon Dioxide and Calcification	Students act out parts of the carbonate system as it relates to coral. Main message: CO_2 enters water, coral use carbonate to build their skeleton, and the ocean dissolves their skeleton. Active way for younger kids to learn about the carbonate system, but content may be too advanced. Would likely require a lot of teacher coaching and discussion, and the conclusion would likely be corals will dissolve.	2010	E, M	1	/yas64r5v
Bermuda Institute of Ocean Sciences	**You be the Chemist: Investigation of Ocean Acidification**	Experimental procedure for testing how lower pH impacts brine shrimp hatching. A novel idea for something to explore possible impacts on non-calcifying organisms. Some details and guidance are missing; this would be tough for elementary students. Could be a good starting point for high schoolers to design an experiment. No background on OA for students.	2012	E, M	2	–

Organization	Resource Title	Summary	Date	Grade	Days	TinyUrl
Better Lesson	Acid Alert! The Effects of Climate Change on Ocean Ecology	Walkthrough of how to use Stanford's Virtual Urchin lab. Finishes with a discussion of how climate change impacts marine organisms. This would be a helpful resource for teachers trying to figure out how to implement the online lab. It includes student work samples, a hook, and tips for the teacher.	–	H	1	/y82x25uw
	Acid Oceans part 1 & 2	Part1: Lesson on pH with slight OA connections. Includes: reading, PPT on acids/bases; make cabbage juice indicator; test pH of solutions; complete writing prompt on why soda won't make an upset stomach feel better. Part 2: review acids & bases with foldable; blow into cabbage juice indicator; use Virtual Urchin intro to connect to OA. Sample video shows student explaining that the CO_2 in their breath causes OA (possible misconception from demo).	–	M	2	/ybo2nfm6
	The Chemistry of Ocean Acidification: Exploring the Basics of pH	This lesson follows the Acid Alert lesson (see above). Brainstorm what students know about pH; quick lecture/PPT; test pH of solutions in lab; At end, students discuss the connections between pH and climate change. Revisiting the intro slides from Virtual Urchin after pH lab seems like a good way to make the connection. Teacher has also already done a carbon footprint analysis, which helps students make connections between OA and climate change.	–	H	1	/yamujjpa

Organization	Resource Title	Summary	Date	Grade	Days	TinyUrl
BIOACID / GEOMAR Helmholtz Centre for Ocean Research	**Ocean Acidification: The Other CO_2-Problem: Eight Experiments for Students and Teachers**	L1: Blow into indicator; place into varying temperature water baths. L2: Light candles floating on indicator. L3: Create CO_2 with TUMs, funnel to indicator solution. L4: Fill graduated cylinders with varying temperature water; place over a TUMs, see less air space form in cold water, suggesting it is holding more CO_2. L5: Explore alkalinity and buffering by lighting candles and aerate water (seawater vs tap) in beakers, measure pH change with probes. See that alkalinity buffers pH change. L6- compare color (indicator) of DI and seawater with Na_2CO_3, $NaHCO_3$, and plain. Blow into them and see how they change. Another look at buffering/alkalinity. L7- growing microalgae with CO_2 variation to show some plants may benefit from extra CO2 (seems more intensive lab setup). L8- Using handheld CO_2 loggers, students track CO_2 levels in class (and baseline around school/outside) over the course of a few weeks. Clear explanations, straight forward experiments with increasingly difficult concepts. L8 may reinforce misconception that breathing causes OA. Similar to CarboSchools writeups, but more polished. Each experiment has extension ideas.	2012	M, H	>8	/yaqqwa8n
Birch Aquarium	Got Shells?	Aquarium activity/demo. After brief intro, visitors dropper different solutions onto baking soda and look for signs of dissolution (bubbling). Then ask- what do they think will happen to shell building animals if oceans become too acidic? Discuss possible solutions. Modified shells in acid demo, but with extreme language. Does try to bring up solutions, but the actions aren't specific, and it isn't clear why certain actions are being suggested.	2008	G	<1	/ycl4nvue

Organization	Resource Title	Summary	Date	Grade	Days	TinyUrl
British Columbia Teachers Federation	Exploring Ocean Acidification: Climate Heroes Lesson Plans: Grades 8-12	Brainstorm: what is OA? Review pH (no script); Blow into indicator; discuss and debrief; 4-minute free-write; write poem in groups with phrases from their writing; research OA online; discuss findings & possible solutions (no guidance); listen to a song about salmon; read about low salmon runs and hypothesize why and how to help. Eclectic and unfocused. Supposedly spend time thinking of solutions to OA, but not clear when or to what depth. Biased language and tone.	–	M, H	2	/ybmrpzn9
Bureau of Ocean Energy Management	Lesson 4 - Ocean Acidification and Its Effect on *Lophelia*	Brainstorm about OA, then blow into indicator. Review requirements for deep sea coral survival, setup shells in acid experiment with dead coral pieces. Explain how corals calcify, that OA is an energy issue, and that they do survive in the wild (but with extra energy cost). Finish with discussion, then reading. Lesson from larger problem-based unit on deep sea corals. Same experiments as elsewhere but with better information. Heavy on vocabulary and coral biology in parts but provides an even-handed presentation of why OA impacts coral growth. Not sure how engaging students would find this; it seems content heavy.	–	H	3-4	*/ya8ofso2*
California Academy of Sciences	Ocean Acidification Mock Conference	After a teacher presentation on pH, ocean acidification, and possible impacts (in 15 minutes, without any guiding presentation provided), students are divided into stakeholder groups. They prepare for a mock conference, where they present how they are affected by OA and how they affect OA. Then they come together to brainstorm the biggest challenges and possible solutions as task forces. Fun, engaging way for students to engage in thinking about challenges and possible solutions to OA. What solutions do they come up with in this quick brainstorm? Reinforces the idea that corals and shelled organisms will dissolve due to OA.	2011	M, H	2	/y9rva9ts

Organization	Resource Title	Summary	Date	Grade	Days	TinyUrl
CarboSchools	Atmospheric CO_2 can produce ocean acidification	Write-ups of a few experiments: measuring pH change when blow in seawater; float candles in water and cover, measure pH change; put shells in low-pH water, measured change in mass after 2-weeks; blowing into jar. One of the only demonstrations showing CO_2 can leave water (gas exchange goes in both directions).	2010	–	1	/yb37asyb
	Comparison of the Effects of Increased CO_2 in the Air to Seawater and Distilled Water	Examines how different waters respond to the addition of CO_2. Candles are lit inside an aquarium; use probes to monitor changes. Complicated setup; clever way to show that combustion changes pH. Leads into discussions of alkalinity and how lakes and oceans differ.	2010	E, M	1	/ybnpnqgb
	Interaction at the Air-Water Interface II	Write up of floating candles in water and detecting a pH change at the boundary layer. Also includes ice cubes/temperature and a suggestion for showing deep-water formation.	2009	E, M	1	/ybzxd6l2
	pH Regulation of Seawater: The Role of Carbonate (CO_3) and Bicarbonate (HCO_3)	Examines how the pH of different water samples responds to addition of CO_2 (via a straw). Uses indicators; students add Na_2CO_3 and $NaHCO_3$ to distilled and seawater. An easier way to explore the buffering capacity of seawater and distilled water. A bit quantitative; shows how different buffers impact buffering capacity. Good extension for chemistry teachers.	2010	E, M, H	1	/ybjnanpos
	Uptake of Carbon Dioxide from Water by Plants	Two experiments measuring impacts of aquatic plants on pH (via an indicator). L1: *Cabomba*, a freshwater aquarium plant, indicator, and samples in light, wrapped in foil, and a control with no plants. L2: marine phytoplankton, seawater, and a pH meter. Students blow into a flask, measure the pH change, then expose phytoplankton to light and watch the pH rise. Simple ways to show that plants uptake CO_2, which raises pH. Might be harder to culture or obtain phytoplankton, but they seem to alter CO_2 more quickly. Possible extension/inquiry lab.	2009	E, M	<1	/ybhzjfda

Organization	Resource Title	Summary	Date	Grade	Days	TinyUrl
Carnegie Mellon University	Ocean Acidification	OA Brainstorm, then show egg bubbling in vinegar; examine an egg that sat in vinegar overnight. Blow into indicator, then grind shells and add in until color changes, finish with discussion. Loosely compiled outline. Scope of discussions unclear.	2013	–	1	/y7e339md
Center for Microbial Oceanography: Research & Education	C-More Science Kits: Ocean Acidification	L 1: pre-survey, students drop vinegar on different sands, watch calcium carbonate sand bubble. Then present/play narrated PowerPoint on OA, and if time, have students begin reading. L2: experiment using yeast, chambers, and CO_2/pH probes to simulate OA. To save time, the first day could be demo instead of an experiment and the second day could use baking soda and vinegar to create CO_2 instead of yeast. The materials border on alarmist tone at times.	–	M, H	2	/ydhvf3lb
Centers for Ocean Sciences Education Excellence	Ocean Acidification	Show pictures of shelled marine organisms and discussing what they have in common (CaCO3 shells). Discuss that CO_2 makes soda bubbly. Setup 5 solutions and put chalk into each. Finish with a discussion of what happened. There is supposedly a discussion about what can be done, but this takes place at the end of the 60-minute lesson and does not provide clear guidance to teachers.	2010	–	1	/ybg5tue6
Centers for Ocean Sciences Education Excellence	Ocean Acidification Demonstration	A simple demonstration showing that adding CO_2 to water (in this case dry ice) changes the pH via an indicator solution.	–	–	<1	/lbukl8x
	Oceanic Carbon Chemistry and pH Relationship Lessons and Labs	L1: pH lab with cabbage juice indicator and pH strips. L2: add dry ice to a flask, siphon CO_2 to flask; watch pH change; shells in acid lab; blow into CaOH solution and watch pH change. L3: brief reading on OA, then students graph CO_2, pH, and carbonate data from Hawaii. I like the version of the dry ice demo and good to have students graph data. Info on impacts is just student inferences. Reading has good info but not sure students would remember it b/c it isn't reinforced.	–	M	3-4	/yc8l8bhq

Organization	Resource Title	Summary	Date	Grade	Days	TinyUrl
	pH, Carbon Cycle and Ocean Acidification	L1: KWL chart then lecture about pH. L2: students measure the pH change of river and seawater when dry ice is added for 5 min. L3: lecture about the carbon cycle that slightly touches on impacts of OA. OA is never explicitly explained. Impacts are only hinted at.	–	M, H	3	/ybppqsos
	Shells and the Impacts of Ocean Acidification	A variation on the idea that shells dissolve in acids. Uses egg shells in cola/vinegar, water, soap, and other solutions. Suggests you can weigh the shells before and after, and has students guess what possible consequences of OA (not explained) might be. Background info is confusing.	–	-	1	/kasoq4v
Channel Islands National Park/ Marine Sanctuary	**Ocean Acidification Curriculum**	L1: Examines local biodiversity via reading, underwater video, and food web activity. L2: Introduces upwelling via demo: blow across water surface and watch dye rise. L3: Students color a sea surface temperature map then read. L4: Introduce OA; combustion demo with candle and indicator; students illustrate steps of OA. L5: review OA with video; shells in acid lab (chalk into vinegar then weigh after 1 and 5 minutes). L6: Discuss differences between tropical, temperate, and polar marine environments, abiotic vs biotic factors, and connect photosynthesis and pH. L7: Students interpret pH graphs from different ocean regions and determine origins of a mystery graph. L8: Examine carbon sources and sinks, take a carbon footprint test, and brainstorm ways to lower footprint; group Call to Action project. Solid curriculum. Some lessons could be shortened, and it reinforces shells dissolve misconception. Coloring may not be the best way for students to engage with data.	–	M	9	/ybjldgbk

Organization	Resource Title	Summary	Date	Grade	Days	TinyUrl
Cool Australia	Activity: Acid oceans	Teacher draws and “explains" the carbon cycle; students brainstorm carbon sources/sinks; discuss impacts of increasing C on land and ocean; watch 3-min Acid Test video. Students adjust carbon cycle drawing. Suggested extension: students research on an organism or ecosystem impacted by OA. Might be hard for students to synthesize all these discrete pieces of information into something meaningful. Good extension idea.	–	H	1	/yd8nb736
	Activity: Blue: Ocean Acidification Science	Watch Climate Change 101 video (Bill Nye) at home. Part A: Discuss video; agree-disagree in responses to statements. Part B: watch OA video; outline OA equation/ steps. Part C: 2 experiment options: shells in vinegar (3-4 days) or OA in a cup (10-15 min). Create posters of experiment, peer-review posters using rubric. Part D- OA vs Coral bleaching: Show video and respond. Discuss what we can do to stop bleaching and OA. Seems biased. Focused on making kids feel scared not on understanding OA. Teacher background isn't about the science; it is a threat statement. Lacks clear distinction between OA and climate change. Doesn’t explain coral bleaching is. Unclear if all students do the same experiment or if they do different ones. If different ones, the timing is very different.	2017	M	2	/yba675p7
	Activity: Blue: Ocean changes affecting coral reefs	Part A: watch short video and discuss; brainstorm what they already know about OA, climate change, and coral loss. Part B: jigsaw- students read about OA or coral bleaching; share with partner. Finish by making a poster on how increasing CO_2 impacts reefs. Part C: watch coral bleaching video. A lot of time spent brainstorming. Readings feel more like propaganda than informative text. No clear guidance on what students should take away from this lesson; no checks for understanding. Underestimates timing.	2017	H	1	/yd2o9so3

Organization	Resource Title	Summary	Date	Grade	Days	TinyUrl
	Weather Makers: Oceans and Sinks	Brainstorm ocean's role in C-cycle; watch 3-minute Acid Test video and discuss; make OA infographic. Acid Test video is main source of info; biased. Like infographic creation and that they explain why the term OA might be misleading.	2017	H	1	/y9myxt28
	Weather Makers: Understanding ocean acidification	Students look at OA equations and write an explanation for a 5-6-year old; design experiment on the role of temperature; create an ad campaign on keeping the ocean cool. Very little concrete here. Wrongly implies that OA will get less bad over time as the ocean warms.	2017	–	1-2	/y75rb849
CPALMS (Florida State University)	Changing World Oceans - An Ocean Acidification Simulation	L1: Discuss prior knowledge; teacher presentation on OA; read about the rate of OA for HW and lab prep. L2: 3 simultaneous experiments: funnel CO_2 into covered aquarium and measure pH and CO_2 change; shells in vinegar for a day; fish fillets in lemon juice for a day. L4-5: write up results. May underestimates timing.	2014	H	5-7	/y934ufmk
Creative Discovery Museum	Ocean Acidification	Put an egg shell in water and acid and observe for 3 days. Potential discussion ensues.	–	E, M	3	/ya357wfv
Digital Explorer	Frozen Oceans: An Ocean Acidification Case Study for GCSE Science	L1- Acid Test video & questions; slideshow on OA equations; blow into indicator or test pH of still and sparkling water; reflect. L2- Work with Hawaii data on pH change (differentiated options for activity). L3- show pH vs temperature maps; show video on Catlin Survey; day in the life of an arctic scientist; present. L4- introduce copepods (via fact sheet and PPT); work with copepod data (differentiated options). L5- Share research: present on how scientists communicate findings; analyze scientific paper vs press release; debate how science could be of more use to society. L6- poster session. Use a real arctic research expedition as the organizing theme. Multiple opportunities to work with data. Day in the life of an arctic scientist is good for career exposure.	2014	H	6-10	/yd5zx69k

Organization	Resource Title	Summary	Date	Grade	Days	TinyUrl
EarthLabs - Carleton College	**Lab 7: Ocean Acidification**	Video on PNW oysters; examines pH; students blow into indicator; look at data from atmosphere, ocean, and pH; introduces carbonate system via ACE video. Part B-watch Khan Academy video on impacts; read short article on exposure experiments; Virtual Urchin lab to connect impacts to carbon cycling. Well put together, thorough presentation of OA. Fits into larger discussion of C-cycle (prior lessons). Rigorous. Good for self-directed students. Purposeful use of online lab as application learning.	–	H	2-4	/yacxtvlw
Exploratorium	Ocean acidification in a cup	Demo where baking soda + vinegar creates CO_2, changes color of indicator below. Well-done, simple demo. Good video explanation; Tries to address shells dissolve misconception, but likely insufficient.	–	–	<1	/y7unbfkt
	Shell Shifts	Shell into vinegar. Demo how baking soda into water makes bicarbonate; adding $CaCl_2$ releases Ca; mixing the two forms calcium carbonate; adding vinegar dissolves precipitate, add OH and precipitate returns. While the explanation is scientifically correct, reinforces the shells dissolve misconception.	–	–	<1	/yb76l69bs
Hawai`i Institute of Marine Biology	Engaging Students in the Pacific and Beyond Using an Inquiry-Based Lesson in Ocean Acidification	L1- test pH of household solutions; bubble CO_2 from soda into solutions of tap, sea, and DI water; record pH change. L2- lecture on OA (possible script provided); students design experiment; record pH and Ca ion concentration (calcium test kit) after 30 minutes of incubation. L3- interpret and present results. This is an article writing up the HIMB curriculum. Less dramatic version of shells in acid. Opportunity to design an experiment. Reinforces shells dissolve misconception but calls out the other experiments that use HCl or vinegar as extreme. If someone is going to do the shells in acid lab, this would be a better one to do.	2013	H	3	/ya4dqbrc

Organization	Resource Title	Summary	Date	Grade	Days	TinyUrl
International Fund for Animal Welfare	Climate Change and the Marine Environment: Lesson 2: Ocean Acidity	Intro on pH; test pH of water, vinegar, and soap with indicator; blow into indicator; show partially dissolved shell compared to shell in water and discuss what OA would mean (supposed to conclude harder to grow shell and grow more slowly, but students will likely conclude shells and corals will dissolve). After a slightly informative and biased intro on ocean circulation, temperature rise, and OA, the lesson itself lacks teaching materials.	–	M, H	1	/y9qxlfzm
Jonathan Bird's Blue World	Coral Reefs in Danger: Ocean Acidification Lesson	Background reading on acids/bases/pH; egg in vinegar demo, says this serves as a model for what marine organisms will face with OA. Part 2- blow into indicator; introduce OA equations; watch video (dead link); read a National Geographic article; look at data from atmosphere and ocean pH. Lots of info, not really clear if students read or if teacher presents. Not clear when/if the webisode (doesn't mention OA) is shown.	–	M	4	/y7xvxh97
Lawrence Hall of Science	Ocean Acidification!	A series of exploration activities for an aquarium/science center; guiding questions/script for a presenter. Part A: blow into indicator. Part B: put "low pH water" (white vinegar) on different substances (gelatin, shells, seaweed, rocks), and see what happens; blow into lime water & lime water with vinegar; precipitate forms more readily without vinegar. Part C: Shows maps, then science on a sphere images of pH/omega over time. Part D: Discuss ways to decrease CO_2 via EPA solutions sheet; action plan worksheet to plan to do one or two of the things. Good scripting and scientifically accurate background info at end. Good background on C-cycle and description of impact on calcifiers (activities don't communicate this same idea).	2015	E, M, H, G	1	/ycz7uc9n
Massachusetts Marine Educators	pH, CO2, and Ocean Acidification	Egg in vinegar, blow into indicator, then discussion defining OA. Standard activities lumped into a lesson.	2014	M	1	/y9owhmla

Organization	Resource Title	Summary	Date	Grade	Days	TinyUrl
MERITO Academy	Marine Osteoporosis	Start with reading (not provided) then two experiments: shells in tap water and vinegar, then shells in tap water and carbonated water. Then watch Acid Test video and do Virtual Urchin online lab. No actual lesson provided.	–	E, M, H	1	/ya4n553t
Mission Science Workshop	Breathing Blue	Write up of breathing into indicator and comparing to lemon juice in indicator.	2013	E, M, H	<1	/y9k9zkt6
Monterey Bay Aquarium	The Power of pH: Changing Ocean Chemistry	Two experiments: L1: serial dilution of HCl and NaOH to make a pH scale. L2: adding CO_2 (from a balloon) lowers the pH of sea and distilled water; observe effects of HCl on a shell; brainstorm ways to reduce excess CO_2 in atmosphere. The connection to OA is weak and tacked on at the very end of L2.	2014	H	1.5	/y9cqokso
Monterey Bay Aquarium Research Institute	Ocean Acidification: Is there a problem?	L1: Video on OA with high-level vocabulary; web quest with lots of reading. L2: Respond to questions and plot data. L3: blow into indicator then drop shells in vinegar and observe. Vocabulary heavy and advanced readings. Reinforces that vinegar dissolves shells and implies corals will disappear.	2011	–	3	/y77tax9h
National Oceanic and Atmospheric Administration	Acidification: What does it mean for oysters?	Shells placed in jars with water, water-vinegar mix, and vinegar prior to instruction; students examine shells and see that the ones in vinegar dissolved; brainstorm how to lower emissions. National Network for Ocean and Climate Change Interpretation (NNOCCI) ideas added to pretext but not incorporated in lesson.	–	E, M	1	/ybyxtlvz
	Climate Change "The Heat Is On"	Write-up of adding dry ice to indicator and watching what happens; blow into indicator. Two other activities focus on thermal expansion and ice caps melting. Nearly identical to “Climate Change & Coral Activities,” available on OA Curriculum Hub	–	E, M, H	<1	/y7hzgasf

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	Help Nemo Find His Home!	Game to teach kids about OA impacts on Clownfish navigation. Several add-on activities suggested. A basic game that might be fun but would likely be hard for students to make the connection to OA. Provides board game and data sheet. Likely fun and engaging, but learning depends on how the teacher crafts their follow up to this activity.	2015	E, M	1	/yd5w7fdq
	Data in the Classroom	(unavailable for review)	–	–	–	/y7y5gqxx
	Lesson 3: Ocean Acidification	Brainstorm elements in the ocean; lecture about OA; demo where vinegar dropped on chalk; discuss what it might mean for organisms (they'll dissolve). Sample Salmon Bowl questions/quiz at end.	–	H	1	/y7udxm7w
	Marine Osteoporosis	Observe shells in vinegar/tap water; compare to shells left in carbonated and tap water for multiple days; watch Acid Test video and complete Virtual Urchin as "assessment."	–	E, M	2-3	/y7osswxo
	Ocean acidification experiment: Impacts of carbonated seawater on mussel and oyster shells	Students place mussel/oyster shells in water with varying pH (CO_2 added with Soda Stream). Measure change in shell weight each week for four weeks.	–	E, M	3	/ycdwnr3y
	Ocean Acidification Toy Car Activity	Demo using CO_2 bike pump to show that adding CO_2 to water changes the pH. Bike pump removes implication that breathing causes OA.	–	–	<1	/yad2tufc
	Ocean Acidification: Building Blocks of the Sea	Lego activity to simulate OA impacts on shell building. Cool idea, but might create the misconception that carbonate availability, not energy demand, is the reason calcifiers are impacted.	–	E, M	1	/y92uufn2

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	Ocean Acidification: pH and the Ocean's Balance	Introduces pH via lecture/guessing; small OA discussion tacked on. Brainstorm ways to reduce CO_2 emission at the very end. Includes pieces from NNOCCI recommendations, but just introduces pH; misses the mark on OA. Doesn't get at causal chain, just states CO_2 is culprit. Solutions "discussion" a brainstorm. Instructor may mention one or two, but kids don't explore why it might help.	–	E, M	<1	/y8nw53fp
	Ocean Acidification: Plotting the Dangers	Starts with background on CO_2 in atmosphere (not provided); students blow into indicator; graph CO_2 levels in atmosphere; answer "what can you do to decrease atmospheric CO_2 levels?" as last question on student handout/discussion.	–	M	1	/y8l96jeq
	Ocean Acidification: Rugose Reef Tag	Students play tag in a classroom with things in/out of the way to communicate that reef structure is important. Activity doesn't match objectives or evaluation. Might be a fun demo, especially for younger students.	–	E, M	1	/y8uxh39c
	Off Base	Introduce pH, buffering, and La Chatlier's principle (no guidance provided); students read 2nd Symposium on the Ocean in a High CO_2 World and answer reading questions; lab: add vinegar and NaOH to distilled water and seawater, checking pH with pH strip after each drop. Teaching instructions are vague. Multiple versions available with different formats.	–	H	2	/guujxnf
	Whale Jenga: A Food Web Game	Students play a version of Jenga, which represents the ocean food web and sensitivities to OA/human impacts. Some possible extensions. Likely fun and engaging. Relies on existing knowledge; vocabulary heavy. Mentions many human impacts and possible solutions to OA, but no explanation of why certain events would increase or decrease organism abundance. Kids could read the instructions and have fun but learn little.	2015	E, M	1	/yap3fbxf

Organization	Resource Title	Summary	Date	Grade	Days	TinyUrl
National Socio-Environmental Synthesis Center	A case study on Ocean Acidification	Advanced reading introducing OA and asking students to interpret a graph and identify some information. Reading would be challenging for many high school students.	–	H	1	/y7rlcu2c
New Jersey Sea Grant	The Basics of Ocean Acidification	Two activities: L1: burn a candle and capture CO_2; add indicator to observe color change. L2: add seltzer to powdered $CaCO_3$ (version of shells in acid) and students watch it disappear (dissolve) in the seltzer but not water. Samples of follow up experiments, but all involve shells in acid. Recommended extension to research impacted animals, possible solutions. The candle activity might be easy for students to burn themselves.	2014	M, H	2	/yc27up9z
North American Marine Environment Protection Association	Ocean Acidification - Extended 9-12 Lesson	Provides lots of information on OA; then a few activities: OA in a cup (OCB lab on alkalinity, below), test pH of different waters; carbon footprint calculator; last slide asks, "what can we do?" Unclear if this is just a presentation or if it is meant to be done in a classroom. Uses OCB lab ideas.	2015	–	3-5	/ybrq47o4
OAR Northwest	Lesson 3.2 Ocean Acidification	Brief intro on C-cycle; test the pH of water/salt water using phenol red, blow into it and see pH change; Discuss equation; chalk into vinegar.	2013	–	1	/y9waqgmk
Ocean Carbon & Biogeochemistry Project	Ocean Acidification Lab	Collection of experiments: L1: general pH scale with household chemicals. L2: alkalinity and pH change from blowing through a straw. L3: vinegar dissolves shells. Lacks a comprehensive lesson framework. Listed references are good sources of background on OA.	2009	E, M, H	2.5	/y7c7hsqe
Pulitzer Center	**The Effects of Ocean Acidification**	Media analysis comparing print vs videos focusing on OA. Video and readings on crab in Alaska and pteropods (from Seattle Time's Sea Change series). I really like this lesson. Not necessarily for a Science classroom. The media comparison is interesting, and the themes explored are great.	2015	M, H	1	/y9pgxdx8

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Royal Geographical Society	Ocean acidification	IB curriculum highlighting 2010 Arctic field work. L1: intro with video (not provided); read over scientist blog (wrong link); students groups research; create 3 blog entries on OA (background, what the arctic research was about, impacts and ways to prevent OA). L2- Students watch a video (not provided); analyze data (intro to Spearman Rank Correlation calculation & practice exam question, answers provided). L3: experiment: blow into cup of salt water with a straw & lid; put shells in saltwater and vinegar, observe; compare strength of shells in vinegar for 2 days by piling books on top.	–	H	4-5	/yb9djx8b
Science Bridge (UC San Diego)	Ocean Acidification	Watch footage from Itschia Island 3x (1min long; teachers might be unable to access: Nature.com); write observations and what might be happening; observe shells that sat in vinegar for 6 and 12 hours; teacher presents PPT; blow into universal indicator, then modify with hot/cold/tap water; lecture with OA equations; shells in acid lab. (record weight of shells and place in vinegar for 30 min, strength test with books/weights); finish with PPT brief mention about food webs/why we should care. Additional transect activity, but unclear directions. Resource and material rich, but the lab isn't much different from others. I like the focus on an active research area (biodiversity at seep site in Italy), and that it starts by watching the video and noting differences. Would this lesson suggest to some students that OA is only a natural phenomenon?	2011	H	3	/ybng74hp
Science Learning Hub	Ocean acidification and eggshells	Starts with a video of a fast-talking scientist talking about OA and bryozoans. Then, eggs into water, vinegar, and ammonia. Check back every day for 3 days. A few discussion questions at the end.	2009	–	1	/y878wq5h

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Scientific Research and Education Network	OA Lesson Plan	Intro on pH and carbonate (unclear on specifics); students drop TUMS in water and soda water and observe; connect to marine organisms and food webs; finish with a solutions brainstorm. Format hard to follow. Unclear what is extra info for the teacher, what should be said, and what students are doing most of the time.	–	H	1	/y847s8vh
Scripps Institution of Oceanography	Ocean Acidification Exploration for Middle School Students	Part 1- Compare seawater pH to common substances using cabbage indicator. Part 2- Blow into indicator mixed with tap and seawater, note rates of change. Part 3- eggs in vinegar (2 days). Part 4- Brainstorm favorite snacks and choose the top 6; told it isn't available and they have to repick, over and over; discussion: What would happen to marine animals their food goes extinct? What would happen to humans? Two of the activities are modified from OCB labs.	2013	M	4-5	/yd8ov4k3
	Seawater Acid-Base Chemistry and Ocean Acidification	Series of five, 5-E lessons on chemistry of OA. Demos include: Alka-Seltzer rainbow (add CO_2 to universal indicator); measuring pH; Acid-Base solutions online lab; add carbonate sand to distilled and seawater (watch pH change); add acid/base to distilled and seawater; chemical modeling w/ modeling kit; hold breath; car exhaust into solution; balloon lab (fill balloon with air, bubble into seawater, measure pH change); candle demo (float candles in indicator, light and seal, note indicator change); blow into indicator; student designed experiment on photosynthesis/ respiration impact on pH; shells in acid lab (measure weight change over time); OA brochure project. A strong curriculum that considers misconceptions. Lots of demos, some student experiments. Info on OA is dissolution heavy. While misconceptions are considered throughout, shells dissolve misconception is reinforced. Chemistry focused. Demos reinforce the same idea (adding CO_2/acid to water changes the pH).	2013	H	9-12	/y7apbls9

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Share My Lesson	Ocean Acidification Unit	L1- Brainstorm ways physical environment effects them & ways to counter effects; discuss how small changes matter; then video. L2- Discuss impacts to animals (not clear what this includes); place shells in acid & seawater (for later analysis); introduce pH; test pH of various solutions. L3- Test reaction of HCl with limestone (not clear how); teacher discusses reaction; students model with Styrofoam balls. L4- Dry ice in water, discuss, then drink it; blow into water; place candle in jar, light and cap jar; measure pH. HW- explain OA to someone. L5- Beach day: take pH readings; list "creatures" found; make food web with string and cut one showing what happens if krill die; students draw a food web. Week 2 is a list of possible questions and ideas to explore. Incomplete. I like the final poster on developing a plan to limit the damage of OA in their community (although it is not clear where students get this info from or how it is evaluated). Lots of activities, but how OA is defined and guidance for student responses is not provided.	2017	H	10-15	/y9fld328
SMILE (Oregon State University)	Dissolving Issues: Ocean Acidification	Early version of shells in acid demo with chalk in vinegar. Open a soda and funnel CO_2 into water; measuring pH change. Students weigh chalk and place it in tap water, tap water with lemon juice, and tap water with soda; observe and measure pH change.	2008	H	1	/ycpgv3uq
	Ocean Acidification: From a Geological and Chemical Perspective	Examines the role of alkalinity in buffering pH change when CO_2 is added. Students setup 4 cups with varying alkalinity; blow into the cups with indicator; note time until color change. Attempts to discuss differing rates of change and compares alkalinity now versus previous times when CO_2 levels in the atmosphere were high. Might not make a clear connection for teachers less familiar with these concepts. Doesn't fully explain OA.	2016	H	1	/y7o43wct

Organization	Resource Title	Summary	Date	Grade	Days	TinyUrl
Stanford University	**Virtual Urchin**	Online virtual lab: Intro to OA; enter virtual lab to study the effects of OA on sea urchin larval growth. Emphasizes the process of doing science, replicates, sample size, etc., in addition to focusing on urchin development (and possible impacts). Clever way to "run" an experiment without all the logistics of raising larvae in class. Pre-lab certification orients students to the interface. Good checks for understanding. Amount of clicking could frustrate some students. Lesson plans available on website.	2008-2015	H	1	/ph6bvwf
Systems Education Experiences	**Ocean Acidification: A Systems Approach to a Global Problem**	A 6-lesson curriculum that uses systems thinking to explore OA. The emphasis is on inquiry, experimental design, and systems thinking, with less direct instruction on OA itself. Uses OA to teach critical thinking and systems thinking. Thus, this is a higher level, more wholistic curriculum. While this curriculum takes longer than others, it is a good example of NGSS-style learning. Students get to design and run their own experiments. Extremely comprehensive; many supporting resources, examples, supplemental materials, etc.	2014	H	14-30	/ydeyc36u
The American Biology Teacher	Demonstrating the Effects of Ocean Acidification on Marine Organisms to Support Climate Change Understanding	Article presenting two versions of shells in acid lab in a 5E format. L1- Students observe chalk in vinegar, weigh the change in weight and pH every 5 minutes. Students are evaluated by designing and evaluating a solution for reducing impacts on the environment (no guidance on what this could entail or how this is evaluated). L2-extended experiment where shells are placed in a bucket of vinegar-water for weeks. Shells are weighed and observed every week for at least 3 weeks. Well-written and the design allows for some inquiry. Reinforces shells dissolve misconception. While a few examples of data tables are shown, actual teaching resources (student or teacher) are not.	2015	H	2	/yd66kd8d

Organization	Resource Title	Summary	Date	Grade	Days	TinyUrl
Unaffiliated	Ocean Acidification	Four activities included: L1- collect plankton sample with net (or raise brine shrimp); talk about food webs and cross out shelled zooplankton (loss due to OA); cross out some fish up the food chain because of less food. L2: shells in vinegar. L3: Test pH of soft drinks with litmus paper. L4: brainstorm ways to reduce CO_2 emissions. I like the plankton investigation at the start. The information part of these is brief and unclear how teachers should implement many of the activities beyond activity one.	–	E, M, H	2	/73wb42h
UNC Institute for the Environment	Using the EATS Model to Investigate Ocean Acidification	Part 1: Read 1 of 3 articles, jigsaw with questions to share what they learned. Part 2: Discuss: how is plankton/photosynthesis important to ocean CO_2 levels? Discuss NASA satellites and unanswered questions relating to OA. Watch Sea Change videos (Seattle Times); keep a list of organisms affected by OA; read article. Part 3: NOAA Lesson 3 OA (students drop vinegar on chalk and watch it bubble/dissolve). Part4: Use CliMate app, \summarize what is happening to ocean temperature, salinity, pH, and sea level. Part 5: students make graphic organizer to link all topics from lessons. Discuss: are we doing enough/what can we do better to prevent OA? Lots of reading, discussion, and synthesis, but then uses shells in acid lab. Unclear if students ever get a concise definition and explanation of OA. Underestimates timing. Unclear if this was taught.	2014	H	2.5	/ybz64sbp

Organization	Resource Title	Summary	Date	Grade	Days	TinyUrl
University of Gothenburg	**Virtual Marine Scientist**	Online lab: students design and run their own experiments. Lab orientation videos; write short project proposal; teacher approves project; conduct research (up to 15 aquariums, three creatures; 4 pH & temperatures options; with/without feeding). Several variables can be measured. Students receive data, then interpret. Great alternative for OA experiments without having to have all the aquariums running in an actual classroom. Allows students to make choices, gather data (from real experiments?), and interpret. No teacher guidance or instructions, no student handouts or materials.	2013	H	–	/yd2wzm97
University of Massachusetts - Amherst	Ocean Acidification	Extended case study. L1: intro to case studies. L2: pre-quiz of OA knowledge; video about Nisbet farms moving their oyster hatchery to Hawaii. L3: intro to OA process (lecture or video); HW: evidence of OA effects and/or solutions; next day: share findings and choose a topic to research as a team. L4: draw systems diagram; discuss research questions; form hypotheses; design study; do study/research. L5: generate conclusion; prepare communication medium (article, poster, video, etc.); peer-edit; present. L6- reflect. Nicely prepared outline of an extended research project on OA. Time intensive. Unclear if taught.	2016	H	10-15	/y8cfozfb

Organization	Resource Title	Summary	Date	Grade	Days	TinyUrl
University of Otago	**The Ocean of Tomorrow: Ocean Acidification and the Marine World**	L1: OA survey; discuss. Test pH of different solutions. L2: experiment: Interactions of photosynthesis and respiration; measure temperature, dissolved O_2, and pH. discussion while experiment is running. L3: blow into water and record pH change with probe; vary water temperature. Test how quickly snails right themselves with various pH and temperatures. L4: background on carbonate shell formation/dissolution; crushed oyster shells in seawater, vinegar, and HCl. Examine dead shells; estimate time since death by comparing weight and size. L5: retake survey; compare to public responses. Discuss solutions; make behavior change poster. Extension-individual research project. Snail turn-over is a unique experiment. Reinforces shells dissolve misconception. Like the poster project. Would like more guided responses for teachers. PPT presentations seem pretty advanced.	2017	H	10-12	/ydef89cw
University of Rhode Island	Shells in Acid Lab	Variation of shells in acid experiment. Shells presoaked in vinegar. Students place books on top of shells to break them (a measurement of strength). Also put a shell in a bag and observe it under a magnifying glass. Recommends putting chalk in carbonated water and watching it dissolve “in minutes.” Discuss what this might mean for marine organisms and ecosystems, but no clear direction.	–	E, M, H	1	/yayb2ube
University of Washington	**Oysters and Ocean Acidification Module**	Students analyze data from Whiskey Creek Shellfish Hatchery to explain how OA is affecting the oyster industry. It starts with a 30-60-minute intro lecture, then there are three 60-90-minute sessions where students work with data in excel and answer questions. Advanced, but great way to have students working with real data.	–	H	3-5	/ybebb75k
US Environmental Protection Agency	Corals and Chemistry	Intro on anthropogenic CO_2 creation, absorption; blow into cabbage juice indicator and watch it turn color; brief discussion.	–	–	1	/ycgavxfj

Organization	Resource Title	Summary	Date	Grade	Days	TinyUrl
Washington Sea Grant	A Tale of Two Acids' Demonstration protocol	Breathe into cabbage indicator to show pH change. Meant to clarify scope of “acidification” expected and mentions that the ocean will not become “acidic.” Contrasts change from lemon juice vs change from blowing (CO_2). Straightforward demo that starts to get at the idea of pH change and just what we mean by OA.	–	M, H, G	<1	/y87gbrtd
	Case Study: Sea Urchins, Ocean Acidification and Adaptation	In-depth look at how OA could impact sea urchins on the West Coast. Focuses on research from the Hofmann lab at UCSB on sea urchin evolution and includes multiple readings (from Seattle Times' Sea Change, Nature), videos (NBC and AMNH), and the Virtual Urchin online lab. Meant for advanced students as a follow up to information already learned. Reinforces ideas of evolution, genetic variability, and explores the more complex possibilities of responses to OA. Readings would be challenging.	2014	H	3-5	/y8vrl73e
	Crossing Thresholds Demonstration Protocol	Drop ice into root beer to demonstrate normal variation and how rampant CO_2 adds onto that. Attempts to address how a small change can matter even in the context of larger natural variation. Abstract; unclear whether the key idea would be understood. Good sources provided about how small, long-term shifts can be a problem despite large short-term variation.	–	M, H, G	<1	/ycc4nhcv
	Hold Your Breath Activity	Short demo where crowd holds breath and presenter explains that a small change in blood pH has significant repercussions for humans. Low-cost way to show people that small changes in pH can matter. But, the reason and process behind our body responding to pH changes is different than the reasons OA is a concern, and this is not stated.	–	M, H, G	<1	/yaydd7u5
	Shells on Acid Demonstration Protocol	Drop shell into vinegar and watch it bubble. Reinforces shells dissolve misconception.	–	M, H, G	<1	/ya8yme2m

Organization	Resource Title	Summary	Date	Grade	Days	TinyUrl
Windows to the Universe	Changing Planet: Ocean Acidification - The Chemistry is Less than Basic!	Part 1: mix baking soda and vinegar to create CO_2 (confusing procedure); transfer to test tube; watch indicator change color. Part 2: Blow into indicator to show that animals are a source of CO_2. Part 3: Put *elodea* (plant) in indicator for 24 hours in dark; examine color change. Part 4: Leave *elodea* tube unwrapped and watch color change back. Part 5: Collect car exhaust in balloon, use straw to bubble this into indicator to change color. Part 6: Blow into indicator; add crushed shell to watch dissolution. Answer some questions, then interpret graph of CO_2 in atmosphere and ocean and pH. Unclear lesson progression.	2011	M, H	2	/y9cgpl8c

CURRICULUM MERIT REVIEW

GENERAL FEATURES

Publication Date

Nearly half (n=42) of all resources did not list a publication date. Considering the rapid increase in scientific knowledge on ocean acidification, this lack of publication date made it more difficult to gauge whether the resource utilizes the most relevant scientific information.

Target Audience

Most (n=74) resources focus on a middle or high school audience (n= 31 high school only, n= 8 middle school only), and 14 do not specify an intended audience. While 22 resources state a possible elementary audience, no resource was designed solely for an elementary school audience (thus, elementary resources listed are intended for elementary and middle or high school audiences as well). Additionally, six resources state they are for a general audience; four of these were demonstrations from Washington Sea Grant, one was from the Birch Aquarium, and one was from Lawrence Hall of Science.

Duration

The time required varied widely for instructional resources on ocean acidification. The shortest resources required <10 minutes while the longest needed over four weeks of class time. Over half (n= 47) of resources were designed to last one to two days, 14% (n= 13) lasted <1 day, 20% (n= 18) lasted 3-5 days, and 11% (n= 10) took more than a week.

CURRICULUM CONTENT

Instructor Background

Nearly two-thirds of resources (n= 57) included some amount of background information for teachers (see Table 2.2). The content or completeness of the background information was not evaluated. If a resource provided links to other sources of information but did not include a summary of OA, this was not considered providing instructor background.

Key Points

Only 10% (n= 9) or resources include key points. Thus, many resources presented background information but did not help teachers distill the background science into the most important messages about ocean acidification. Key points help establish the goals for the lesson/curriculum. This is especially important when multiple, complex ideas are introduced.

Variations on a Few Themes

While there are numerous instructional resources available to teach about OA, most include one or more of these key components: (i) CO_2 lowers the pH of solutions; (ii) calcium

Table 2.2 - Curriculum merit review: curriculum content.

Organization	Resource Title	Instructor background	Key points	CO_2 changes pH	Shells in acid	Alkalinity buffers pH	pH of household products	Addresses solutions[1]	Acid Test video
Percent Checked (*n*= 90)		63	10	53	49	11	14	7/32[2]	27
Aquarium of the Bay	HS Chemistry Resource	●		●	●		●	○	●
Around the Americas	Coral, CO_2 & Calcification	●	●						
Bermuda Institute of Ocean Sciences	**You be the Chemist…**	●							
Better Lesson	Acid Alert!							○	
	Acid Oceans part 1 & 2			●			●		
	The Chemistry of OA…						●		
BIOACID	**Ocean Acidification: The Other CO_2-Problem…**	●		●		●			
Birch Aquarium	Got Shells?				●			○	
British Columbia Teachers Federation	Exploring OA			●				○	
Bureau of Ocean Energy Management	Lesson 4 - OA and Its Effect on *Lophelia*	●		●	●				
California Academy of Sciences	Ocean Acidification Mock Conference	●						●	●
CarboSchools	Atmospheric CO_2 can produce OA			●	●				
	Comparison of the Effects of Increased CO_2 …			●		●			
	Interaction at the Air-Water Interface II			●					
	pH Regulation of Seawater…	●		●		●			
	Uptake of CO_2 from Water by Plants	●		●					
Carnegie Mellon University	Ocean Acidification	●		●	●				
Center for Microbial Oceanography: Research & Education	C-More Science Kits: OA	●		●	●				●
Centers for Ocean Sciences Education Excellence	Ocean Acidification	●			●			○	●
Centers for Ocean Sciences Education Excellence	OA Demonstration	●		●					●
	Oceanic Carbon Chemistry and pH Relationship	●		●	●		●		
	pH, Carbon Cycle and OA			●		●			
	Shells and the Impacts of OA	●			●				●
Channel Islands National Park/ Marine Sanctuary	**Ocean Acidification Curriculum**	●		●	●			●	

Organization	Resource Title	Instructor background	Key points	CO_2 changes pH	Shells in acid	Alkalinity buffers pH	pH of household products	Addresses solutions [1]	Acid Test video
Percent Checked (*n*= 90)		63	10	53	49	11	14	7/32[2]	27
Cool Australia	Acid oceans	●							
	Blue: OA Science	●		●	●			○	
	Blue: Ocean changes affecting coral reefs	●						○	●
	Weather Makers: Oceans & Sinks	●							
	Weather Makers: Understanding OA	●							●
CPALMS (Florida State University)	Changing World Oceans - An OA Simulation			●	●				
Creative Discovery Museum	Ocean Acidification	●			●			○	
Digital Explorer	Frozen Oceans: An OA Case Study for GCSE Science	●		●					●
EarthLabs - Carleton College	**Lab 7: Ocean Acidification**			●					
Exploratorium	Ocean acidification in a cup	●		●					
	Shell Shifts	●			●				
Hawai`i Institute of Marine Biology	Engaging Students in the Pacific and Beyond…	●		●	●	●	●		
International Fund for Animal Welfare	Climate Change and the Marine Environment: Lesson 2: Ocean Acidity	●		●	●		●		
Jonathan Bird's Blue World	Coral Reefs in Danger: Ocean Acidification Lesson			●	●				●
Lawrence Hall of Science	Ocean Acidification!	●	●	●	●			●	
Massachusetts Marine Educators	pH, CO2, and Ocean Acidification			●	●				
MERITO Academy	Marine Osteoporosis	●			●			○	
Mission Science Workshop	Breathing Blue	●		●					●
Monterey Bay Aquarium	The Power of pH: Changing Ocean Chemistry	●		●	●	●		○	
Monterey Bay Aquarium Research Institute	Ocean Acidification: Is there a problem?			●	●				●
National Oceanic and Atmospheric Administration	Acidification: What does it mean for oysters?		●		●			○	●
	Climate Change "The Heat Is On"	●		●					
	Help Nemo Find His	●						○	●

Organization	Resource Title	Instructor background	Key points	CO_2 changes pH	Shells in acid	Alkalinity buffers pH	pH of household products	Addresses solutions [1]	Acid Test video
Percent Checked (*n*= 90)		63	10	53	49	11	14	7/32[2]	27
	Home!								
	Lesson 3: Ocean Acidification	●			●				
	Marine Osteoporosis	●			●				
	OA experiment: Impacts of carbonated seawater on mussel and oyster shells	●			●			○	
	OA Toy Car Activity			●					●
	Ocean Acidification: Building Blocks of the Sea	●	●					○	
	Ocean Acidification: pH and the Ocean's Balance		●				●	○	
	OA: Plotting the Dangers	●		●				○	
	OA: Rugose Reef Tag	●	●					○	●
	Off Base	●				●		○	
	Whale Jenga: A Food Web Game	●							
National Socio-Environmental Synthesis Center	A case study on Ocean Acidification								
New Jersey Sea Grant	The Basics of OA	●		●	●			○	
North American Marine Environment Protection Association	Ocean Acidification - Extended 9-12 Lesson			●			●	○	
OAR Northwest	Lesson 3.2 OA			●	●				●
Ocean Carbon & Biogeochemistry Project	Ocean Acidification Lab	●		●	●	●	●		
Pulitzer Center	**The Effects of OA**								
Royal Geographical Society	Ocean acidification			●	●			○	
Science Bridge (UC San Diego)	Ocean Acidification	●		●	●				
Science Learning Hub	OA and eggshells				●			○	
Scientific Research and Education Network	OA Lesson Plan		●		●			○	
Scripps Institution of Oceanography	OA Exploration for Middle School Students			●	●		●		●
	Seawater Acid-Base Chemistry and OA	●		●	●	●	●	○	

Organization	Resource Title	Instructor background	Key points	CO_2 changes pH	Shells in acid	Alkalinity buffers pH	pH of household products	Addresses solutions[1]	Acid Test video
Percent Checked (*n*= 90)		63	10	53	49	11	14	7/32[2]	27
Share My Lesson	Ocean Acidification Unit			●	●		●	●	●
SMILE (Oregon State University)	Dissolving Issues: OA			●	●				
	OA: From a Geological and Chemical Perspective	●		●		●			
Stanford University	**Virtual Urchin**								●
Systems Education Experiences	**OA: A Systems Approach to a Global Problem**	●	●	●				●	●
The American Biology Teacher	Demonstrating the Effects of OA on Marine Organisms…	●			●				
Unaffiliated	Ocean Acidification	●			●			○	
UNC Institute for the Environment	Using the EATS Model to Investigate OA				●			○	
University of Gothenburg	**Virtual Marine Scientist**								
University of Massachusetts - Amherst	Ocean Acidification							○	●
University of Otago	**The Ocean of Tomorrow: OA & the Marine World**	●		●	●		●	●	
University of Rhode Island	Shells in Acid Lab				●				
University of Washington	**Oysters and OA Module**	●							●
US Environmental Protection Agency	Corals and Chemistry	●		●					
Washington Sea Grant	A Tale of Two Acids'…	●	●	●					
	Case Study: Sea Urchins, OA & Adaptation	●						○	
	Crossing Thresholds…	●							
	Hold Your Breath Activity	●							
	Shells on Acid' Demo	●			●				●
Windows to the Universe	Changing Planet…	●		●	●			○	

[1] Solutions options were: yes, somewhat, and no. All other categories were dichotomous (Yes/No). [2] Listed as % fully addressing solutions/ % somewhat addressing solutions to ocean acidification.

carbonate (shells, chalk, eggshells, sand) dissolves in acidic solutions; (iii) alkalinity buffers pH changes; and (iv) a basic introduction to pH via testing the pH of familiar solutions.

CO_2 Acidifies Water

A majority (53%) of resources included at least one demonstration showing that CO_2 added to water lowers the pH. There were differing ways to show this; 33 resources have students blow through a straw into a solution and watch the pH change (via an indicator, pH strips, or pH probe), seven use dry ice as the CO_2 source, seven mix baking soda with vinegar to form CO_2, one uses a CO_2 canister for a bike pump, two use CO_2 gas released from a soda bottle, and 11 use combustion (typically a candle, but two use car exhaust).

$CaCO_3$ Dissolves in Acids

Nearly half (49%) of resources included a demonstration or lab that involved placing calcium carbonate, typically marine shells, chalk, or eggs, into an acid (vinegar). The length of this demo/experiment varied from <10 minutes to 4 weeks (checking 1x/week), and the ways of measuring dissolution also varied. This was used to show the impact of ocean acidification on shelled organisms, and usually came with no caveats. Sometimes students are asked after completing this activity, “What does this imply about how ocean acidification will impact marine organisms?”

Alkalinity Buffers pH Changes

Some resources (11%) included a demonstration that alkalinity buffers pH changes (pH changes are less severe or take longer). Typically, this was done by having students blow into solutions of ionized, tap, and seawater and recording how long it took for the color to change (via indicator) or to record how much of a change in pH occurred over a constant period of time. Few resources connected this concept back to OA. They didn't explain why it matters that alkalinity buffers pH. These lessons imply that the ocean should be okay because of its buffering capacity. At least one resource compares the current ocean to periods in the past when CO_2 was high, but alkalinity was also high at that point in history. As far as I could tell, none point out how alkalinity varies across the globe, nor do they discuss what this means (some locations with lower alkalinity will likely see greater acidification. Additionally, places with higher alkalinity may appear more resilient to OA since saturation states are higher in those locations.

pH of Household Solutions

One other common approach (14%) was to introduce pH by testing the pH of various solutions like lemon juice, soda, water, soap, etc. It is likely that more classrooms use this lab but simply do not relate it back to ocean acidification. Most resources introduce pH as ranging from 0-14, acids are <7, bases are >7. Only a few introduce $[H^+]$; very few explore pH quantitatively.

Addresses Solutions to Ocean Acidification

Most resources (60%) do not mention actions that could reduce or limit ocean acidification (“possible solutions”), 32% (n=29) mention but do not focus on solutions (“partially address”), and 7% (n=6) focus on solutions (“fully address”). Of those resources that do mention ways to address OA, most include a short brainstorm or discussion using variations of the prompt, “What can we do…?” In other instances, students respond to a similar question in a student handout. Often these discussions or questions are toward the end of a lesson/handout. If teachers are short on time, this is the piece that will likely get cut. Additionally, many resources lack guidance for the teacher on what could/should be included in the discussion. Of the few resources that do provide suggestions for what can be done to reduce OA and/or its impacts, little explanation is provided for why those actions, and not others, were selected.

Links to Fear-Based Video

At least 24 resources link to National Resource Defense Council's "Acid Test" video and at least one links to "Lethal Seas," by NOVA, as a source of information on the topic. While both videos include several scientists who are actively engaged in ocean acidification research, they rely heavily on fear-based messaging and highly charged language.

Evaluation of Resource

Very few (8%, n=7) resources report evaluating the effectiveness of the teaching materials (see Table 2.3). While it is likely more were evaluated, at least informally, this is not made explicit. Of those resources reporting evaluation, two CarboSchools experiments say they were tested but don’t explain how. The remaining evaluated resources report using pre/post surveys.

Table 2.3 - Curriculum merit review: evaluation, objectives, and comprehensiveness.

		Evaluated?	Evaluation Criteria	Objectives: Measurable	Objectives: Aligned to standards	Structure: Comprehensive	Teacher materials	Student materials
Percent Checked (*n*= 90)		8	6	29	50	30	33	60[1]
Aquarium of the Bay	HS Chemistry Resource							●
Around the Americas	Coral, CO_2 & Calcification				●	●	●	n/a
Bermuda Institute of Ocean Sciences	**You be the Chemist…**				●			
Better Lesson	Acid Alert!			●	●	●	●	●
	Acid Oceans part 1 & 2			●	●			●
	The Chemistry of OA…			●	●			●
BIOACID	**Ocean Acidification: The Other CO_2-Problem…**					●	●	●
Birch Aquarium	Got Shells?			●		●	●	n/a
British Columbia Teachers Federation	Exploring OA				●			
Bureau of Ocean Energy Management	Lesson 4 - OA and Its Effect on *Lophelia*			●	●			●
California Academy of Sciences	Ocean Acidification Mock Conference				●	●	●	●
CarboSchools	Atmospheric CO_2 can produce OA							
	Comparison of the Effects of Increased CO_2 …							
	Interaction at the Air-Water Interface II							
	pH Regulation of Seawater…	●	?					
	Uptake of CO_2 from Water by Plants	●	?					
Carnegie Mellon University	Ocean Acidification			●				
Center for Microbial Oceanography: Research & Education	C-More Science Kits: OA	●	Survey[2]			●	●	●
Centers for Ocean Sciences Education Excellence	Ocean Acidification							●
	OA Demonstration					●	●	n/a
	Oceanic Carbon Chemistry and pH Relationship				●			●
	pH, Carbon Cycle and OA			●	●	●	●	●
	Shells and the Impacts of OA							
Channel Islands National Park/ Marine Sanctuary	**Ocean Acidification Curriculum**			●	●	●	●	●
Cool Australia	Acid oceans							●
	Blue: OA Science				●			●
	Blue: Ocean changes affecting coral reefs				●			●
	Weather Makers: Oceans & Sinks				●			●
	Weather Makers: Understanding OA				●			●

		Evaluated?	Evaluation Criteria	Objectives: Measurable	Objectives: Aligned to standards	Structure: Comprehensive	Teacher materials	Student materials
CPALMS (Florida State University)	Changing World Oceans - An OA Simulation				●	●	●	●
Creative Discovery Museum	Ocean Acidification							●
Digital Explorer	Frozen Oceans: An OA Case Study for GCSE Science				●			●
EarthLabs - Carleton College	**Lab 7: Ocean Acidification**			●	●	●	●	n/a
Exploratorium	Ocean acidification in a cup					●	●	n/a
	Shell Shifts					●	●	n/a
Hawai`i Institute of Marine Biology	Engaging Students in the Pacific and Beyond…	●	Survey[2]		●	●	●	
International Fund for Animal Welfare	Climate Change and the Marine Environment: Lesson 2: Ocean Acidity			●	●			●
Jonathan Bird's Blue World	Coral Reefs in Danger: Ocean Acidification Lesson				●			●
Lawrence Hall of Science	Ocean Acidification!				●	●	●	●
Massachusetts Marine Educators	pH, CO2, and Ocean Acidification							●
MERITO Academy	Marine Osteoporosis				●			●
Mission Science Workshop	Breathing Blue			●	●			
Monterey Bay Aquarium	The Power of pH: Changing Ocean Chemistry			●	●			●
Monterey Bay Aquarium Research Institute	Ocean Acidification: Is there a problem?			●				●
National Oceanic and Atmospheric Administration	Acidification: What does it mean for oysters?				●	●	●	
	Climate Change "The Heat Is On"							
	Help Nemo Find His Home!				●			●
	Lesson 3: Ocean Acidification			●	●	●	●	●
	Marine Osteoporosis							
	OA experiment: Impacts of carbonated seawater on mussel and oyster shells				●			n/a
	OA Toy Car Activity							
	Ocean Acidification: Building Blocks of the Sea				●			
	Ocean Acidification: pH and the Ocean's Balance						●	
	OA: Plotting the Dangers			●	●			●
	OA: Rugose Reef Tag							

		Evaluated?	Evaluation Criteria	Objectives: Measurable	Objectives: Aligned to standards	Structure: Comprehensive	Teacher materials	Student materials
	Off Base			●	●			●
	Whale Jenga: A Food Web Game							●
National Socio-Environmental Synthesis Center	A case study on Ocean Acidification							●
New Jersey Sea Grant	The Basics of OA			●	●			
NAMEPA	OA - Extended 9-12 Lesson							
OAR Northwest	Lesson 3.2 OA						●	
OCB Project	Ocean Acidification Lab							●
Pulitzer Center	**The Effects of OA**			●	●			
Royal Geographical Society	Ocean acidification			●	●			●
Science Bridge (UC San Diego)	Ocean Acidification			●	●	●	●	●
Science Learning Hub	OA and eggshells							
Scientific Research and Education Network	OA Lesson Plan							
Scripps Institution of Oceanography	OA Exploration for Middle School Students							n/a
	Seawater Acid-Base Chemistry and OA				●	●	●	●
Share My Lesson	Ocean Acidification Unit			●	●			
SMILE (Oregon State University)	Dissolving Issues: OA							●
	OA: From a Geological and Chemical Perspective			●	●	●	●	●
Stanford University	**Virtual Urchin**			●				●
Systems Education Experiences	**OA: A Systems Approach to a Global Problem**	●	Survey^2		●	●	●	●
The American Biology Teacher	Demonstrating the Effects of OA on Marine Organisms…							
Unaffiliated	Ocean Acidification							
UNC Institute for the Environment	Using the EATS Model to Investigate OA			●	●			
University of Gothenburg	**Virtual Marine Scientist**							●
University of Massachusetts - Amherst	Ocean Acidification			●	●	●	●	●
University of Otago	**The Ocean of Tomorrow: OA & the Marine World**	●	Survey^2		●			●
University of Rhode Island	Shells in Acid Lab							

		Evaluated?	Evaluation Criteria	Objectives: Measurable	Objectives: Aligned to standards	Structure: Comprehensive	Teacher materials	Student materials
University of Washington	**Oysters and OA Module**	●	Survey[2]	●		●	●	●
US Environmental Protection Agency	Corals and Chemistry				●			●
Washington Sea Grant	A Tale of Two Acids'…					●	●	n/a
	Case Study: Sea Urchins, OA & Adaptation							
	Crossing Thresholds…					●	●	n/a
	Hold Your Breath Activity					●	●	n/a
	Shells on Acid' Demo					●	●	n/a
Windows to the Universe	Changing Planet…				●			●

[1] Twelve resources did not require student materials. [2] Surveys were administered before and after instruction.

(*note- we distinguish between evaluating student learning (assessments) and evaluating the quality of a teaching resource. This section refers to resource evaluation.*)

Objectives

Measurable

Only 29% of resources had measurable objectives. A measurable teaching objective is an indicator for what students should be able to do by the end of the lesson that includes an action verb that can be measured or evaluated. Two unmeasurable action verbs commonly used in resources objectives are “know” or “understand”. In contrast, objectives with measurable verbs include words such as “define,” “explain,” and “compare and contrast.”

Standards-Aligned

Half of all resources include objectives that were aligned to standards. It is worth noting that some resources were aligned to standards that are no longer in use (e.g., the old national science standards).

Comprehensiveness

Resources were evaluated for their comprehensiveness, meaning they included necessary teacher and student facing materials. For a resource to be considered as including teacher materials, it needed to have a lesson plan/outline, a sample script or presentation (suggestions for what could be said), and answers to discussion questions/answer keys for student handouts. Only 30% of resources were comprehensive by this metric. Most often, resources lacked answers to discussion questions or an answer key, making it difficult for teachers less familiar with the subject to confidently guide students. In contrast, 60% of resources included student materials. Resources that mention students recording notes/data in “science journals” were marked “n/a” for student resources. If no information was to be recorded (e.g., informal demonstrations), this was also recorded as “n/a.”

CHAPTER 3: FIRST MANUSCRIPT [THE SCIENCE TEACHER]

Teaching Solutions to Ocean Acidification

"What the heck is ocean acidification?" writes a student on their pre-survey. Their question reflects a larger trend: while scientific knowledge of ocean acidification has increased dramatically over the past decade, most Americans know little about it.

Ocean acidification is the progressive decrease in marine pH and carbonate ion concentrations that result when the ocean absorbs anthropogenic CO_2 from the atmosphere (Frisch et al., 2015). It is already impacting the shellfish industry in the Pacific Northwest (Barton et al., 2015) and, over the next few decades, is predicted to have major cascading impacts on marine ecosystems and the humans that rely on them for food and income.

Since 2008, educators have created over 90 teaching resources on ocean acidification, including some previously published in NSTA magazines (Bruno et al., 2011; Kapsenberg et al., 2015; Ludwig et al., 2015). These resources are essential tools for raising awareness and building support for action. However, in reviewing the existing resources, we found that few fully address solutions to the problem and many imply the main, or only, impact will be dissolution of most coral reefs and shelled marine organisms.

The four-lesson high school module outlined here builds on the strengths of existing resources by incorporating many of their approaches. We intentionally avoid the most common ocean acidification lab, placing shells in vinegar and watching them dissolve, because we've found some evidence that this experiment reinforces misconceptions about pH and ocean acidification's impacts. We contribute new ideas on how to teach about the impacts of and solutions to ocean acidification. Additionally, in considering solutions to ocean acidification and engaging students in discussions of ways to maximize and expand their impact, we hope to help teachers show their students that ocean acidification is a large environmental issue, but one that we can address if we work together.

CURRICULUM OVERVIEW

The curriculum module (see On the Web: Changing Ocean Chemistry) introduced here was created according to the Understanding by Design framework (Wiggins & McTighe, 2006) and most of the lessons rely on the 5E Instructional Model. In establishing the goals for this curriculum, we identified links to Next Generation Science Standards, interviewed ocean acidification researchers, reviewed scientific literature on the topic, and evaluated 90 existing teaching resources using a curriculum merit checklist (Kowalski, 2016). The module was developed in a reiterative process that included revision after each major phase: pilot study, teacher focus group, and classroom implementation. We have taught this module to over 300 high school students in ten classrooms in a coastal Oregon school district in a variety of science classes, and the curriculum is presented here after its most recent round of revision.

The goal of this module is to increase student understanding about ocean acidification and leave students with a sense that it is an issue that can be addressed. Lesson 1 begins by exploring the true story of the near collapse of the US West Coast's oyster industry that occurred from 2005-2009. It continues with an overview of ocean acidification and exploration of how humans have altered the carbon cycle. Lesson 2 is split into two parts: in part one, students explore pH and how carbon dioxide causes acidification, while in part two, students learn about changes in carbonate ion concentration, something important to calcifying marine organisms that make shells and hard structures out of calcium carbonate (e.g., shellfish and corals). They apply their learning by interpreting water quality data from Whiskey Creek Shellfish Hatchery. In lesson 3, students conduct independent research on the possible impacts of ocean acidification to ecosystems and humans then present their findings to the class. In lesson 4, students examine solutions to ocean acidification by exploring which household actions lead to the greatest energy savings. The curriculum finishes with a recommended Call to Action project.

LESSON DETAILS

LESSON 1 – INTRODUCTION TO OCEAN ACIDIFICATION

Lesson 1 starts with a formative probe, inspired by the *Uncovering Student Ideas in Science* series, to identify students' existing understandings. Next, students watch a five-minute video about the near collapse of the Pacific Northwest oyster industry that took place from 2005-2009. Narratives can be powerful tools to motivate environmental action (Kelly et al., 2014), and the Postcard from the Oregon Coast video (see On the Web) frames ocean acidification as an environmental issue that is already impacting people and highlights the connections between humans and natural systems. Lesson 1 continues by introducing an explanatory chain (see Figure

3.1) that allows students to connect the dots between the causes of ocean acidification (human CO_2 emissions, primarily from fossil fuel use) and its broad impacts (Aubrun & Grady, 2005; Bales, Sweetland, & Volmert, 2015). To elaborate on this introduction, students explore how carbon cycles through the system via photosynthesis and respiration. They are then challenged to answer: “Does human breathing increase CO_2 in the atmosphere?” This question preemptively confronts a misconception that arose for some students during instruction, namely that human breathing contributes to ocean acidification.

a)

Description	Explanation
When we burn fossil fuels like coal and gas, we release carbon dioxide into the air. When excess CO_2 from the air gets absorbed into the ocean it causes ocean acidification. Ocean acidification makes it hard for shellfish to build their shells. The loss of these organisms affects the whole ecosystem.	When we burn fossil fuels like coal and gas, we release carbon dioxide into the air. The ocean absorbs a lot of this carbon dioxide, which is changing the ocean’s chemistry – a process called ocean acidification. One result of this change in chemistry is that carbonate – something shellfish use to build their shells – becomes scarce. This means there will be fewer shellfish in the food chain for other creatures to eat, which then affects the whole ecosystem.

b)

i. Human activities release CO_2
ii. The ocean absorbs ~25% of anthropogenic CO_2
iii. Changing ocean chemistry
iv. Carbonate, used for shell building, becomes less available. It takes more energy to make shells, leading to fewer & smaller shellfish
v. Shellfish filter water. Fewer shellfish could lead to cloudier water. Cloudy water makes it harder for seagrasses to do photosynthesis. Seagrass beds are important habitat for young fish
vi. Less seagrass could mean fewer fish to catch
vii. This could impact humans who rely on fish for food & jobs

Figure 3.1 - Explanatory and descriptive chains
a) Comparison of description and explanations of ocean acidification. Reproduced, with permission, from: Bales, S.N., Sweetland, J., & Volmert, A. (2015). *How to Talk about Climate Change and the Ocean: A FrameWorks MessageMemo*. Washington, DC. b) Our explanatory chain on ocean acidification, modified based on feedback from ocean acidification researcher scientists.

Lesson 1 concludes with an in-class or homework assignment. Students watch as carbon dioxide concentrations increase and decrease over the course of a year in a NASA simulation (see On the Web). Then they examine graphs of atmospheric CO_2 concentrations over different time scales (60 years, 10,000 years, and 800,000 years), interpret the graphs, and identify evidence for natural and human caused variations in atmospheric CO_2.

LESSON 2 – CHEMISTRY OF OCEAN ACIDIFICATION

This optional lesson, included for teachers looking to go deeper into the chemistry of OA, is split into two sublessons. Part one begins with a teacher-led demonstration of adding CO_2 to water with a Soda Stream and measuring the change in pH with universal indicator. The lesson continues with an introduction to acids and bases. At this point we avoid discussing the interaction of H^+ and carbonate ions, choosing to save this topic for part two. To reinforce key ideas on pH, students use the PhET online pH Scale simulation (see On the Web) to explore the molecular basis of acids and bases.

Lesson 2 part two begins with a demonstration that utilizes candles floating in an indicator solution (See On the Web: CarboSchools). As the candles burn they generate CO_2, which eventually lowers the pH of the surface layer of the solution. Students are challenged to explain what they see through annotated drawings. This activity serves as a formative assessment of student learning for the teacher. Following this activity, the teacher introduces two key points: the reaction of H^+ with carbonate removes a building block needed for the shells and skeletons of many marine organisms and seasonal upwelling in the Pacific Northwest makes this region especially vulnerable to ocean acidification. Students synthesize their learning by analyzing water quality data from a Pacific Northwest shellfish hatchery (see On the Web: Palevsky).

LESSON 3 – IMPACTS OF OCEAN ACIDIFICATION

Lesson 3 focuses on the impacts of ocean acidification. It begins with a short video featuring scientists describing some of the possible impacts of ocean acidification (see Figure 3.2). We were surprised to find that many students expressed fear and/or anxiety after watching this clip. For example, when asked how it feels to hear scientists say, “we don’t know what the impacts will be for ecosystems,” one student wrote, “It makes me anxious for the future of the

Figure 3.2 - Snapshot from video discussing impacts of ocean acidification.

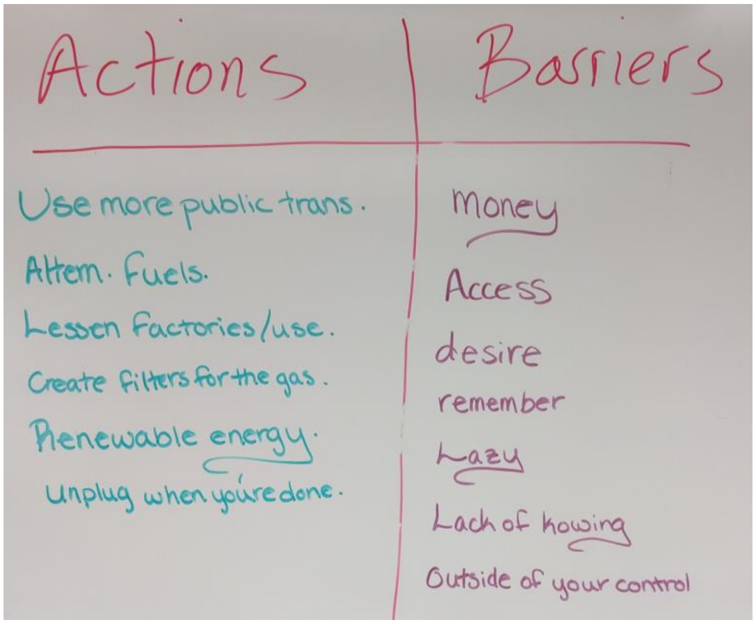
earth and what events could happen…" Another explained, "It makes me feel like the problem is an unsolvable situation because no one knows what will happen and how to solve it." These student reflections reminded us of the possible unintended consequences of instruction on environmental problems and reinforced, in our minds, the need to conclude with a hopeful and solutions-focused final lesson.

Following the video, students choose an organism and research the ways that this organism is predicted to be impacted by ocean acidification. This project allows students to practice conducting research and presenting their findings to the class. Additionally, it allows students to gain a broader, more complex understanding of the possible impacts of ocean acidification. By taking notes on each other's presentations, students see the scope of impacts, connections to people, and some of the complexity involved.

LESSON 4 – WAYS TO ADDRESS OCEAN ACIDIFICATION

The final lesson in this module focuses on ways to address ocean acidification. Many students we worked with expressed a desire to help but lacked knowledge of what they could do. For example, one student wrote, "I would like to help our oceans & other waters but I'm not sure what the best thing to do would be." Another explained, "I want to do more, but I don't really know what to do and how to do it."

This lesson begins with a brainstorm of actions that could be taken to reduce carbon dioxide emissions (see Figure 3.3); however, unlike other curricula, we also ask students to brainstorm barriers to taking action (i.e., reasons why someone might not take one or more of these actions). By asking students to consider barriers, we are priming students to think about motivations for their final project.



Actions

Use more public trans.
Altern. Fuels.
Lessen Factories/use.
Create filters for the gas.
Renewable energy.
Unplug when you're done.

Barriers

Money
Access
desire
remember
Lazy
Lack of kowing
Outside of your control

Figure 3.3 - Student brainstorm of actions and barriers.

Most ocean acidification curricula stop after a brief brainstorm of solutions. Unfortunately, research has shown that most of us are unaware of which of our actions use the most energy, and thus which changes would have the most impact on our carbon footprint (Attari et al., 2010). Thus, this brainstorm-only approach may unintentionally reinforce misconceptions about which actions will lead to the greatest emissions reductions. We challenge students' preexisting beliefs through an activity we developed that uses Gardner & Stern's (2008) The Short List. Student pairs are given 12 cards, each of which has an action on it that reduces energy use (and thus CO_2 emissions). Students arrange these cards from actions that save the most to the least amount of energy. After an initial attempt, students are shown data about household energy use in the U.S. and are given an opportunity to adjust their answers. Then, the order of actions is revealed which leads to a class discussion. This activity's key message is that the actions we think will have the greatest impact might not be the most effective.

Following this activity, students calculate their own carbon footprint using Berkeley's Cool Climate calculator (see On the Web), identify actions they might be willing to take, and calculate the relative CO_2 and dollar savings if more people took this action. While there are multiple carbon footprint calculators available, we found the Cool Climate calculator to be easy to navigate and have an action list that allowed students to easily compare and adjust the relative impact of various actions.

The end of lesson 4 leads into a Call to Action final project where students choose a target audience, identify an action they want their target audience to take, and create a persuasive message (speech, video, ad, flyer, letter, etc.) to convince their target audience to act. Many of our students expressed feeling that ocean acidification was beyond their control, and we developed this final project to give students an opportunity to try to persuade those they think do have control to take action.

CONCLUSIONS

Our ocean acidification curriculum module adds to existing resources by proposing a new way to teach about the impacts of and solutions to ocean acidification. We hope that it helps you and your students develop a realistic understanding of the potential impacts of ocean acidification and the numerous actions that could help reduce or reverse the problem. Our goal is that by talking about solutions and encouraging students to create Calls to Action, more students may view ocean acidification as an environmental problem than can be fixed. As one of our students wrote, "we can all change this, but we have to try. Someone else isn't going to do it for you."

If you use this curriculum in your classroom, we'd love to hear about your experience via email: Brian Erickson (brian.erickson@oregonstate.edu), Tracy Crews (tracy.crews@oregonstate.edu).

ACKNOWLEDGMENTS

This curriculum would not be possible without the input and participation of the students and educators that worked with us. Many thanks to the scientists and curriculum experts who provided insight along the way, and the educators who have shared their own approaches to

teaching ocean acidification. This project is funded by a grant from Wendy and Eric Schmidt to the OSU Foundation.

STANDARDS

Connecting to the Next Generation Science Standards (NGSS Lead States 2013).

Standards
HS-ESS2 Earth's Systems
HS-ESS3 Human Sustainability
HS-LS2 Interdependent Relationships in Ecosystems

Performance Expectation(s)

The chart below makes one set of connections between the instruction outlined in this article and the NGSS. Other valid connections are likely; however, space restrictions prevent us from listing all possibilities. The activities outlined in this article are just one step toward reaching the performance expectations listed below.

HS-ESS2-6. Develop a quantitative model to describe the cycling of carbon among the hydrosphere, atmosphere, geosphere, and biosphere.
HS-ESS3-4. Evaluate or refine a technological solution that reduces impacts of human activities on natural systems.
HS-LS2-6. Evaluate the claims, evidence, and reasoning that the complex interactions in ecosystems maintain relatively consistent numbers and types of organisms in stable conditions, but changing conditions may result in a new ecosystem.
HS-LS2-7. Design, evaluate, and refine a solution for reducing the impacts of human activities on the environment and biodiversity.

Dimension	**Name and *NGSS* code/citation**	**Specific Connections to Classroom Activity**
Science and Engineering Practices	**Constructing Explanations and Designing Solutions** • Design, evaluate, and refine a solution to a complex real-world problem, based on scientific knowledge, student-generated sources of evidence, prioritized criteria, and tradeoff considerations. (HS-LS2-7), (HS-ESS3-4)	Students justify their reasoning for promoting a specific solution to ocean acidification in their Call to Action project.
	Engaging in Argument from Evidence • Evaluate the claims, evidence, and reasoning behind currently accepted explanations or solutions to determine the merits of arguments. (HS-LS2-6) • Construct an oral and written argument or counterarguments based on data and evidence. (HS-ESS2-7)	Students analyze data and empirical evidence related to the signs and impacts of ocean acidification. Students justify their positions in formative probes.
Disciplinary Core Ideas	**ESS2.D: Weather and Climate** • Changes in the atmosphere due to human activity have increased carbon dioxide concentrations and thus affect climate. (HS-ESS2-6)	Students determine whether breathing contributes to ocean acidification. Students examine graphs and simulations of atmospheric CO_2.

	LS2.C: Ecosystem Dynamics, Functioning, and Resilience • A complex set of interactions within an ecosystem can keep its numbers and types of organisms relatively constant over long periods of time under stable conditions. If a modest biological or physical disturbance to an ecosystem occurs, it may return to its more or less original status (i.e., the ecosystem is resilient), as opposed to becoming a very different ecosystem. Extreme fluctuations in conditions or the size of any population, however, can challenge the functioning of ecosystems in terms of resources and habitat availability. (HS-LS2-2), (HS-LS2-6) • Moreover, 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. (HS-LS2-7) **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. Thus sustaining biodiversity so that ecosystem functioning and productivity are maintained is essential to supporting and enhancing life on Earth. Sustaining biodiversity also aids humanity by preserving landscapes of recreational or inspirational value. (secondary to HS-LS2-7), (HS-LS4-6) **ETS1.B: Developing Possible Solutions** • When evaluating solutions, it is important to take into account a range of constraints, including cost, safety, reliability, and aesthetics, and to consider social, cultural, and environmental impacts. (secondary to HSLS2-7), (secondary to HS-LS4-6), (secondary to HS-ESS3-2), (secondary to HS-ESS3-4)	Students research the predicted impacts of ocean acidification on various organisms and synthesize individual findings to develop a conclusion about what the problem might mean for ecosystems. Students list ways that humans and ecosystems are interdependent. Students consider various possible solutions and justify the solution they advocate for in their Call to Action project.
Crosscutting Concept(s)	**Cause and Effect** • Empirical evidence is required to differentiate between cause and correlation and make claims about specific causes and effects. (HS-LS2-8), (HS-LS4-6)	Students generate lists of evidence that would support the argument that ocean acidification caused oyster die-offs at hatcheries.

	Stability and Change - Much of science deals with constructing explanations of how things change and how they remain stable. (HS-LS2-6), (HS-LS2-7)	Students compare cycles of natural variation and linear trends of ocean acidification.

ON THE WEB

Changing Ocean Chemistry curriculum (detailed lessons including sample scripting, videos, PowerPoint presentations, student handouts, teacher answer keys, and additional background reading): https://brianderickson.weebly.com/oa-curriculum.html.

CarboSchools. Interaction at the Air-Water Interface II: http://tinyurl.com/ybzxd6l2.

Greenpeace USA. Postcard from the Oregon Coast: https://youtu.be/IFwrkQ-eZ3E.

NASA. A Year in the Life of Earth's CO_2: https://youtu.be/x1SgmFa0r04.

Palevksy, Hilary. Ocean Acidification and Oysters Lab. http://tinyurl.com/y8ou5nwp.

pH Scale PhET simulation: http://tinyurl.com/mc4m4b3.

University of California, Berkeley. CoolClimate Calculator: http://tinyurl.com/yctbxdxz.

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CHAPTER 4: SECOND MANUSCRIPT [AMBIO]

KNOWLEDGE TO ACTION? EFFECTS OF TEACHING HOUSEHOLD ACTIONS TO ADDRESS OCEAN ACIDIFICATION ON STUDENT KNOWLEDGE AND ATTITUDES

ABSTRACT

Ocean acidification (OA) is an area of active scientific research, yet the public remains largely unaware of the issue. It is often presumed that raising awareness will lead to public support and action to address OA. However, conservation psychology suggests that knowledge is only a prerequisite to action and is not the only barrier preventing OA mitigation. In this two-group, non-randomized longitudinal experiment, we examine the effects of a teaching intervention on student knowledge and attitudes about OA. To our knowledge, this is the first OA intervention study to include a follow-up survey. We found that instruction increased student knowledge but that misconceptions persisted over time. Additionally, our control group exhibited no change in attitudes over time while our treatment group showed short-term increases in concern, norms for action, and knowledge of ways to address OA. These changes in attitude did not persist 10-weeks after instruction. Although our results are restricted to a single school district in Oregon, this study questions whether short-term responses to intervention will translate to long-term attitudinal and behavior change and highlights the need to include ways to help address OA if we want students and adults to contribute to mitigation.

INTRODUCTION

Ocean acidification (OA) is the change in ocean chemistry due to increasing amounts of carbon dioxide (CO_2) in the atmosphere (Doney, Fabry, Feely, & Kleypas, 2009) and is primarily the result of human activities (fossil fuel combustion, land use changes, and cement production)(Ciais et al., 2013). With 93% of all peer-reviewed papers on OA published since 2010 (Web of Science, 2018) and 1 in 5 papers published since the start of 2017, OA is a new and rapidly expanding area of scientific research. OA is already impacting the U.S. West Coast (e.g. Barton et al. 2012; Bednaršek et al. 2014; Waldbusser et al. 2015; Bednaršek et al. 2017) and is predicted to cause cascading impacts for marine ecosystems and humans in coming decades. There are increasing calls for action from the scientific and conservation communities (e.g.

Washington State Blue Ribbon Panel on OA 2012; Cooley et al. 2016), yet non-scientists remain largely unaware of the issue (Bales et al., 2015; Buckley et al., 2017; Capstick et al., 2016; Corner et al., 2014; Danielson & Tanner, 2015; Epperly et al., 2016; Frisch et al., 2015; Gelcich et al., 2014; Mabardy, Waldbusser, Conway, & Olsen, 2015; Schuldt et al., 2016; The Ocean Project, 2012).

This disparity in knowledge between scientists and non-scientists suggests an intuitive solution: raise awareness and public concern about OA will rise. Many outreach and education efforts hope awareness will raise support for and engagement in OA mitigation. As the Washington State Blue Ribbon Panel on OA (2012) explains, "[outreach and education] can empower citizens and businesses to help develop and implement solutions,"(p.xviii) while Strong et al. (2014) suggest, "public literacy of OA can increase the demand for science-based decision making and can accelerate regional responses to OA impacts." However, research confirms what we know from personal experience: lack of knowledge is an inadequate explanation for lack of public concern or action (e.g., Evans & Durant 1995; Fauville et al. 2013; Kahneman 2011; Kelly et al. 2014; McKenzie-Mohr 2011; Stern 2000). Gardner & Stern (2002) conclude that education alone can change knowledge, attitudes, and beliefs, but has little to no impact on behaviors, especially when external barriers to action exist. As the Washington Marine Resource Advisory Council (2017) acknowledges, knowledge is only a prerequisite to action.

If knowledge alone does not lead to action, what makes some people act to reduce a threat while others with similar concerns do little or nothing about it? Three theories of action, Value-Belief-Norm theory (Stern, 2000), the Theory of Psychological Coping (Lazarus & Folkman, 1984), and the Extended Parallel Process Model (Witte, 1994), while different in their details, all include the same key concept. According to these theories, two factors determine action: (i) you view a situation as a threat to something you care about and (ii) you believe you can do something to improve the situation. As Lazarus & Folkman explain, if we think we have control over a threat, we will engage in danger control (i.e., we will try to fix the problem). In contrast, if we do not think we can control the threat, we will respond with fear control (i.e., reduce our feelings through denying, ignoring, or dismissing the threat). When applied to OA, these theories suggest that if we perceive OA as a threat and if we feel we can do something to fix it, we will likely engage in danger control. In contrast, if we think OA is a problem but we do not think there is anything we can do about it, we are likely to ignore it, deny it, or downplay its possible consequences (see Figure 4.1). Similarly, if we do not perceive OA as a threat, we will not take mitigating actions.

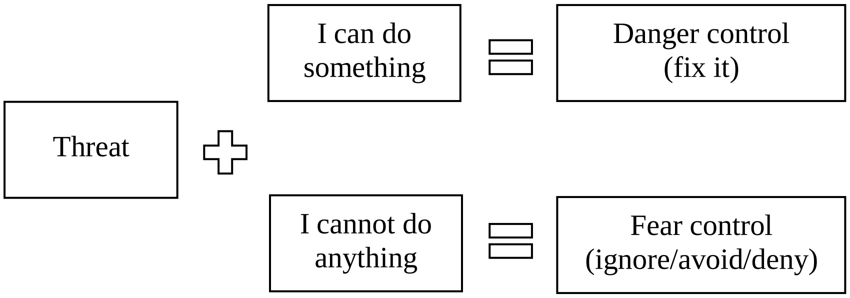

Figure 4.1 - Theories of action.

Despite increased efforts to gauge public understanding of OA, there is little research on the impacts of outreach and education efforts. This study examined the impacts of a four-day high school teaching intervention on students' knowledge and attitudes regarding OA via a two-group non-randomized experiment. We measured responses along multiple attitudinal scales with surveys at three timepoints and compared responses between students who learn about ways to reduce OA (treatment) and students who do not (control). To our knowledge, this is the first study to measure the effects of OA information efforts at multiple points following an intervention.

METHODS

STUDY PARTICIPANTS AND PARTICIPATION

This study took place in Lincoln County School District (LCSD), Oregon. LCSD was chosen for this study because it partners with Oregon Sea Grant and Oregon State University's Hatfield Marine Science Center (HMSC) for support in marine science, and teachers in the district have participated in professional development workshops through HMSC. LCSD is a rural, coastal school district with a high school enrollment of 1,601 students in the 2016-17 school year. High school demographics for LCSD include: >95% of students are eligible for free/reduced price meals, 15% are students with disabilities, and 12% are Ever English Learners (a.k.a., "English Language Learners"). The high school student population is 64% White, 20% Hispanic/Latino, 7% Multi-racial, 6% American Indian/Alaska Native, 1% Asian and Black/African American, and <1% Native Hawaiian/Pacific Islander.

Classroom teachers in LCSD who had an existing relationship with HMSC were contacted via email with a notification about this study. Four teachers from three of four high schools in LCSD chose to participate. The experiment included 10 classrooms (two biology, six chemistry, one integrated science, and one combined classroom of physical ocean science/AP environmental science) with 318 enrolled students.

To prioritize participant anonymity, no demographic information was collected. Students recorded their birthday (month and date only) and first initial on all surveys. A total of 166 students (control: n= 83; treatment: n= 83; 52% of students receiving instruction) completed surveys at all timepoints. Data analyses were conducted on this reduced, complete survey set.

EXPERIMENTAL DESIGN

This study used a two-group longitudinal design without random assignment (Bernard, 2000). Classrooms were divided into two intervention groups, control and treatment, so that there were: (i) equal numbers of classrooms per group at each school, (ii) equal distributions of subjects per group, and (iii) roughly equal numbers of students per group. Both control and treatment groups contained three chemistry classes, one biology class, and one other science class and 159 potential participants. All instruction was carried out in Fall 2017 by the lead author, who is a formerly certified high school science teacher with a master's degree in teaching secondary biology.

Students completed surveys at the start of the first day of instruction (T0), at the end of the fourth day of instruction (T1), and roughly 10-weeks following instruction (T2; see Figure 4.2). All students received the same instruction for the first three days of the experiment. This instruction included an introduction to the oyster hatchery failures in the Pacific Northwest between 2007-2009 (Barton et al., 2012), a general introduction to OA, discussion of chemistry changes associated with OA, analysis of water quality data from an Oregon shellfish hatchery, and exploration of possible impacts of OA.

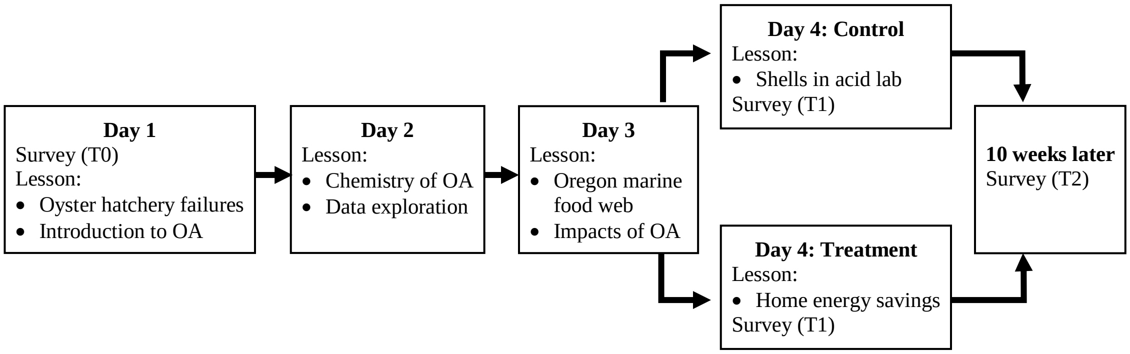

Figure 4.2 – Experimental design.

On day 4, the control group conducted a lab experiment where students placed shelled marine organisms (i.e., oysters, clams, sand dollars) into acidic solutions (vinegar, carbonated water) and seawater, and observed as the shells bubbled in the acidic solution. This lab was considered standard curriculum because it appeared in 50% (n= 45) of OA resources reviewed while developing this curriculum.

The treatment group participated in a lesson that focused on actions students could take to reduce OA. In the lesson, students brainstormed ways to reduce CO_2 emissions and barriers to taking these actions and evaluated the relative impact (energy savings) and cost of various household energy saving actions (modified from Gardner & Stern, 2008).

Most available OA curricula do not mention ways to mitigate OA. Our treatment group modified a common approach taken by those resources that do address mitigation (Erickson, 2018). Most lessons on mitigation only include a brainstorm or homework question probing for possible actions. Few provide students with new ideas, none compare the impacts of multiple actions nor assess barriers to action, and few provide teachers with guidance on which actions might be more effective and why. Thus, this mitigation lesson was an attempt to update and improve upon existing approaches.

CURRICULUM DESIGN

The lessons used in this study were designed using the Understanding by Design curriculum development framework (Wiggins & McTighe, 2006), where curriculum developers first establish overarching goals, then identify assessment targets, and finish by identifying specific learning activities and sequences. Goals were identified based on links to education standards (Next Generation Science Standards, Common Core State Standards, and Ocean Literacy Principles), as well as a review of existing curricula, literature review, and three informal, semi-structured interviews with OA researchers at Oregon State University. Where it matched our teaching goals, existing resources were used or modified.

We used a reiterative process to revise our curriculum. A first draft of the curriculum was tested with a pilot study at a HMSC high school summer camp. Sixteen students (80% of participants) completed baseline & post surveys (no follow-up survey was used). Pilot surveys and student work were analyzed, leading to curriculum and survey modifications. This revised curriculum was presented to an educator focus group (n=7) composed of teachers, instructional coaches, and informal science educators with experience in LCSD. This session led to additional revisions. A final revision followed the experiment described in this study can be accessed at: https://brianderickson.weebly.com/oa-curriculum.html.

SURVEY DESIGN

The survey was designed to assess high school student knowledge and attitudes regarding OA. Where possible, survey questions from peer-reviewed research on OA were used or modified. Since surveys were administered to students in classrooms, they were paper-based and questions and answer options were presented in identical order on all surveys.

Perceived knowledge of OA

Participants were asked, “How much, if anything, would you say you know about OA?” Responses to this question were on a five-point scale and included the following options: I have not heard of OA; I have heard of OA, but I know almost nothing about it; I know just a little about OA; I know a fair amount about OA; and I know a great deal about OA. This question is identical to previous studies of public perceptions of OA (Capstick et al., 2016).

Knowledge of causes and consequences

Two questions were used to gauge students' knowledge of causes and predicted consequences of OA. The first question, modified from Capstick et al. (2016), asked participants, “Which, if any, do you think is the main cause of OA?” Participants were directed to check one answer from the following options:

- Carbon dioxide in the atmosphere that is naturally-occurring being absorbed by the ocean
- Carbon dioxide in the atmosphere from human activities being absorbed by the ocean
- Increased sea water temperatures from climate change
- Normal cycles of change in ocean chemistry
- Over-fishing (catching too many fish) leading to disruption of ocean food chains
- Pollution, such as from oil spills and discharge of waste
- None of these
- I don't know

As noted in Capstick et al. (2016), only "carbon dioxide… from human activities…" accurately represents current scientific understanding. This answer was considered the correct response and all other answers were marked incorrect.

The second question, also modified from Capstick et al. (2016), asked participants, "Which, if any, do you think are possible consequences of OA?" Participants were instructed to "check all that apply" from a list of possible options. This list of possible consequences included seven options that represent possible impacts described in scientific literature and six options that aligned with common misconceptions about OA and served as distractors (see below). Student responses were coded as correct if they correctly checked predicted impacts or did not check distractors.

Potential impacts in scientific literature

- Worse conditions for some larger marine organisms (including fish)
- Better conditions for some larger marine organisms (including fish)
- Worse conditions for some small marine organisms
- Better conditions for some small marine organisms
- Coral reefs will grow more slowly
- Making and repairing shells will require more energy
- There will be problems, such as decreased profits, for people who make a living from the sea

Incorrect answers (distractors)

- The ocean will become acidic (below pH=7)
- Most living marine animals will have their shells completely dissolve
- Making and repairing shells will require less energy
- People spending long periods of time at sea, such as fishermen, will have skin damage
- The metal hulls of ships will be damaged

Student knowledge score represents the number of correct answers (out of 14) provided by each student and converted to a percentage correct (0 to 100%). Since these questions measure knowledge, “I don't know” responses were considered incorrect. No reliability calculations were conducted on this scale since it represents the percentage of correct answers given by each student (Vaske, 2008).

Stated concern

Participants were asked, “How concerned, if at all, are you about OA?” Responses to this question were on a four-point scale and included the following options: not at all concerned; not very concerned; fairly concerned; very concerned; and I don't know. This question was modified from Capstick et al. (2016), which is a modified version of a standard survey item used to gauge climate change concern (Spence, Venables, Pidgeon, Poortinga, & Demski, 2010).

Knowledge of threat proximity

Participants were asked to show how much they agreed or disagreed with three statements from Mabardy et al. (2015) about where OA is currently happening. Each statement included a five-point scale with the following options: strongly disagree; somewhat disagree; neither agree nor disagree; somewhat agree; strongly agree; and I don't know. The statements were:

- OA is happening in my local estuary
- OA is happening along the U.S. West Coast
- OA is happening globally

The reliability analysis indicated that removing “OA is happening globally” substantially improved subscale internal consistency for post and follow-up surveys. This item was deleted to create a two-item proximity of threat scale with questionable to acceptable reliability (α_{Baseline} = 0.69, α_{Post} = 0.77, $\alpha_{\text{Follow-up}}$ = 0.76).

Perceived control

Participants were asked four questions regarding their perceived control over OA, modified from McKenzie-Mohr, McLoughlin, & Dyal (1992). Each question included a five-point scale with the following options: none at all; very little; a moderate amount; a lot; a great deal; and I don't know. Control was divided into two subscales: personal and collective control. Personal control questions included:

- How much control do you feel that you, alone, have in reducing OA in your local estuary?
- How much control do you feel that you, alone, have in reducing OA in the global ocean?

Collective control questions included:

- How much control do you feel that you, working with others, have in reducing OA in your local estuary?
- How much control do you feel that you, working with others, have in reducing OA in the global ocean?

The reliability analysis indicated that both subscales had an acceptable to good level of internal consistency (personal control: $\alpha_{\text{Baseline}} = 0.80$, $\alpha_{\text{Post}} = 0.81$, $\alpha_{\text{Follow-up}} = 0.77$; collective control: $\alpha_{\text{Baseline}} = 0.83$, $\alpha_{\text{Post}} = 0.76$, $\alpha_{\text{Follow-up}} = 0.77$).

Perceived norms of action

Participants responded to three statements gauging perceived norms for taking action. Each question included a five-point scale with the following options: strongly disagree; somewhat disagree; neither agree nor disagree; somewhat agree; strongly agree; and I don't know.

- Reducing OA is the right thing to do
- People should be taking action to reduce OA
- I should be taking action to reduce OA

The first two questions were grouped into a subscale (group norms) which reliability analysis indicated to have an acceptable to excellent level of internal consistency ($\alpha_{\text{Baseline}} = 0.79$, $\alpha_{\text{Post}} = 0.90$, $\alpha_{\text{Follow-up}} = 0.91$). The final statement was treated as a measure of personal norms.

Knowledge of actions to reduce OA

Participants were provided an empty table with five rows and directed to “list actions someone could take to reduce OA.” This question was modified from Kowalski (2016) to address OA. Student responses were inductively coded (Bernard, 2000)

DATA ANALYSIS

Linear mixed model analysis was used to estimate the effect of the intervention. Mixed models allow for analysis of clustered, repeat measures data (Tabachnick & Fidell, 2007). The basic model included intervention, time (T0, T1, T2), and the interaction between intervention and time as fixed effects. Student, classroom, topic (chemistry, biology, other), and school were entered as random effects. Redundant parameters were removed from the model for each dependent variable. We conducted subgroup analyses to examine between and within group differences by intervention.

ETHICAL CONSIDERATIONS

This project was approved by the Institutional Review Board (IRB) at Oregon State University and complied with all regulations on research involving human subjects. The researcher introduced the project to potential student participants at least two weeks before classroom instruction, and all participants consented to participate through a paper-based process.

RESULTS

Responses to intervention exhibited three patterns: (i) significant increases from T0 to T1 remained over time, (ii) significant increases from T0 to T1 that regressed to baseline, and (iii) no significant changes over time.

KNOWLEDGE SCALES

Both groups showed significant increases on all three knowledge scales from T0 to T1 and remained significantly higher than baseline at T2 (see Figure 4.3). Additionally, the only significant knowledge difference between groups occurred at T1 on knowledge of causes and impacts. There were no other significant differences in knowledge between groups at any other timepoint.

At T0, 55% of students indicated knowing nothing or “almost nothing” about OA while 36% knew “just a little.” In contrast, nearly all students (91%) reported knowing a “fair amount” or “great deal” about OA at T1. Perceived knowledge decreased over time with a shift towards “just a little” knowledge at T2.

Initial knowledge scores were below 50% for both groups. At T0, 42% of students correctly identified anthropogenic CO_2 as the main cause of OA, while 21% identified “pollution” and 25% responded “I don’t know.” In contrast, the majority of students correctly identified anthropogenic CO_2 as the primary cause of OA after instruction (T1= 81%; T2= 73%) and very few suggested “pollution” was the cause (T1= 2%; T2= 5%).

Student knowledge of predicted impacts increased with some exceptions. Students rarely agreed (< 10%) that OA will be better for some large or small organisms. Additionally, a majority of students thought “the ocean will become acidic” (control: T0= 58%, T1= 55%, T2= 60%; treatment: T0= 65%, T1= 60%, T2= 70%). Groups differed in whether they thought “most living marine animals will have their shells completely dissolve.” Nearly half (47%) of control group students initially endorsed this misconception. Instruction increased this misconception (T1= 57%; T2= 55%) despite multiple warnings that the lab was unrealistic. In contrast, 58% of the treatment group initially endorsed this misconception. Instruction decreased endorsement (T1= 34%), but the misconception returned (59% endorsed) at T2.

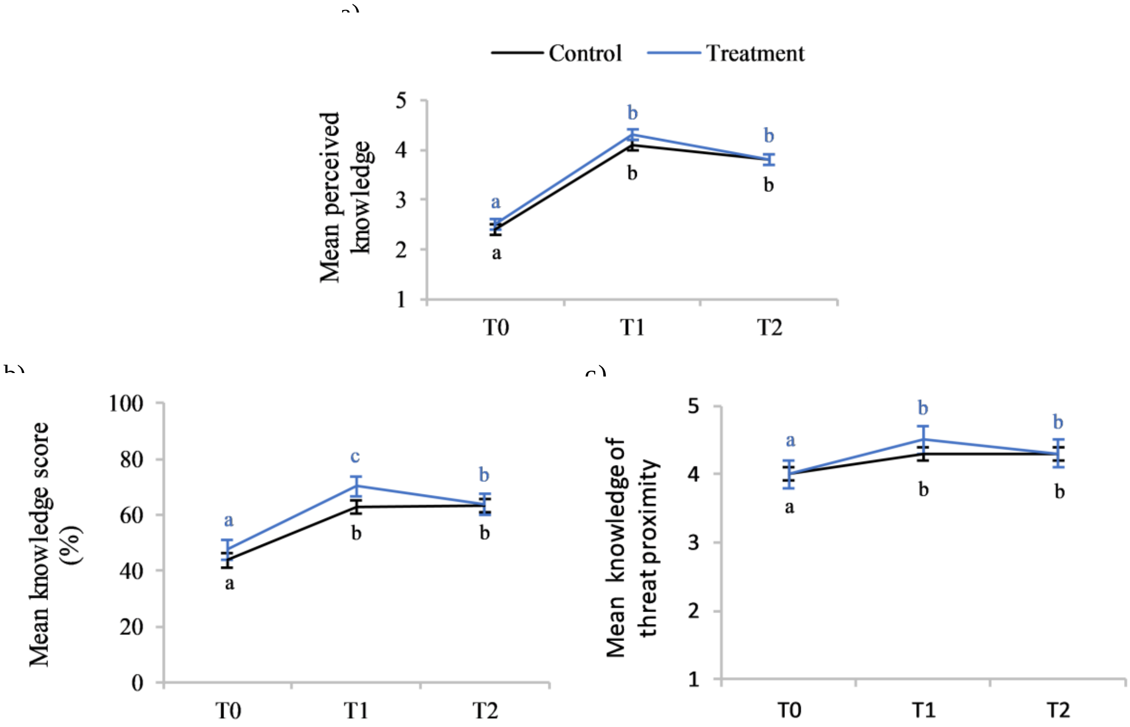

Figure 4.3 - Mean knowledge over time.
Estimated marginal means on knowledge scales generated using linear mixed model analysis. a) Mean perceived knowledge, by intervention (1= "I have not heard of OA" to 5= "I know a great deal about OA"). b) Mean knowledge score, by intervention (0 to 100%). c) Mean knowledge of threat proximity of OA, by intervention (1= "strongly disagree" to 5= "strongly agree"). Error bars ± standard error. Unlike letters above/below lines indicate significant difference between means ($p < 0.05$). T0= baseline; T1= immediately post instruction; T2= 10-weeks post instruction.

Students who answered the two proximity-of-threat knowledge questions generally agreed that OA was happening (mean score of 4.0^+ out of 5.0 at all timepoints). Students' uncertainty of the proximity of threat decreased over time (percent responding "I don't know" T0= 16-43%; T1= 2-16%; T2= 1-12%).

ATTITUDE SCALES

There were no attitudinal changes in the control group. Treatment group concern and norms for action significantly increased from T0 to T1 and regressed to baseline at T2 while their perceived control showed no significant change over time (see Figure 4.4).

A majority of students were “fairly” or “very” concerned about OA at all timepoints (T0: 58%; T1: 87%; T2: 77%), but 22% of students at T0 did not know how concerned they were about OA. There were no significant differences in concern between groups at any time point.

Both groups agreed that they and others should act to reduce OA (mean norm 4.0^+ out of 5.0 at all timepoints). Groups significantly differed on perceived individual and group norms for action at T1 but did not significantly differ on either scale at T0 or T2. In contrast to the other attitudinal scales, mean perceived personal and collective control did not differ significantly between groups at any time nor within groups over time. Most students expressed “very little” personal control and “a moderate amount” of collective control.

ACTIONS TO REDUCE OA

The number of students recommending at least one action to reduce OA increased significantly for both groups and remained significantly higher than baseline at T2 (see Figure 4.5). Groups significantly differed in the percentage of students recommending at least one action at T1 but did not significantly differ at T0 or T2.

Student recommendations for ways to reduce OA were inductively coded into three hierarchical levels of actions (see Table 4.1). There were four overarching suggestions (clean energy, ecofriendly, energy savings, and knowledge). Each of the two most common overarching categories (ecofriendly and energy savings) were subdivided. Additionally, the most common response in each of these two subcategories (pollution and daily actions) was also subdivided.

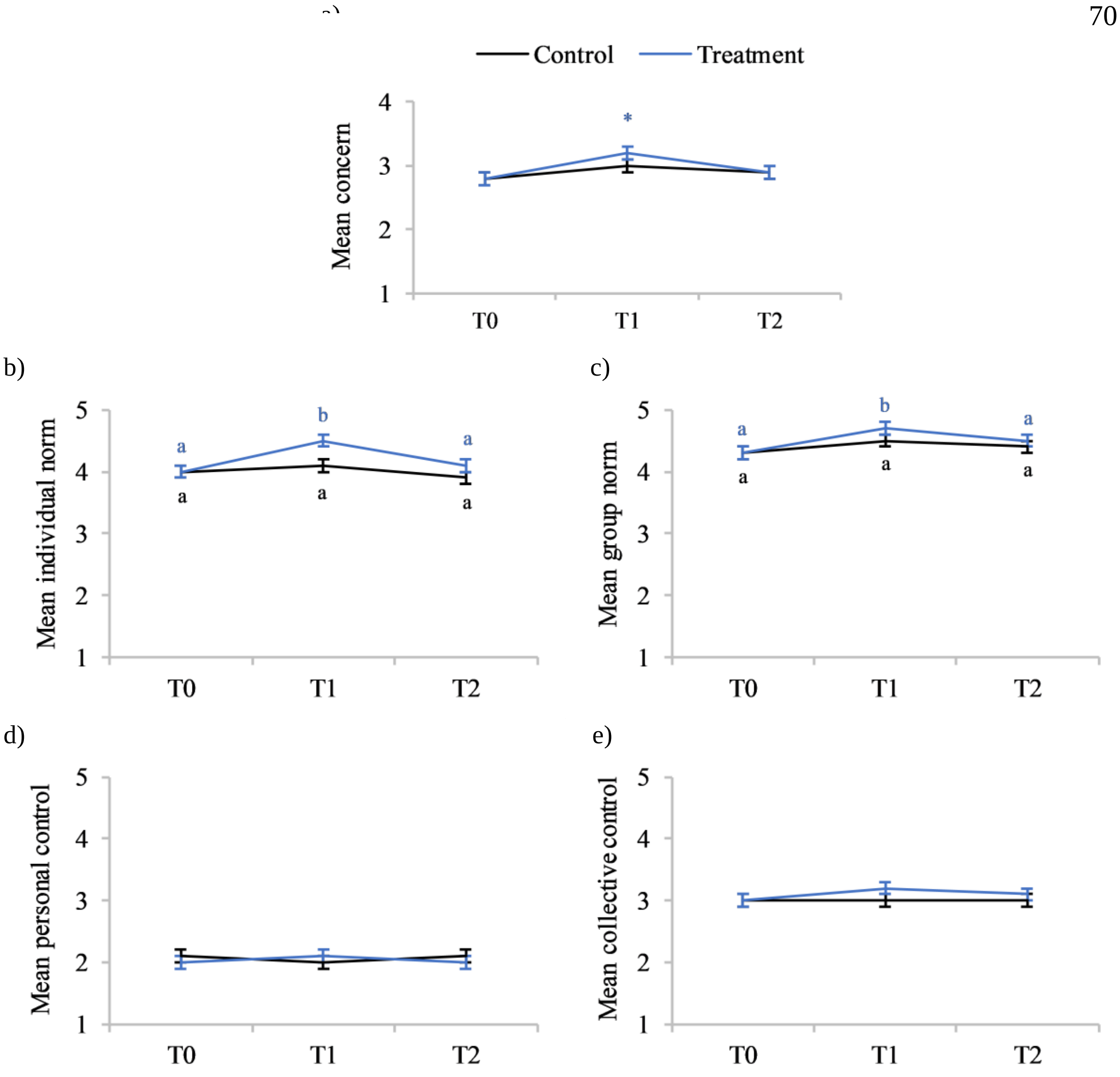

Figure 4.4 - Mean attitudes over time.
Estimated marginal mean for attitude scales generated using linear mixed model analysis. a) Mean perceived concern, by intervention (1= “not at all” to 4= “very”). b) Mean perceived individual norms for action (“I should”), by intervention (1= “strongly disagree” to 5= “strongly agree”). c) Mean perceived group norms for action (“People should”), by intervention (1= “strongly disagree” to 5= “strongly agree”). d) Mean perceived personal control, by intervention (1= “none” to 5= “a great deal”). e) Mean perceived collective control, by intervention (1= “none” to 5= “a great deal”). Error bars ±standard error. Unlike letters above/below lines indicate significant difference between means ($p < 0.05$). T0= baseline; T1= immediately post instruction; T2= 10-weeks post instruction. * Significant difference ($p < 0.05$) from T0 to T1 but no significant difference between groups at T1.

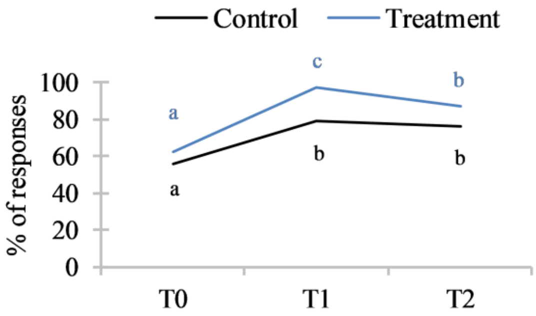

Figure 4.5 – Percentage of students listing one or more actions to reduce OA.
Unlike letters above/below lines indicate significant difference between means ($p < 0.05$). T0= baseline; T1= immediately post instruction; T2= 10-weeks post instruction**.**

The types of actions listed by students differed by intervention group and time point (see Figure 4.6). At T0, ecofriendly actions were the most common type of overarching recommendation. Nearly half (n= 142) of all actions listed focused on reducing pollution (an ecofriendly action), especially cleaning up/not littering, reducing chemical pollution, and recycling. Transit-related recommendations were also common, especially in the solutions group.

Recommendations at T1 varied by group. For the control group, ecofriendly actions remained the most common type of recommendation. Of these ecofriendly actions, 70% mentioned pollution, although references to "reducing litter" decreased in frequency compared to T0. Energy savings actions were the second most commonly recommended action type, and of these, 78% addressed transit. Of transit actions, carpooling was listed twice, and the remaining 33 recommendations were variations of "walk/bike more, drive less." Of the seven efficiency actions listed by this group, five mentioned cars and two highlighted appliances. At T1, no control group students suggested taking public transit nor mentioned replacing inefficient lightbulbs.

In contrast, at T1, the treatment group listed 7.5 times more energy savings actions than at T0 and 4.8 times more energy saving actions than the control group at T1. Most (68%) energy savings recommendations focused on daily actions; however, efficiency-related recommendations made up 23% of energy saving responses and were split between getting a more efficient car (n = 21) and upgrading lights to LEDs (n = 28). Additionally, treatment group students were the only ones to mention weatherization or maintenance at any timepoint. Pollution-related recommendations were less common for this group at T1 compared to T0.

Table 4.1 – Types of actions recommended to address OA.
Inductively coded hierarchy of student responses to the prompt, "list actions someone could take to reduce OA."

Action type	Examples of student responses
Clean energy	Use alternative/clean energy (solar/wind/etc.); use less fossil fuels
Ecofriendly	
Plants	Plant a tree/forest; don't kill plants
Habitat/wildlife	Catch less fish; protect habitat/the environment
Consumer habits	Shop local/organic; change diet; compost; don't use plastic
Pollution	
Don't pollute	Don't pollute; reduce pollution
Don't litter	Don't litter; clean up the beach
Chemicals	Don't dump chemicals/waste
Recycle	Recycle; reduce reuse recycle
Carbon	Reduce CO_2 emissions; reduce your carbon footprint; don't burn…
Organize	Organize others, pass laws, donate money
Knowledge	Raise awareness/educate others; monitor; conduct research
Energy Saving	
Daily	
Transit	Combine errands into a single trip; don't speed/slam on the brakes; carpool; drive less; use public transit; walk; bike; skateboard
Electricity	Turn off the lights/appliances; unplug electronics when not in use; use a power strip; use fewer electronics (e.g., watch less TV); line dry clothes;
Generic	Save energy; use less electricity
Home temperature	Don't use a heater/air conditioner as much
Water use	Use less (hot) water; wash with cold water; take shorter/fewer showers
Efficiency	Install LED lights; get a more efficient car (electric, hybrid, better MPG)
Maintenance	Maintain your car (including tire pressure)
Weatherization	Insulate; install more efficient windows; replace inefficient heating/cooling

Daily actions recommended by the treatment group were diverse, but the majority were transit- related. In addition to saying "walk more, drive less," treatment group students also mentioned carpooling, trip chaining, not speeding, and accelerating slowly. Electricity-related actions were mentioned 42 times even though the lesson emphasized that turning off lights and televisions saved the least energy of all options discussed. Unplugging electronics to reduce standby energy use was not mentioned in the lesson, but 13 students recommended this action at T1.

Responses still varied by group at T2, but less so than at T1. Control group responses were similar to T1 while treatment group responses decreased in frequency and specificity of

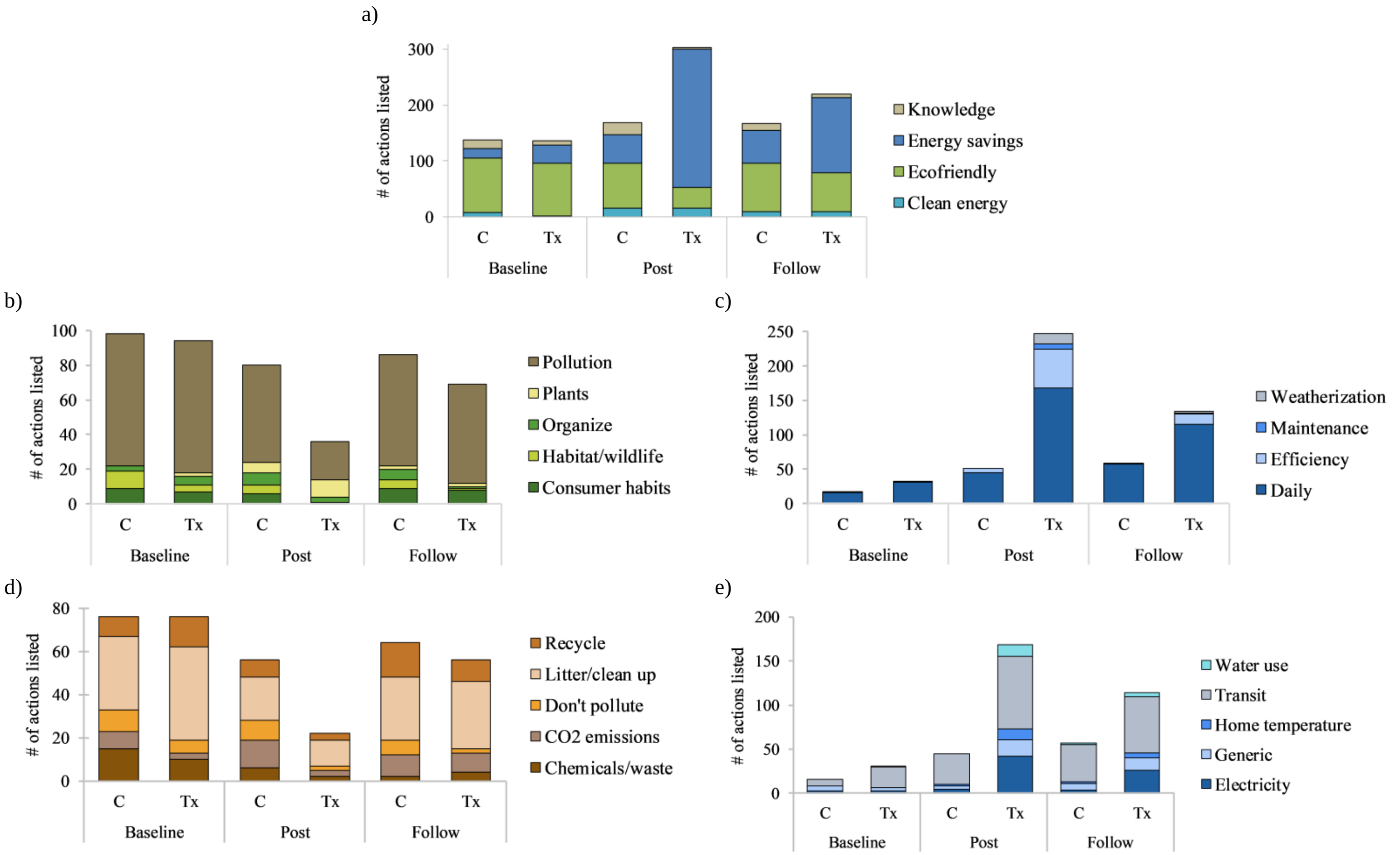

Figure 4.6 - Recommended ways to reduce OA.
Students recommendations for "actions someone could take to reduce OA," inductively coded. Common responses were subdivided (b & c; d & e). a) Overarching recommendations. b) "Ecofriendly" recommendations. c) "Energy savings" recommendations. d) "Pollution" recommendations. e) "Daily" recommendations. C= control; Tx= treatment.

energy savings responses and increased in frequency of ecofriendly responses. Of the ecofriendly actions listed, both groups recommended pollution-related actions most often, and the majority of these focused on reducing litter/cleaning up and recycling. Daily actions made up most of the energy savings actions listed, and transit made up the majority of these daily actions. Of these transit-related recommendations, "drive less, walk more" was the most common response for both groups while carpooling was mentioned occasionally (control: n= 4; treatment: n= 16) and taking public transit was mentioned four times by the treatment group. Finally, half of the students in the treatment group who listed an efficiency action mentioned changing light bulbs (n= 9) while no control students did. The remaining efficiency actions focused on car efficiency.

DISCUSSION

As previously discussed, in this study we measured student knowledge and attitudes about OA at three timepoints in a two-group, non-randomized teaching intervention to test whether increased knowledge of OA led to changes in attitude. While some results were expected, others were surprising.

OA KNOWLEDGE AND ATTITUDES

Similar to previous studies (e.g., The Ocean Project 2012; Frisch et al. 2015; Capstick et al. 2016; Schuldt et al. 2016), we found that initial student knowledge of OA was low. Unsurprisingly, four days of instruction increased student perceived and tested knowledge, although misconceptions persisted.

Despite knowledge increases, attitudes did not change from T0 to T2 in either group. This could be interpreted as a failure of the intervention to create long-term attitudinal change. Different activities might lead to different results. Unfortunately, no other teaching interventions report measuring attitudes about OA, thus no comparisons were possible. Another interpretation is that education does not change attitudes; however, prior research suggests education can change knowledge, attitudes, and beliefs (e.g., Clayton & Myers, 2015; Gardner & Stern, 2002; McKenzie-Mohr, 2011).

It might be that one's level of OA knowledge is less important for determining attitudes than simply having some knowledge. On its own, the term "ocean acidification" evokes concern for some people (Frisch et al., 2015), and many students seemed to feel similarly. As one student wrote, “honestly, I don’t know what this is, but it sounds bad.” Overall, students were “fairly” or “very” concerned, perceived “very little” personal control and a “moderate amount” of collective control, and agreed that they and others should be taking action to reduce OA. Additionally, many students said “everyone” should be taking action and that “every bit counts,” suggesting they already felt some responsibility to help. Based on the scope of our study, we cannot determine whether students would take or support OA mitigation efforts. However, while our teaching intervention did not change student attitudes and while there are likely additional barriers to action, student attitudes do not suggest a lack of support for OA mitigation.

KNOWING HOW TO HELP

Knowing how to address OA is different from knowing about OA. Some researchers suggest that the public does not need to be scientifically literate about OA, they just need to know ways to help (The Ocean Project, 2012).

We found that students, in general, did not identify ways to mitigate OA on their own. When recommending OA mitigation actions, control group students reinforced two narratives: reducing pollution helps with environmental problems and driving less and walking more lowers CO_2 emissions. The pollution narrative led students to recommend “not littering” and “cleaning up,” neither of which addresses the primary cause of OA. It is possible that participating in cleanups could lead to further environmentally-friendly behaviors; however, cleanups could also allow individuals to excuse other non-environmentally friendly behaviors (Clayton & Myers, 2015). Students expressing the pollution narrative also recommended “reducing CO_2 emissions,” but it was unclear which actions students thought would reduce their carbon footprint. Since Americans, in general, have limited knowledge of how different behaviors use energy (e.g., Attari et al. 2010; Gardner & Stern 2008), students are unlikely to choose high-impact energy saving actions even if they try to reduce their carbon footprint. Similarly, since the transportation sector is the leading source of U.S. CO_2 emissions (Houser & Marsters, 2018), students’ transportation narrative could lead to reduced carbon emissions; however, transportation behaviors are difficult to change even with purposefully designed interventions (e.g., Boudet et al. 2016). For many students in this study, “driving less and walking more” is likely unfeasible due to lack of regional public transit, travel distance, and the fact that adults make many transportation choices for students. Overall, the dominance of the pollution narrative suggests students did not figure out how to help reduce OA on their own, while the transit narrative suggests the few specific actions students did come up with are difficult to implement.

If the above is true, then instruction specifically focused on OA mitigation might increase student knowledge of how to help. After learning about actions to reduce household energy use, students listed a diverse set of specific actions that would reduce CO_2 emissions. However, immediate recall did not necessarily indicate long-term learning. Ten-weeks after instruction, student responses were similar to their initial recommendations. This suggests that students may have forgotten the specific actions learned or never learned them in the first place. Since spaced repetition and practice over time leads to improved learning (Bahrick & Hall, 2005; Kang, 2016), we suspect that revisiting key ideas from this curriculum at a later date could help solidify student learning.

Mitigation Lesson Limitations

The experimental lesson's focus on identifying high-impact, low cost household actions may have had unintended consequences. We focused on household actions because time, resources, and attention can be barriers to taking action (Clayton & Myers, 2015) and we hoped that students would find these actions empowering because they were achievable and within their control. Notably, some researchers argue that the scale of OA and pre-existing mental models suggest that we should focus on collective actions not individual ones (FrameWorks Institute, 2014). Our choice may have overemphasized daily, curtailment-focused actions (i.e., using less). This is concerning because while the public already tends to think of curtailment over efficiency when identifying ways to save energy (Attari et al., 2010; Clayton & Myers, 2015; Gardner & Stern, 2008), curtailment actions save less energy than energy efficiency upgrades. Additionally, curtailment actions require ongoing decision making whereas efficiency upgrades, albeit costlier, are one-time choices. Thus, our focus on high-impact, low cost actions may have reinforced misunderstandings about the best ways for households to save energy.

Persistence of Misconceptions

New knowledge is added onto what we already know and believe (Bransford, Brown, Cocking, & National Research Council, 2000). From an early age, our experiences shape our explanations for how the world works. While these preconceptions are sufficient to explain daily phenomena, they can be at odds with scientifically accepted explanations. For scientific understanding to replace preconceptions (also called misconceptions, naïve beliefs, alternative conceptions, etc. (Barke, Hazari, & Yitbarek, 2009)), preconceptions must be revealed and students need to see where their ideas fall short (Bransford et al., 2000). As Bransford et al. (2000) summarize,

> "If [student] initial understanding is not engaged, [students] may fail to grasp the new concepts and information that are taught, or they may learn them for purposes of a test but revert to their preconceptions outside the classroom." (p.14)

Thus, being told a scientific explanation is not enough to counter misconceptions and often does not lead to conceptual change.

There are numerous potential misconceptions associated with OA across multiple disciplines. Our survey revealed at least two misconceptions resistant to change: that the ocean will become acidic and that most shells will dissolve. Both of these misconceptions are commonly expressed in articles and videos intended for the public. While our curriculum was developed with student misconceptions in mind, it might not have adequately demonstrated to students where their misconceptions fell short. As a result, we saw that students reverted to these misconceptions over time.

Most students initially held vague understandings of pH. Despite repeated emphasis that the ocean was not and would not become acidic, instruction did not rid students of the misconception that OA would lead to an acidic ocean. Defining OA as the progressive decline in pH may further reinforce this misconception. While some OA teaching resources discuss the buffering capacity of the ocean, they do not explain why this will prevent the ocean from becoming acidic. Instead, buffering is discussed with regards to slower changes in pH, but no reference is made to pH projections beyond 2100. Thus, the practice of defining OA as a long-term decrease in pH but not explaining why decreasing pH will not lead to an acidic ocean may help perpetuate this misconception.

Misconceptions about pH may reinforce the misconception that shells will completely dissolve in the future ocean. For example, research has revealed that many students believe acids "eat away" materials and are dangerous (Barke et al., 2009), and this association with acids being corrosive could lead students to believe that OA means an acidic ocean will corrode materials, including shells and coral reefs. The prominence in the public narrative that OA means pteropods and other shelled organisms will dissolve likely adds to the misconception.

This study found that the shells in acid lab increased student endorsement of the shells will dissolve misconception while not placing shells in acid decreased endorsement in the short-term. However, follow-up surveys revealed regression to preconceptions: at T2, the majority of students in both groups endorsed the shells will dissolve misconception (control: 55%; treatment: 59%). Thus, avoiding the shells in acid experiment and telling students the ocean will not become acidic is not enough to correct these prominent misconceptions.

CONCLUSIONS

Initial OA knowledge was low and increased with instruction, but learning about OA did not automatically lead students to know how to mitigate it. Post-intervention results suggested that mitigation-focused instruction changed student attitudes and increased knowledge of ways to address OA. However, follow-up surveys showed that these attitudinal changes were temporary and that students forgot most of the mitigation actions discussed.

To our knowledge, this is the first OA intervention study to include a follow-up survey. Prior studies have provided people with information about OA and recorded short-term changes in attitude and support for OA mitigation. They then assume that these changes will persist over time. While our study was limited to one rural, coastal school district in Oregon, our results question the long-term impact of one-off outreach and education efforts. We suggest that revisiting key messages over time could increase knowledge retention and attitudinal shifts.

Misconceptions present challenges to efforts to accurately increase OA awareness. Our data suggests that telling learners that their preconceptions were wrong did not lead to conceptual change. Additional efforts could focus on developing ways to further identify and confront OA misconceptions. It is unclear whether removing misconceptions will alter how individuals evaluate the perceived risk of OA. For example, some may wonder, “if the ocean will never be acidic and we do not think most shells will dissolve, is OA really a problem?”

Our research questions the efficacy of education approaches to changing attitudes related to OA. Future research could study the effectiveness of various mitigation-focused messages. These efforts could benefit from collaboration with behavior change researchers.

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CHAPTER 5: CONCLUSION

> "In all affairs, it's a healthy thing now and then to hang a question mark on the things you have long taken for granted." – Bertrand Russell

At the heart of this project lies a single question: what drives people to take action on environmental problems? The answer is likely complex and elusive for there isn't a single answer; it depends on the person, the context, and the action in question. Not all environmental problems are created equal and not all people are motivated by the same concerns, values, and messages. We trust different people, think of ourselves differently, hold different values, and strive for different outcomes. To truly answer this question, we likely need to specify which people, which problems, and which actions we are targeting. This thesis focuses on one commonly held assumption about inspiring action on environmental problems: that knowledge leads to action. I used a teaching intervention about ocean acidification (OA) to explore some aspects of this assumption.

NUMEROUS RESOURCES, ROOM TO GROW

In this project I reviewed 90 available teaching resources on OA. While I knew resources already existed, I was surprised by how many resources I found. The sheer quantity of options for teaching about this relatively new phenomenon was both inspiring and overwhelming. Despite the options available to teachers, my curriculum review revealed room for improvement. Many resources reinforce multiple misconceptions, including the notion that the ocean will become an acid that will eat away at the shells of marine organisms. Discussions of the impacts of OA were often outdated, superficial, and mainly focused on dissolution. Additionally, only one-third of resources mentioned ways to address the problem, and only 7% dedicated more than a passing mention to ways people can help. Newer resources, including the materials from the National Network for Ocean and Climate Change Interpretation, available at climateinterpreter.org, are bringing renewed focus to effective communication about impacts and solutions to OA. The curriculum presented in this thesis relied on and builds upon this recent work and hopefully provides educators with new and revised ideas on ways to create more robust discussions of the impacts of OA, as well as ways to address the issue.

KNOWLEDGE TO ACTION

A key component of this project was to test whether I could gather evidence that knowledge of OA might increase one's likelihood of taking action to address OA. Based on the background research conducted, this appears to be the first OA intervention study to include a follow-up survey, and this methodological choice dramatically changed my conclusions. Similar to previous studies, I found that initial knowledge of OA was low. Unsurprisingly, four days of instruction led to an increase in perceived and actual knowledge, although misconceptions remained. For students who did not learn about ways to address OA, there were no significant changes in attitudes over time. In contrast, students who did learn about solutions showed a short-term increase in concern and norms for action; however, these changes were no longer present 10-weeks after instruction. While this teaching intervention did not lead to long-term changes in attitude, student responses were generally conducive to supporting OA mitigation. While students who knew about OA were generally concerned and agreed that they and others should take action, they largely did not know how to help address the problem.

It is difficult for knowledge to lead to action if you do not know what actions to take. Initial student survey responses suggested there was a gap in student knowledge:

> "I want to do more, but I don't really know what to do or how to do it."
> "I would like to help our oceans & other waters but I'm not sure what the best thing to do would be."
> "I am aware that OA is a problem, I'm just too ignorant to actually do something about it"
> "I look forward to learning how to help, how to make a difference instead of just the how, why, and what."

I found that students who did not explicitly learn about mitigation actions were largely unable to identify concrete ways to help reduce ocean acidification. In contrast, their peers, who learned about ways to reduce household energy use, listed a diverse set of actions to address OA immediately after instruction; however, many of these students could no longer remember what they learned 10-weeks later. As one student explained,

> "A lot of the information learned from the labs and such I forgot because of all the other information I'm constantly bombarded with. Therefore, I feel like regular reminders would be useful."

These findings have led me to the following conclusion: we need to be realistic about what one-off education and outreach efforts can achieve. Even if they seem to produce a short-term increase in concern and demand for action, these responses may fade with time. Additionally, if we want people to take specific actions on ocean acidification, we need to tell them what they can do. Repetition of key messages will likely lead to improved learning and knowledge over time. There are numerous additional barriers to action beyond knowledge, and the sooner we can identify key actions for the public to take and barriers to these actions, the sooner we will accelerate progress on addressing OA.

Self-reflection revealed some of these additional barriers to action. I knew next to nothing about ocean acidification when I started this project 1.5 years ago. It is somewhat incredible to look back and consider my own change in understanding over this time. Despite my increased knowledge, I have similar responses to the students regarding perceived control; I also feel like I have very little to no personal control over OA and very little to a moderate amount of control when working with others. In many ways, OA feels similar to climate change, coral bleaching, and other wicked environmental problems; they are so big that they feel overwhelming, and they are distant and abstract enough that they are easy to ignore on a day-to-day basis. Even though I know more about ocean acidification than most of my friends, all of my family, and many of my peers, I cannot say that any of my actions have changed as a result of this knowledge. Part of this is because I already try to live fairly sustainably; however, my perceived lack of control and the fact that I do not feel that I have the power to influence decisions in my city, state, or country makes it hard for me to consider doing more. Personally, I would need to feel like my actions were part of a larger effort, and that collectively we were working to improve the situation. Some of the students in this project expressed similar thoughts to my own:

> "No one is motivated to help so you'd have to get a group together so people can feel like they're making a difference and not doing things in vain."
> "The [questions] on whether or not we can fix ocean acidification were difficult because I know how little impact we have."
> "Without laws, everything you could do is in vain."

For others, the curriculum was enough to cause them express hope and a desire to take action:

> "Thank you for your time and all you have taught us. You have definitely made me want to take more action to reduce OA, and I'm sure others believe this as well."
> "I loved learning about OA and how I could help to fix it. Also learning what I can do in daily life to produce less CO_2."
> "We can make a change! All of us."
> "We can all change this, but we have to try. Someone else isn't going to do it for you."

QUESTIONS FOR THE FUTURE

Ultimately, the way we respond to our knowledge of environmental problems is complex. Developing additional ways to talk about OA and inspire action could be productive directions for future research. Much of the current conversation around ways to address OA focuses on dichotomies: personal or collective actions, mitigation or adaptation to inevitable change. It is important to remember that it does not have to be an either/or situation. We can, and probably should, talk about all of these options. Each has its place and should likely be a part of a larger plan of action. Part of our challenge as researchers is to identify which messages are effective for which audiences.

How we, as a society, choose to react to ocean acidification is a collective decision. However, experts have a key role to play in helping the larger public identify potentially high-impact actions as well as those actions that are unlikely to have a meaningful impact. Instead of providing exhaustive lists filled with numerous options, experts in natural and social sciences can help us identify the actions that are most likely to help and the tradeoffs involved in pursuing these options. It is important for these experts to remember that most Americans do not know which actions would dramatically impact their energy use and CO_2 emissions. When the public is asked to save energy, they do things like turn off the lights and unplug their phone chargers. Actions like insulating homes, replacing appliances as they fail, and fundamentally changing how we power and move around our world rarely come up. Researchers can use their knowledge to help citizens identify the actions that matter, and they can explain why these actions are more impactful than some of the more commonly considered options.

Social scientists can help us devise action plans that incorporate what we know about human behavior and behavior change. Identifying the primary barriers preventing people from taking action is one key step. For example, there are numerous possible barriers preventing individuals from weatherizing their homes. The specific barriers likely vary by individual and group. Social science methods can help us develop plans that work around the many possible barriers, which might include: people do not know that weatherization is a high-impact action, people cannot afford to weatherize their homes, people rent instead of own, people do not know how, it is too difficult to hire a contractor, it is too time consuming, people do not know others who are choosing to weatherize their home, and weatherizing does not match with their perceived self-identity. Uncovering what prevents action and determining how to make action easier and more appealing could help us make progress on addressing OA.

While answering these questions will likely provide interesting and useful knowledge, we must not lose sight of the fact that the clock is ticking. The water that upwells every summer along the West Coast of North America carries water that last contacted the atmosphere 50 years ago. Thus, we are locked in for additional acidification for decades to come. I believe that as we expand our knowledge, we should keep in mind that we know the cause of ocean acidification and we know ways to reduce CO_2 emissions. While new technologies could certainly help, we already have much of what we need to make an impact. The sooner we identify and prioritize high-impact actions to reduce CO_2, the sooner we will begin to change our collective future.

> “The best time to plant a tree was 20 years ago. The second best time is now.”-Chinese Proverb

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APPENDICES

APPENDIX A: OCEAN ACIDIFICATION CURRICULUM

The documents in this chapter were developed to provide an ocean acidification curriculum that presents students with an in-depth look at actions households can take to reduce ocean acidification. The lessons were developed using Understanding by Design (Wiggins & McTighe, 2006) principles for curriculum development and are based on high school teaching standards, evaluation of existing curricula, and current research on ocean acidification. The following components are included in the curriculum:

1. Teacher materials:
    - Lesson plans with sample scripting and materials lists
    - Content background
    - Teacher answer key and student work samples (Coming soon)
2. Student materials:
    - Student handouts
3. Links to PowerPoint presentations with lesson content (available online)
4. Links to supplementary videos (available online)

The curriculum is presented in its final version, which has been revised after analyzing data from the experiment presented in Chapter 4 of this thesis. This final version includes several key changes made post instruction, including: lesson 2 is now optional (ideal for teachers wanting to go in depth on the chemistry of ocean acidification) and is split into two days to allow for in-depth exploration of pH; lesson 3 on ocean acidification's impacts has been transformed into a student research project; lesson 4 has been expanded to include calculations of the impact of an energy saving action at different scales (individual, school, city, state), and a Call to Action project was added to the end of the curriculum. Because this version of the curriculum has been revised, it does not reflect exactly what students experienced while participating in this study.

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CHANGING OCEAN CHEMISTRY

A HIGH SCHOOL CURRICULUM ON OCEAN ACIDIFICATION'S CAUSES, IMPACTS, AND SOLUTIONS

Oregon State University

Sea Grant
Oregon

Written by Brian Erickson as part of a master's thesis in Marine Resource Management at Oregon State University.

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Dear educator,

This curriculum document was created through a reiterative process that will never truly be complete. The ideas contained within were developed after a review of 90 existing ocean acidification teaching resources, as well as three rounds of classroom testing. There are other great resources available (see Chapter 2 of this thesis for a review), and each have different styles, contexts, and needs. I hope that this resource provides you with some new ideas for how to teach about ocean acidification. You will likely want to modify the lessons contained within, and editable versions of student handouts will be provided on my website (https://brianderickson.weebly.com/oa-curriculum.html). The timing of lessons and background required will vary depending on your students' backgrounds and level of interest.

There are a few features that I believe make this curriculum stand out, including: it starts with a narrative that helps connect this pressing environmental problem to people's lives; it includes a formative probe to gauge student preconceptions; it incorporates many of the National Network for Ocean and Climate Change Interpreters' recommendations (available at climateinterpreter.org) on communicating about ocean acidification; it avoids the common "shells in acid" lab in hopes of avoiding reinforcing common misconceptions; it allows students to explore a range of possible impacts of ocean acidification beyond shell dissolution; and it focuses on solutions to help address the issue.

Several components of this curriculum were added during the latest round of revisions and have not yet been used in a classroom. This includes: lesson 1- the formative probe and section on the carbon cycle; lesson 2 part 1; lesson 3 is highly modified from previous versions; the final Call to Action project. Additionally, I feel that lesson 2 still needs substantial work. I personally have struggled to find the right balance between explaining enough chemistry for students to have a deeper understanding of ocean acidification and getting too deep into the chemistry.

I would love your thoughts and feedback. You can reach me, Brian Erickson, by email: brian.erickson@oregonstate.edu. If you'd be willing to share your modifications, please send them my way so we can pass them along to other educators!

Sincerely,

Brian Erickson

INTRODUCTION

Target Grades: 9-12 Estimated Duration: 5-7 days

OVERVIEW

Ocean acidification is the change in ocean chemistry due to increasing concentrations of anthropogenic carbon dioxide (CO_2) in the atmosphere. It is sometimes called "the other CO_2 problem" because, like climate change, it is a major environmental issue caused by human carbon dioxide emissions, yet unlike climate change, far fewer members of the public have heard about ocean acidification. Ocean acidification is already impacting the shellfish industry along the West Coast of North America and, over the next few decades, is predicted to have major cascading impacts on marine ecosystems and the humans that rely on them for food and income. In recent years, researchers have made significant strides in understanding the causes, consequences, and complexities of ocean acidification. In light of these findings, there have been calls for substantial action to limit the causes and mitigate the impacts of ocean acidification. However, despite efforts by educators and researchers to raise awareness and inspire public support for action around ocean acidification, public discourse and action remains limited in the United States.

This four-lesson high school curriculum seeks to increase student understanding about ocean acidification and leave students with a sense that it is an issue that can be addressed. Lesson 1 begins by exploring a real-life story of the near collapse of the oyster industry along the West Coast of the United States that occurred from 2007-2009. Lesson 1 continues with an overview of ocean acidification and exploration of how humans have altered the carbon cycle. Lesson 2 focuses on the chemistry of ocean acidification and is split into two parts. In part 1, students focus on pH and how carbon dioxide "acidifies" water. In part 2, students learn about changes in carbonate ion concentration, something important to calcifying marine organisms that make shells and hard structures out of calcium carbonate (e.g., shellfish and corals). Students apply their learning by interpreting water quality data from Whiskey Creek Shellfish Hatchery. In lesson 3, students research the possible impacts of ocean acidification to ecosystems and humans. In lesson 4, students examine possible solutions to ocean acidification by brainstorming ways to reduce CO_2 emissions, identifying barriers to taking action, and exploring which household actions have the greatest potential impact. A recommended culminating Call to Action project has students identify a target audience and try to persuade their chosen audience to take action.

BIG IDEAS

Big Ideas, Essential Questions, and Enduring Understandings are all ideas from Understanding by Design (Wiggins & McTighe 2006).

- Anthropogenic CO2 emissions are leading to multiple changes in the ocean's chemistry in a process called ocean acidification.
- Ocean acidification is impacting marine organisms and the humans that rely on them.
- There are ways to reduce ocean acidification.

ESSENTIAL QUESTION

- To what degree do humans and natural ecosystems rely on each other for survival?

ENDURING UNDERSTANDINGS

- Marine ecosystems and the humans that rely on them are interconnected.
- Human actions lead to changes in ecosystems.
- Changes in one portion of a system can lead to multiple changes in the rest of the system.
- Individual and collective actions are needed to effectively manage resources for all.

STANDARDS

While standards addressed in this module were identified prior to lesson creation as recommended by Understanding by Design methodology, they are listed after the lesson materials (see table of contents) in an attempt to streamline this document and make it easier for teachers to focus on teaching the lessons.

MATERIALS INCLUDED

Materials included in this resource:

- Teacher Lesson plans with sample scripting and materials lists
- Content background
- Student handouts with teacher answer keys
- Supplementary materials (PowerPoint presentations, videos)

STUDENT PRIOR KNOWLEDGE

This module was designed for broad use and can be used in various high school science classes, including: chemistry, biology, environmental science, and marine science. Students will be better prepared for this module if they are familiar with pH; chemical notation, equations, and reactions; the carbon cycle; ecological food webs; and photosynthesis and respiration. As such, this module would be a good review of concepts learned throughout the year. If students are not familiar with key concepts presented in the module, teachers should expect that additional time may be needed.

LESSON 1: WHAT IS OCEAN ACIDIFICATION?

OVERVIEW

This lesson introduces students to ocean acidification (OA). After teachers uncover existing student beliefs through a formative probe, students watch a 3-minute video, or read, about the Pacific oyster hatchery failures of 2007-2009. Afterwards, the process of OA is introduced. Students then examine the natural and human-altered (anthropogenic) carbon cycles and try to explain how carbon moves through various reservoirs. Students are challenged to apply this discussion of natural and anthropogenic carbon cycles to a NASA visualization of CO_2 in the atmosphere over the course of a year and to graphs of historic atmospheric CO_2 concentrations.

TIME

1-2 60-minute Periods

MATERIALS

- Copies of student handout (1 per student)
- Computer, projector & speakers
- Presentation slides and videos

Enduring Understandings

- Marine ecosystems, and the humans that rely on them, are interconnected.
- Human actions lead to changes in ecosystems.
- Changes in one portion of a system can lead to multiple changes in the rest of the system.

Key Points

- Ocean acidification is the change in ocean chemistry due to increasing concentrations of anthropogenic carbon dioxide (CO_2) in the atmosphere.
- The Pacific oyster hatchery failures of 2007-2009 made it clear that ocean acidification is already impacting marine organisms and humans in the Pacific Northwest.
- Carbon naturally moves between reservoirs (atmosphere, ocean, organisms, rocks) through multiple transfers and transformations (photosynthesis, respiration, sedimentation, volcanism, weathering, etc.).
- Human activities have altered the natural carbon cycle.

Objectives

Students will be able to:

- Define ocean acidification.
- Describe evidence of ocean acidification's current impacts in the Pacific Northwest.
- Describe how atmospheric CO_2 concentrations vary over short and long timescales.

Setup

- Make copies of student notebook (1 per student).
- Open PowerPoint presentation and preload video.

LESSON OUTLINE

Engage: Formative Probe

Before presenting information on OA, use this probe to uncover students' prior understandings about OA. This is not meant to see who knows the "right answer." Instead, this probe helps you better plan future instruction by identifying what students currently think.

Some teachers may want to use a survey to test prior knowledge. See Curriculum Appendix for a sample mini-survey.

> Students in Mrs. James' class are discussing ocean acidification. They have different ideas on what causes it.
>
> **James:** I think ocean acidification is caused by litter in the ocean.
> **Tonya:** I think ocean acidification is caused by chemicals spilling into the ocean.
> **Leslie:** I think ocean acidification is caused by carbon emissions from cars.
> **Mark:** I think ocean acidification is caused by animals breathing.
> **Jessica:** I think ocean acidification is caused by acid rain.
>
> Which student do you agree with? Explain why you agree with this student and disagree with the others.

This formative probe was inspired by *Teaching for Conceptual Understanding in Science* and the *Uncovering Student Ideas in Science* series. This probe was created in response to persistent alternative conceptions uncovered in our research project. This probe has not been classroom tested.

Explanation: The best answer is Leslie's: "I think ocean acidification is caused by carbon emissions from cars." This answer hints at the gas that causes OA (CO_2) as well as the fact that this gas is absorbed from the air into the ocean. All other responses represent common alternative conceptions that were held by students we taught.

Administering the probe: Give students ~2 minutes to write a response to the probe in their notes. Afterwards, have them discuss their ideas with a partner or small group, then as a class. During this discussion, the teacher should listen to understand what students know and what has led them to this current belief. The discussion should be between students, not between student and teacher.

Explore: The Case of the Dying Oysters (15 minutes)

Show a 5.5-minute video to introduce students to an example of how OA is already impacting some businesses in the Pacific Northwest. This narrative is helpful in presenting OA as an issue that is already impacting people and ecosystems.

Before showing the video, say:

> "We're going to explore a story that took place in the mid-2000s in the Pacific Northwest. This story served as a wakeup call for many scientists Before we do, I wanted to define a few terms that will come up often over the next four days."

Present slide to define shellfish. Show video (Postcard from the Oregon Coast, http://tinyurl.com/y9bmvuxc) and have students write answers to the viewing questions in their notes. Then, discuss the viewing questions from the student handout:

We originally presented this story in murder mystery format where OA was not immediately revealed as the cause of the problem. This approach didn't work as well as we had hoped (students presumed OA was the cause since we'd be talking about OA for the next four days). If you'd like to take this mystery approach, see the Curriculum Appendix.

Alternatively, students can read about the hatchery issues instead of watching the video clip (see Curriculum Appendix for readings).

For more on the Whiskey Creek story, see: Barton et al. (2015).

What do they grow at Mark & Sue’s hatchery? (*Shellfish, including oysters.*)

What happened at the hatchery in 2007? (*The baby oysters that they grow started dying. It got so bad that at some points all of the oysters died, and even some dissolved!*)

Why does ocean acidification affect baby oysters? (*It starts to take too much energy to build their shells. This means they do not have enough energy left over to develop organs that would allow them to feed.*)

How often are conditions currently favorable for shell formation? (*About half the time.*)

How might this change in the future? (*With OA, there will be fewer times when conditions are favorable. This means more larvae will struggle to develop because they will be more likely to encounter unfavorable water.*)

Nearly 70% of oyster farms along the US West coast rely on Mark & Sue for their baby oysters. What could happen to these farmers, and the restaurants they supply, if Mark and Sue’s hatchery cannot cope with ocean acidification? (*If Mark and Sue’s hatchery fails, farmers won't have larvae to grow, restaurants won't have oysters to sell, drivers won't have oysters to transport…*)”

Some students may confuse salmon and shellfish hatcheries.

It is a common misconception that all shelled organisms will dissolve due to OA. While baby oysters are especially vulnerable, not all organisms or life stages will dissolve. See Educator Background, Avoiding Misconceptions for more.

Larval oysters cannot feed until they build their first shell. With OA, larvae can run out of energy before they can start feeding, which leads to death.

Oysters are a $100 million/year industry in the Pacific Northwest.

Explain: What is Ocean Acidification? (30 minutes)

Present slide to introduce the ocean acidification explanatory chain:

i. Human activities release CO_2.
ii. The ocean absorbs ~25% of anthropogenic CO_2.
iii. This changes ocean chemistry.
iv. Carbonate, used for shell building, becomes less available. It takes more energy to make shells, leading to fewer & smaller shellfish.
v. Shellfish filter water. Fewer shellfish could lead to cloudier water. Cloudy water makes it harder for seagrasses to do photosynthesis. Seagrass beds are important habitat for young fish.
vi. Less seagrass could mean fewer fish to catch.
vii. This could impact humans who rely on fish for food & jobs.

Explanatory explain **how** causes lead to effects. The process outlined here represents one possible causal chain for OA. It differs from one used by Simon et al. (2014) who say, “less carbonate leads to fewer and smaller shellfish, which leads to fewer fish.” Ocean acidification experts we interviewed said the notion of fewer fish as a direct result of fewer and smaller shellfish was a stretch. While there could be fewer fish due to decreased plankton availability (leading to a trophic cascade) or loss of coral habitat, we decided to emphasize the potential losses to fish nursery habitat.

Students take/fill in their notes with each step. Use slide to define OA as "the progressive decrease in marine pH and carbonate ion concentrations that result when the ocean absorbs anthropogenic CO_2 from the atmosphere" (Frisch et al., 2015).

Anthropogenic is likely new for some students. We define anthropogenic as something "human created."

Elaborate: The Carbon Cycle (time?)

NOTE: Prior versions of this curriculum did not include direct instruction on the carbon cycle. However, we found that many students had difficulty connecting the dots between photosynthesis, respiration, and ocean pH. Thus, we've included a brief introduction to the carbon cycle here, but your students' needs will depend on their background knowledge.

Some students will need a more in-depth discussion of the carbon cycle than provided here. For an interactive walk through the cycle, see Maria Laws' activity on Better Lesson: http://tinyurl.com/y99u4jxw.

Begin your discussion of the carbon cycle by connecting it to a cycle that students may be more familiar with, the water cycle.

> "Carbon moves through a system just like water does: it takes on different forms in different places. Water is found in clouds, in our blood, in ground water, and in many other places. Carbon also moves from place to place, taking different forms along the way."

Lesson 2a from University of Otago's Oceans of Tomorrow (http://tinyurl.com/yc2x7g2s) is a good source for examining connections between photosynthesis, respiration, and the carbon cycle within the context of ocean acidification.

Brainstorm examples of carbon-containing molecules:

> "What are some forms that carbon might take? (CO_2, methane, macromolecules (carbohydrates (sugars), lipids (fats), nucleic acids, proteins, etc.)"

Explore how carbon moves through parts of the food web via photosynthesis and respiration. Have students examine the image provided in their notes (see Figure A.1) and discuss with a partner what the diagram is showing. Then discuss as a class.

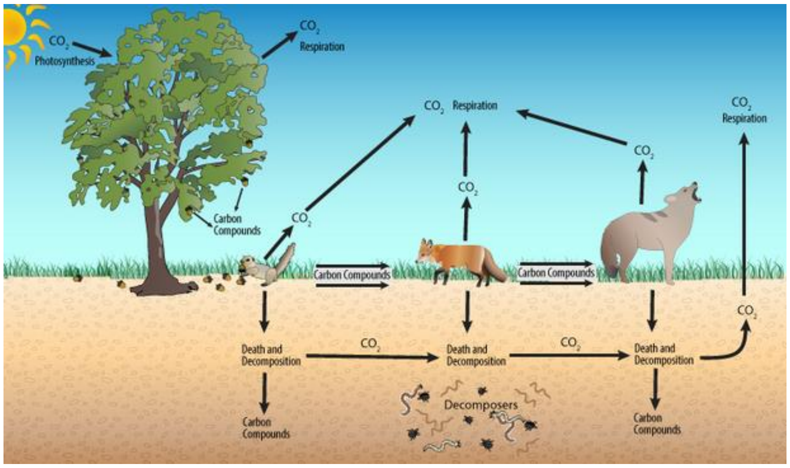


Figure A.1- Terrestrial carbon cycle.
From Carbon on the Move, Earth Labs http://tinyurl.com/y7aqbakj

Writing the simplified equations for photosynthesis and respiration on the board might be helpful for students. You could have students count then number of atoms of each element written on each side of the equations (e.g., 6 carbons on the left and right sides, 18 oxygen on both sides) to help emphasize that the equations are balanced, and thus, the carbon is transformed from one molecule into another.

Photosynthesis (simplified): $6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$

Respiration (simplified): $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$

Potential guiding questions for discussion:

In what form do trees (and other plants) take in carbon? *(CO_2)*

In what form does it store carbon? (*Carbohydrates/sugars, in the simple equation for photosynthesis we describe plants storing carbon as glucose*)

How does carbon get into animals? *(They eat the plants)*

Through what natural processes is carbon re-released to the atmosphere? *(Respiration and decomposition/decay)*

What types of organisms respire? (*All living organisms respire, including plants*)

KEY POINTS: Carbon is removed from the atmosphere by plants (and other photosynthesizers). They convert CO_2 into sugars. When animals eat plants, the carbon is transferred from the plants to the animals.

Discuss this challenge question as a class:

> Is human breathing responsible for the rise of CO_2 in the atmosphere? (*No. The CO_2 that humans respire comes from "burning" the food we eat (plants or an animal that ate plants or ate something that eats plants). Thus, the CO_2 we breathe out was already previously removed from the atmosphere, leading to no overall change.*)

Several students mentioned this misconception during testing of this curriculum. If you find that this idea persists with your students, you might have them read the brief discussion on the topic found at Skeptical Science: http://tinyurl.com/yb6wzxtn}.

COMPARING NATURAL AND ANTHROPOGENIC CARBON CYCLES

Show image from IPCC 2013 (see Figure A.2). Similar to the previous diagram, give students a minute to work with a partner to determine what the diagram is showing them. Then, use questions to help students make sense of this information-rich image.

Begin with the boxes:

> What do the boxes represent? (*Places where carbon is stored. These are called "reservoirs."*)
>
> What do the arrows represent? (*Where carbon goes/how carbon moves. These are called "transfers."*)
>
> According to this diagram, what is one way that carbon gets into the atmosphere? *(Students could list any of the arrows pointing towards the atmosphere.)*
>
> According to this diagram, what is one way carbon is removed from the atmosphere? (*Students could list any of the arrows pointing away from the atmosphere.*)
>
> What do the red arrows indicate? (*Human changes to the carbon cycle.*)

Now look at the numbers, beginning with the black arrows:

> In the past (black arrows), did land add or remove carbon from the atmosphere? Explain. *(The land removed carbon from the atmosphere. I know this because the black arrows point toward land. 1.7 PgC were absorbed per year.)*

Students are likely unfamiliar with the unit "petagram" (1 Pg = 10^{15} grams). That is likely okay since the main goal of including this diagram is to show that humans have changed the carbon cycle so that carbon is now absorbed by the ocean.

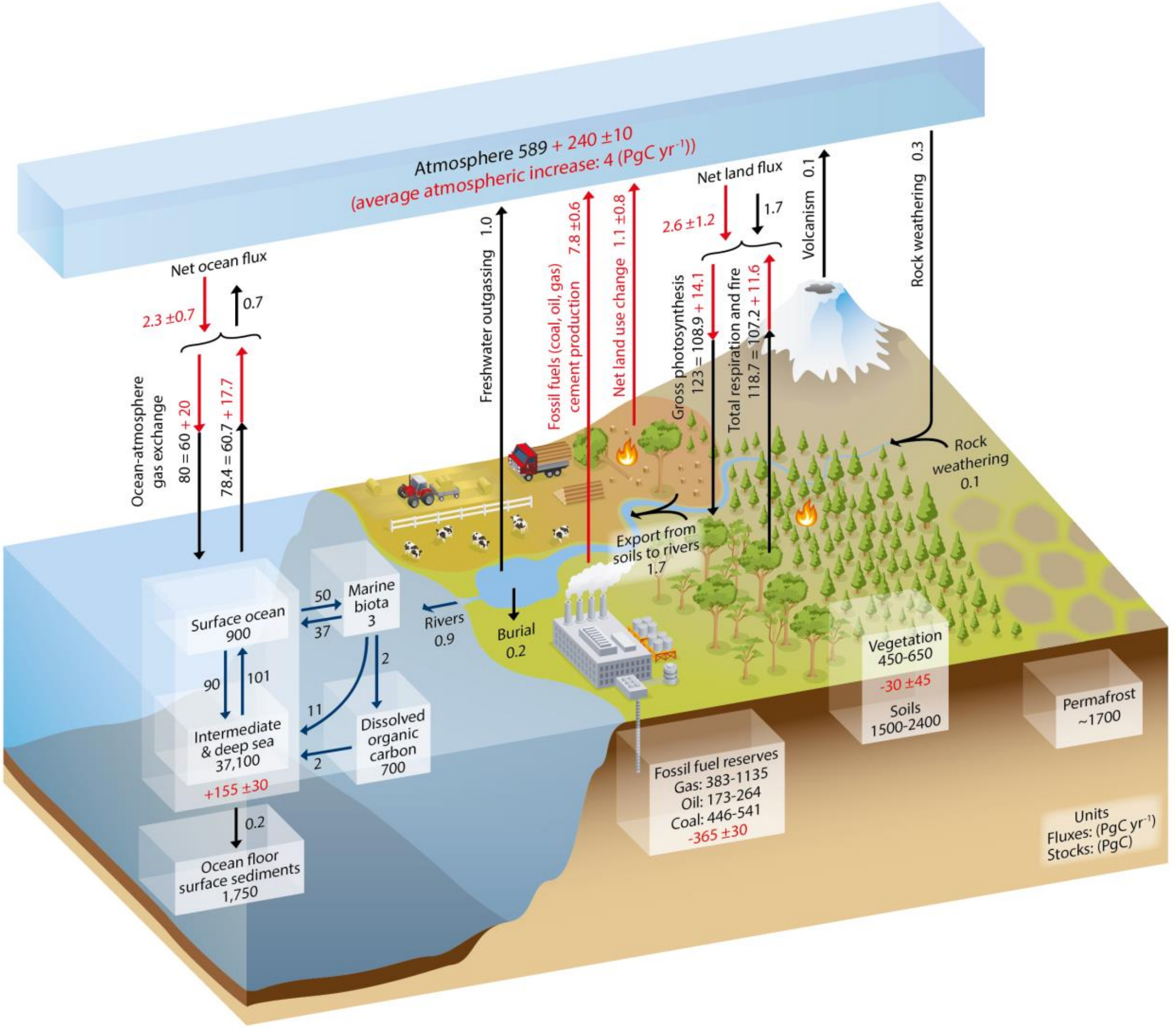


Figure A.2 - The carbon cycle.
From IPCC 2013, Chapter 6.

Transition to human changes to the carbon cycle (red arrows):

What is the main way that humans add carbon to the atmosphere? *(Burning fossil fuels.)*

How has the flow of carbon into/out of the ocean changed between Pre-Industrial times and now? (*In the past, the ocean released carbon to the atmosphere. Now the ocean absorbs carbon from the atmosphere*.)

This shift may seem small when expressed in petagrams (Pg); however, remember that one Pg is a quadrillion grams of carbon. This shift from releasing to absorbing carbon is what is leading to ocean acidification.

Evaluate: Short-term Changes in Atmospheric CO_2

NOTE- This could be used as an in class or homework assignment.

See student homework handout.

First, students watch NASA's "A Year in the Life of Earth's CO_2" (3:10). After watching, they describe, in writing, what happens to CO_2 in the atmosphere over the course of a year.

Available from NASA on YouTube: http://tinyurl.com/qgbc3bb

KEY POINTS:

- You can see hotspots of CO_2 emissions around population centers, especially in the northern hemisphere.
- CO_2 levels cycle seasonally (decrease during northern summer due to net uptake by plants (photosynthesis); increase during northern winter increase due to net respiration (decrease in photosynthesis); daily flashes and pulses visible (day-night photosynthesis cycle).
- CO_2 levels do not go to zero in the summer (the minimum value on the scale shown is 377 ppm).

Then, students analyze three graphs of CO_2 levels in the atmosphere over different time periods: since 1957 (direct observation); in the past 10,000 years (recent geologic past), and over the past 800,000 years ("longer" view) and answer the following questions in their homework:

All three graphs from Scripps Institute of Oceanography's The Keeling Curve website: https://scripps.ucsd.edu/programs/keelingcurve/.

What is shown on the y-axis for each graph? What is the range of values on each graph?

What is shown on the x-axis? How does this measure vary between graphs?

See Curriculum Appendix for answer key.

Describe what you observe in each graph. Do you see any patterns or trends?

How does the time scale shown (60 years, 10,000 years, 800,000 years) influence the conclusions you would make about co2 in Earth's atmosphere?

Finally, students are challenged to answer the following synthesis questions:

- What parts of the animation and graphs could be used as evidence for natural variation in atmospheric CO_2 levels?

- What parts of the video and graphs could be used as evidence for human-caused (anthropogenic) variation in atmospheric CO_2 levels?

LESSON 2, PART 1: CHEMISTRY OF OA (OPTIONAL)

TEACHER NOTE: *Substantial changes were made to this lesson after classroom testing of this curriculum. In our experience, students had a superficial understanding of pH and had not learned about ions, concentrations, or balancing equations yet. This meant that at some point the chemistry went over most students' heads. For this version, we added an additional day to allow for an in-depth discussion of pH. Additionally, we have split the chemical reactions of ocean acidification into parts (part 1 focuses on changes in pH and part 2 explains how this leads to changes in carbonate ion concentration). This depth is likely not necessary for non-chemistry students, thus lesson 2 is considered an optional part of this curriculum.*

We tested the curriculum during the fall quarter and these topics are often taught later in the year. If you teach this module at the end of the year students may be better prepared.

OVERVIEW

Lesson 2 is an optional add-on for chemistry classes. In part 1, students examine pH in detail. They begin by brainstorming what they already know about pH. Then, the teacher conducts a two-part demonstration: household chemicals are used to show how indicators can estimate pH, then CO_2 from a Soda Stream is added to water. Following this demonstration, the teacher presents a short lecture on acid-base chemistry and introduces part of the chemical equations dealing with ocean acidification. Students solidify their understanding of acids and bases using an online simulation. To evaluate their understanding, students are asked to explain WHY the addition of CO_2 lowers the pH of a solution like seawater.

Part 2 expands student understanding of the chemistry of OA by focusing on additional changes to ocean chemistry that result from the addition of CO_2. It begins with a demonstration that challenges students to explain what they see using information from the previous day's lesson: floating candles are

TIME

2-3 60-minute periods

MATERIALS

- Copies of student handout (1 per student)
- Computer, projector & speakers
- Presentation slides and videos
- Computers with internet for homework

For CO_2 in water demo:
  - Soda Stream
  - Aquarium airline tubing
  - 250mL beakers
  - Universal indicator
  - Solutions (water, seawater, vinegar, etc.)
  - Sodium bicarbonate powder
  - (Optional) aquatic plant

lit in a closed aquarium, and students watch as the pH of the surface layer of an indicator solution changes. Following the demo, the teacher provides a short lecture on two topics: (1) carbonate concentration also decreases when CO_2 is added to seawater, and (2) summer upwelling exacerbates ocean acidification along the U.S. West Coast. Students then synthesize their learning as they work with water quality data from Whiskey Creek Shellfish Hatchery.

MISCONCEPTION ALERT: This lesson likely introduces a misconception about ocean acidification – that the ocean will become acidic. While teaching we emphasized multiple times that the ocean is not predicted to become acidic; however, on follow up surveys, the majority of students endorsed this misconception anyway. We found some evidence that directly confronting this misconception following instruction helps students combat this belief. Additionally, the term "ocean acidification" can appear misleading to some since the ocean is basic and will remain so.

See Woods Hole Oceanographic Institution's FAQ for more on this apparent misnomer: http://tinyurl.com/ycrz8goq.

Enduring Understandings

- Human actions lead to changes in ecosystems.
- Changes in one portion of a system can lead to multiple changes in the rest of the system.

Key Points

- The pH scale estimates the $[H^+]$ in a solution.
- Adding CO_2 to water decreases the solution's pH, increasing the solution's $[H^+]$ which makes it more acidic.
- pH is a logarithmic measurement; small changes in pH represent large changes in $[H^+]$.

Objectives

Students will be able to:
- Describe the relationship between pH and $[H^+]$.
- Explain how the addition of CO_2 to seawater lowers the pH.

Setup

- Make copies of student notebook (1 per student).
- Open PowerPoint presentation and preload.
- Gather supplies for CO_2 in Seawater demo (see Supplies List).

Lesson Outline

Introduce today's lesson:

> "Yesterday we introduced ocean acidification, generally. Today and tomorrow we are going to focus on the chemistry of ocean acidification."

Engage: Brainstorm (5 minutes)

As a warmup and to gauge prior knowledge, ask students what they already know about pH.

> "Today we'll focus on pH. How many of you have heard of pH before? What do you know about pH?"

Show slide summarizing how most student define pH (0-14 scale, acids pH < 7; neutral pH = 7; bases pH>7) and previewing what students will learn today.

Students typically say: pH is a scale, it measures if something is an acid or base. it ranges from 0-14, acids have pH<7, bases have pH>7 neutral solutions have pH=7 neutral. We've found that very few students have an understanding of what an acid is beyond this basic definition.

This slide does not make reference to the logarithmic nature of the pH scale because saying the scale was logarithmic seemed to have little meaning for students without exploring the relationship between pH and $[H^+]$ in more detail. This lesson builds to the logarithmic nature of pH.

Explore: Indicators, pH, & CO_2

This is a two-part demo. In the first part, the teacher uses universal indicator to acquaint students with one method for estimating pH. In part 2, students observe how pH changes when CO_2 is added to water and consider ways to counter this reaction.

DEMO PART 1: INDICATING PH

This demonstration uses household chemicals to help students gain a basic understanding of the pH scale. It offers an opportunity to introduce or remind students of indicators and compare their use to other instruments that can be used to measure pH. Begin by filling an Erlenmeyer flask half way with distilled water.

> I have a flask with distilled water in it. I also have a bottle of universal indicator. Has anyone ever heard of or used an indicator before? What does it do? (*Students might explain that it changes colors depending on the pH of the solution*)
>
> Indicators are used to approximate the pH of a solution. Different indicators show different pH ranges, but in general they turn a certain color depending on the pH of a solution [project chart showing color range of universal indicator]. Let's add indicator to our water.

Add indicator and swirl to mix. Add enough indicator so that the color is clearly visible. Show students the flask and ask a student what the indicator tells us about the pH of the water:

> Based on our color key, what is the approximate pH of our water? *(7)*
>
> Would our water be considered acidic, basic, or neutral? *(Neutral)*

This activity is done as a demo to save time but is often done as a student-centered lab. E.g., see this lesson from Maria Laws on Better Lesson: http://tinyurl.com/yamujjpa.

The pH of tap water is not guaranteed to be 7.0 and varies by location.

You could compare indicator and pH probe results and discuss the pros and cons of different scientific technology:

> Okay, now let’s look at another solution. I have some vinegar here (pour vinegar into a flask until it is about half full).
>
> Do you think vinegar is acidic, basic, or neutral? (*Some students will predict that vinegar is acidic or basic.*)
>
> If vinegar is acidic/basic, what color should the indicator turn when we add it? (*With universal indicator, it should turn red or orange.*)

Add the indicator [it turns red].

> Based on our color key, what is the approximate pH of vinegar? (*Students will say 4. In reality, it is off the charts; the pH of distilled white vinegar is ~2.5.*)
>
> Would vinegar be considered acidic, basic, or neutral? *(Vinegar is acidic because its pH is below 7.)*”

Repeat this line of questioning for at least one base, such as ammonia.

Universal indicator turns warm colors (yellow, orange, red) when placed in increasingly acidic solutions and cool colors (blue, dark blue, purple) when placed in increasingly basic solutions.

Don't use bleach as your base. It reacts with the indicator and removes almost all pigment over a few minutes. Also, when mixed with vinegar it creates chlorine gas.

DEMO PART 2: ADDING CO_2 TO WATER (5 MIN)

Now that students are generally familiar with pH and indicators, move on to the main attraction: adding CO_2 to water.

> Alright, let’s get back to our flask with water and indicator in it. I also have a SodaStream here. Does anyone know what gas makes soda and carbonated water bubbly? *(CO_2)*
>
> What we’re going to do is add CO_2 to water. What do you think will happen to the pH? (*Student answers will vary.*)

If you don't have access to a SodaStream, there are many options to show this concept. See Teacher Background for alternatives.

Place the aquarium tubing into the water in the flask (so you can direct the CO_2 into the flask). Press the SodaStream button for a few seconds, until the solution turns green/yellow/orange. Discuss as a class:

> What happened when we added CO_2 to water? (*It turned orange, which means the solution became an acid. We could say we "acidified" the water.*)
>
> Do you think we could reverse this reaction? How? (*Student ideas may include: add aquatic plants to remove the CO_2 from the water; wait for a while so it offgases, just like a soda going flat; add a base.*)

Use sodium carbonate to demonstrate how adding a base makes the solution less acidic.

> We have some soda ash (sodium carbonate) here. It is the same stuff that the oyster hatchery, the one we watched the video about yesterday, uses to adjust their seawater. Let's add a little to our acidified water…

Add a small scoop of soda ash (sodium carbonate) to the beaker and stir, it will turn dark blue/purple. You can add more CO_2 from your Soda Stream to this buffered water to acidify it again.

If you have extra aquatic plant around your lab, you can put some in your flask, place it under light, and wait to see what happens. For a complete write up of a similar lab, see CarboSchool's "Uptake of Carbon Dioxide from Water by Plants": http://tinyurl.com/ybhzjfda.

Careful. A little soda carbonate goes a long way!

The solution is now partially buffered. It should take longer for the pH to change this time around

There are multiple labs exploring seawater buffering. See these two resources for ideas: http://tinyurl.com/yaqqwa8n; http://tinyurl.com/y7o43wct.

Explain: Acids, Bases, & CO_2 in Seawater

WATER DISSOCIATES: Explain that in a glass of water there is a small portion of water molecules that dissociate, or break apart, into hydrogen and hydroxide ions.

NOTE- This discussion of acid-base chemistry is a new addition to this version of the curriculum.

> Let's revisit this glass of water. Why does its pH = 7?
>
> We know that water is H_2O. But did you know that roughly 1 in 550 million water molecules dissociates, or splits apart, into charged hydrogen and hydroxide ions? (Hsu & Lab-Aids Inc., 2010)

Show slide.

$$H_2O \leftrightarrow H^+ + OH^- \qquad \text{(A-1)}$$

> If we were to measure how many hydrogen ions were in 1L of H_2O, we would find $[H^+] = 1\text{x}10^{-7}$ mols/L. We would also find that $[OH^-] = 1\text{x}10^{-7}$ M.

> Do you notice anything about our pH and the H^+ concentration? *(The pH is 7 and the concentration is* $1x10^{-7}$*)*

Continue onto next slide.

> One way of defining acids and bases is by comparing the concentrations of hydrogen and hydroxide ions. We just saw that water dissociates and produces equal numbers of hydrogen and hydroxide ions. When concentrations of the two ions are equal, we call this neutral. So, our water sample at pH = 7 is neutral because there are equal concentrations of hydrogen and hydroxide ions.
>
> Similarly, if a solution has more hydrogen ions than hydroxide ions, that is if $[H^+] > [OH^-]$, we call it an acid. In contrast, if a solution has fewer hydrogen ions than hydroxide ions, that is if $[H^+] < [OH^-]$, we call it a base.

Without saying so, we’ve just primed students to think of acids and bases according to the Arrhenius theory. This can be useful for some substances, but we'll need to go beyond this to truly explain ocean acidification. Show slide with definitions of acids and bases: acids are H^+ producers and bases are OH^- producers.

> Comparing concentrations of hydrogen and hydroxide ions gives us a starting point to talk about acids and bases. But, not all chemicals when mixed with water produce both ions.
>
> For example, let's look at vinegar. In our demonstration, was vinegar an acid or a base? (*It was an acid.*)
>
> If vinegar is an acid, what should be written in the two blanks shown?

$$CH_3COOH \rightarrow \_\_\_\_\_\_\_ + \_\_\_\_\_\_\_ \qquad (A-2)$$

Give students a few seconds to come up with an answer.

We said that acids produce a proton, so vinegar releases an H^+ and we're left with CH_3COO^-. So:

$$CH_3COOH \rightarrow \underline{CH_3COO^-} + \underline{H^+} \qquad \text{(A-3)}$$

From this equation, how do we know that vinegar is an acid? (*It releases a hydrogen ion.*)

EQUATIONS PART 1: Now we will connect the dots to answer the question: how does extra CO_2 in the atmosphere lead to ocean acidification? Show slide and walk students through the steps leading to ocean acidification:

$$CO_{2(g)} \leftrightarrow CO_{2(aq)} \qquad \text{(A-4)}$$

Equation A-4 shows CO_2 gas dissolving in the ocean.

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \qquad \text{(A-5)}$$

$$H_2CO_3 \leftrightarrow H^+ + HCO_3^- \qquad \text{(A-6)}$$

Students should be able to fill in the blanks (in their handout and the PowerPoint presentation) for equation (A-6) based on the previous conversation. Then, give students time to examine Error! Reference source not found., in their notes, and discuss the following questions in groups:

1. In what ways does this graph relate to the equations we discussed earlier? (*The equations showed that when you add CO_2 to water, a hydrogen ion is released, making it more acidic. The graph shows that CO_2 in the ocean and atmosphere is going up, and that the pH of the ocean is going down. In other words, it is acidifying.*)
2. How does the Soda Stream demonstration relate to this graph and the equations? (*The Soda Stream adds CO_2 to the water, which made it more acidic. It helps show as the blue line (ocean CO_2) goes up, the green line (ocean pH) goes down.*)
3. Look at the pH values shown on the graph. Is the ocean currently acidic, neutral, or basic? (*The ocean is above pH 7.0, so it is basic.*)

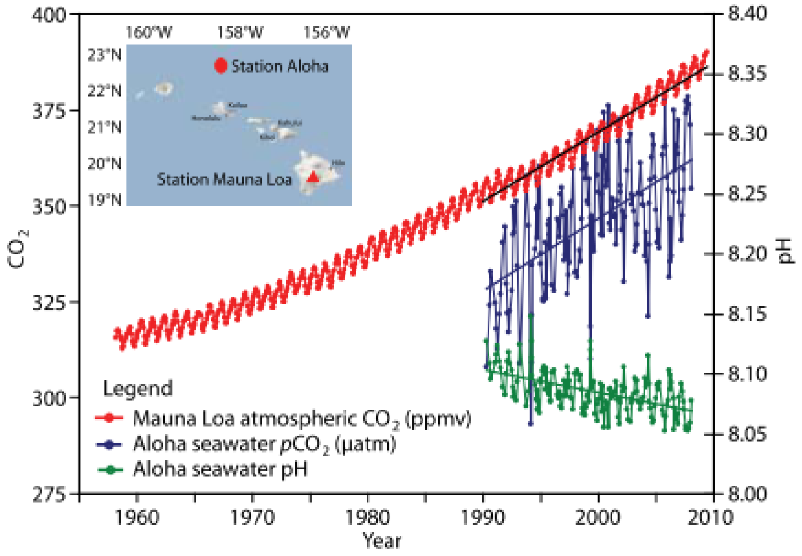


Figure A.3 - Changes in CO_2 and pH.
Changes in carbon dioxide in the atmosphere & ocean, and corresponding changes in ocean pH. From Doney et al. 2009.

4. Scientists predict an average ocean pH of 7.8 to 7.9 by the year 2100. Will the ocean be acidic then? (*No, the ocean will still be basic because the pH will still be above pH = 7.0.*)

5. Considering your answers to #3-4, why do you think we call it ocean acidification? (*See below.*)

If students struggle with question 5, you could have students read this question and answer and discuss what they read:

> Why call it ocean acidification, when the ocean is not acidic?
>
> **Beginner:** The word "acidification" refers to lowering the ocean's pH by any amount. Using this name is similar to how people say it is "warming" when the air temperature goes from -20 °C to 0 °C, even though they still would be happy wearing a warm coat and hat!
>
> **Intermediate:** Ocean acidification refers to the process of lowering the ocean's pH (that is, increasing the concentration of hydrogen ions) by dissolving additional carbon dioxide in seawater from the atmosphere, or by other chemical additions either

From WHOI's FAQ page:
http://tinyurl.com/ycrz8goq

> caused by natural processes or human activity. The word “acidification” refers to lowering pH from any starting point to any end point on the pH scale. This term is used in many other scientific areas (including medicine and food science) to refer to the addition of an acid to a solution, regardless of the solution’s pH value. For example, even though seawater’s pH is greater than 7.0 (and therefore considered “basic” in terms of the pH scale), increasing atmospheric CO_2 levels are still raising the ocean’s acidity and lowering its pH. In comparison, this language is similar to the words we use when we talk about temperature. If the air temperature moves from -20 °C to 0 °C (-4 °F to 32 °F), it is still cold, but we call it “warming.” – J. Orr, C.L. Sabine, R. Key

Elaborate: Online pH simulation

Use PhET's online pH simulation (http://tinyurl.com/mc4m4b3) to reinforce the lesson on pH. Students are responsible for exploring and answering the following question: On a molecular level, what is the difference between acids and bases?

This activity is a slightly modified version of Chris Justus' lesson, available under the “For Teachers” section of PhET's pH Scale simulation: http://tinyurl.com/ya2qvmog

Students begin by watching an introductory video on Youtube (http://tinyurl.com/y7cbqee3) that explains what students have to do (see steps 1-6 on the following page). After completing the first two rows of the table in their notes with data from the demonstration video (coffee and dilute coffee), students repeat steps 1-6 (#4-9 in their notes) for 3 more chemicals (full strength and diluted).

If you cannot access Youtube in your school, you can use your projector to show students how to use the simulation.

Procedure:

1. Choose 1 chemical (coffee, for example).
2. Write down the pH, the [H_3O^+] and the [OH^-]… Remember: [brackets] represent “concentration.”
3. Multiply those numbers together. Write down your data.
4. Make a dilute solution of your chemical. Repeat steps 2 & 3.
5. Repeat this process for a total of 4 different chemicals and their dilutions.
6. Finally, add a ninth row to your table… Repeat steps 1-4 for pure water.

To get pure water, students have to drain the solution (click on the blue handle on the bottom left of the solution) then add water (click on the blue handle next to the water label)

Then, students answer the following questions in their notes:

1. Describe the difference between an acid and a base on the molecular level.
2. What is the product of [H_3O^+] x [OH^-]?
3. What happens to pH as [H_3O^+] increases? Decreases?
4. What happens to pH as [OH^-] increases? Decreases?
5. What do you notice about the relationship between [H_3O^+], [OH^-], and pH for pure water?

Finally, examine Figure A.4 and describe the relationship between pH and H^+ concentration?

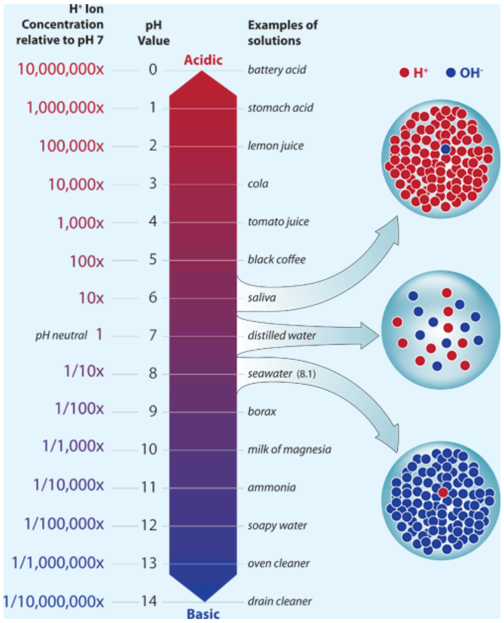


Figure A.4 - The logarithmic nature of pH.
Image source: WHOI.

LESSON 2, PART 2: CHEMISTRY CONTINUED (OPTIONAL)

ENDURING UNDERSTANDINGS

- Human actions lead to changes in ecosystems.
- Changes in one portion of a system can lead to multiple changes in the rest of the system.

KEY POINTS

- Adding CO_2 to seawater causes multiple changes in chemistry, causing both pH and carbonate ion concentration ($[CO_3^{2-}]$) to decrease.
- Some organisms are impacted by the change in pH while others are impacted by the decreased $[CO_3^{2-}]$.
- The pH and $[CO_3^{2-}]$ vary over time due to natural processes like photosynthesis, respiration, and upwelling.
- Different locations experience different levels of natural variation, and organisms are adapted to local conditions.
- Human actions are causing a long-term shift in pH and $[CO_3^{2-}]$; this shift occurs in addition to pre-existing natural variation.

OBJECTIVES

Students will be able to:

- Describe how adding CO_2 to seawater changes ocean chemistry (lowers pH and carbonate ion concentration).
- Explain how natural processes (photosynthesis, respiration, upwelling) influence local water chemistry.
- Explain patterns in water quality data collected at Whiskey Creek Shellfish Hatchery.

SETUP

- Make copies of student notebook (1 per student).
- Open PowerPoint presentation and preload video.
- Obtain supplies for demonstration.

MATERIALS

- Copies of student handout (1 per student)
- Computer, projector & speakers
- Presentation slides and videos

For Candle demo:
  - Universal indicator
  - Distilled water
  - 2 clear salad bowls/aquaria
  - Lighter/matches
  - Floating candles

See Kapsenberg et al., (2015) for more teaching ideas on pH variability.

Lesson Outline

Engage/Explore: Candles floating in indicator

This demo uses candles floating on an indicator solution in a closed container to simulate OA from fossil fuel combustion. Students are asked to connect what they see to OA.

This activity is modified from CarboSchools' "Interaction at the Air-Water Interface II": http://tinyurl.com/ybzxd6l2

Note- While this is presented as a demo, the change on the surface of the indicator is subtle. If you have enough supplies, it might help to do this in groups. Alternatively, you could use a document camera to project the air-water interface.

Procedure:

1. Place a clear salad bowl on top of a white background (paper towel). Fill the bowl ~½-full with distilled water.
2. Add several drops of universal indicator to the bowl. Make sure the water is visibly green in color.
3. Place 2-4 floating candles on top of the solution. Light the candles and cover the bowl with another salad bowl. Take note of the color of the water at the start of the experiment.
4. Observe the change in the color of the water in the bowls. To see any changes, look at the air/water interface (upper few millimeters of the water; see Figure A.5).

The original write-up uses three bowls: room temperature and ice water and a control where the candles are not lit. This would be a nice addition if you plan to go into detail on the relationship between temperature and gas exchange.

Slightly offset the top bowl to have the candles burn longer.

See CarboSchools for additional notes on this demonstration.

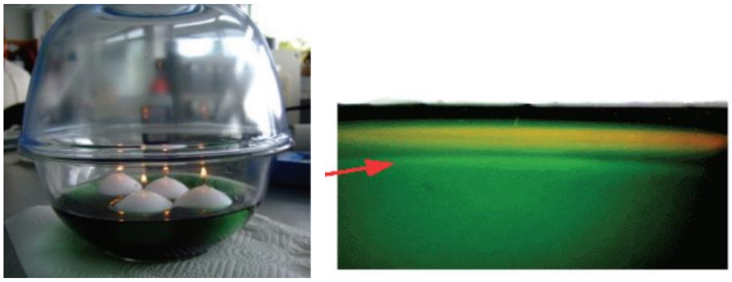


Figure A.5 - Floating candles setup.

After watching the demo, students draw and annotate their notes:

> Explain with pictures and words what happened in this demo? In what ways does it show ocean acidification? In what ways is it different from ocean acidification? (*Explanations should include these key words: combustion (burn),* CO_2*, absorb, reaction, pH*)

After students work on their explanations/diagrams, have a larger class discussion about what they wrote/drew/saw.

EXPLAIN: LECTURE ON CARBONATE & UPWELLING

CHANGES IN CARBONATE

Show the following table:

Table A.1 - Carbonate species.

Name	Chemical Formula
Carbonic Acid	H_2CO_3
Bicarbonate	HCO_3^-
Carbonate	CO_3^{2-}

Have students compare the different molecules. What do they notice? (*Differences include: number of hydrogen atoms and the charge*)

This presentation is similar to Aquarium of the Bay's lesson 2: http://tinyurl.com/ydaopym8

Remind students of the steps to ocean acidification previously discussed. Show equations from lesson 2 part 1, but have students fill in blanks (marked below with an "x""):

$$CO_2\ (g) \leftrightarrow CO_2\ (aq) \qquad \text{(A-4)}$$

$$CO_2\ (aq) + H_2O \leftrightarrow x \qquad \text{(A-5)}$$

$$H_2CO_3 \leftrightarrow x + HCO_3^{2-} \qquad \text{(A-6)}$$

> Why does adding CO_2 to water make it more acidic/decrease the pH? Where do you see that in these equations (*In the last equation, A-6, the product is* H^+ *which means it is created. We saw yesterday that increasing the* $[H^+]$ *decreases the pH.*)

> Some of the H^+ that is created reacts with carbonate, which is naturally occurring in seawater, according to the following reaction:
>
> $$H^+ + CO_3^{2-} \leftrightarrow HCO_3^- \qquad \text{(A-10)}$$
>
> What does this equation suggest happens to the $[CO_3^{2-}]$? (*It decreases, meaning there are fewer carbonate ions around.*)

KEY POINT: Adding CO_2 to seawater lowers the pH AND decreases the carbonate concentration, among other changes. Both changes potentially impact marine organisms.

UPWELLING

The U.S. West Coast is known as an ocean acidification hotspot. We are one of the first places, in addition to the polar oceans, that will experience the impacts of OA. The reason we are so vulnerable is because of something called upwelling.

Definition from NOAA: http://tinyurl.com/ybbmjr58

> Has anyone heard of upwelling? What is it? (*Upwelling is a process where deep, cold water rises to the surface.*)

Explain upwelling:

Channel Islands National Park/Marine Sanctuary's lesson 2 includes an upwelling demo: http://tinyurl.com/ybjldgbk

> During the summer in the Pacific Northwest, winds blow from the north. When they do, this causes deep ocean water to rise to the surface.

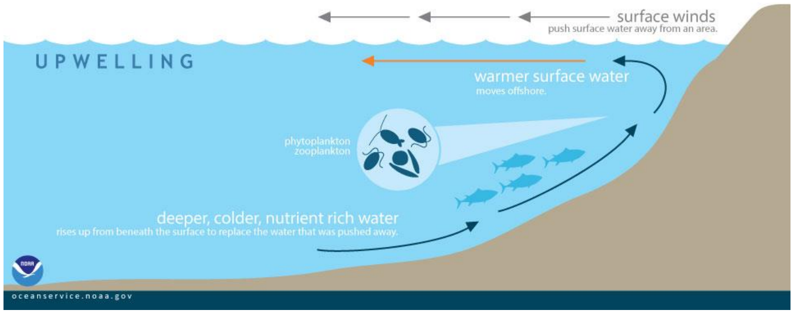


Figure A.6 - Upwelling.
A simplified example of upwelling along the West Coast of North America (NOAA).

Table A.2 - Comparison between surface and deep ocean.

Surface ocean	Deep ocean
● In contact with atmosphere (gases can be exchanged)	● No contact with atmosphere (gases are trapped)
● Sunlight (so photosynthesis can remove CO_2 from the water)	● No sunlight (without photosynthesis, CO_2 builds up)
● Low nutrients (plants use them)	● High nutrients (they're released when organisms respire and decay)

> In what ways do you think deep ocean water might be different from water on the ocean's surface? (*Student responses will vary*)

Draw a t-chart, solicit student ideas (see Table A.2). Then explain:

> In many ways, the surface ocean and deep ocean could be considered two separate parts of the ocean. In the deep ocean it is dark and cold. The water is separated from the surface. But, organisms die and sink, and living creatures in the deep continue doing respiration. This combination makes it so that the deep upwelled water is rich in nutrients (bits of digested organisms) and high in CO_2 (a respiration waste product). These nutrients fuel growth, but the extra CO_2 also lowers the pH and carbonate ion concentrations, making it harder for some organisms to survive.

ELABORATE: WHAT'S HAPPENING TO WHISKEY CREEK SHELLFISH HATCHERY'S WATER?

We have introduced several concepts over the past few days. Each of these influences the water chemistry. We are now going to use real water quality data that was collected at Mark & Sue's shellfish hatchery (named Whiskey Creek) in 2009, and we are going to try to figure out why ocean acidification was blamed for the die-offs.

This is a modification of an activity by Hilary Palevsky, University of Washington: http://tinyurl.com/ybebb75k.

KEY FEATURES OF STUDENT HANDOUT- Students complete a table (see below) where they circle the correct direction of change and provide an explanation. This reminds them of key changes that occur when CO_2 is added to seawater:

Students during our pilot study didn't like how much writing they had to do when analyzing the data. But, students during the classroom sessions generally struggled with slimmed down data analysis assignment.

Feature	How changes	Explanation
$[H^+]$	Increase or Decrease?	
pH	Increase or Decrease?	
$[CO_3^{2-}]$ "Carbonate"	Increase or Decrease?	

Then, help students apply their knowledge of photosynthesis and respiration to ocean chemistry.

PHOTOSYNTHESIS: The equation below shows a simplified formula for photosynthesis:

$$CO_2 + H_2O \rightarrow C_6H_{12}O_6 + 6O_2 \qquad \text{(A-11)}$$

"carbon dioxide + water forms glucose (sugar) + oxygen"

1. Based on the equation above, would photosynthesis by aquatic plants cause the concentration of carbon dioxide in the water to increase or decrease? Explain. (*Photosynthesis would cause the CO_2 in seawater to decrease because plants are taking in CO_2 to make sugar, removing it from the water.*)

2. What would this change in $[CO_2]$ do to the water's pH? Explain. (*The Soda Stream demo showed that adding CO_2 lowers pH. Photosynthesis does the reverse, it removes CO_2, which would make the pH increase. In other words, the water should become more basic because of photosynthesis.*)

3. During what time of day would you expect plant and phytoplankton photosynthesis to influence the [CO_2] and pH of seawater? *Hint: When does photosynthesis occur?* (*I would expect photosynthesis to cause pH to rise during the day because that is when there is sunlight.*)

RESPIRATION: The equation below shows a simplified formula for respiration:

$$C_6H_{12}O_6 + 6O_2 \rightarrow CO_2 + H_2O \qquad \text{(A-12)}$$

"glucose (sugar) + oxygen forms carbon dioxide + water"

1. Based on the equation above, would respiration cause the [CO_2] to increase or decrease? Explain. (*Respiration would cause the CO_2 concentration to increase because the process produces CO_2.*)

2. What would this change in [CO_2] do to the water's pH? Explain. *Hint- think about the Soda Stream demo*. (*The demo showed that extra CO_2 in water makes it more acidic; it lowers the pH.*)

3. What types of organisms carry out respiration? (*All aerobic organisms respire.*)

4. During what time of day does respiration occur? (*Respiration happens all the time. It does not need sunlight to occur.*)

Figure A.7 shows pH at Whiskey Creek Shellfish Hatchery over the course of one week in July 2009. Use the graph to answer the questions that follow:

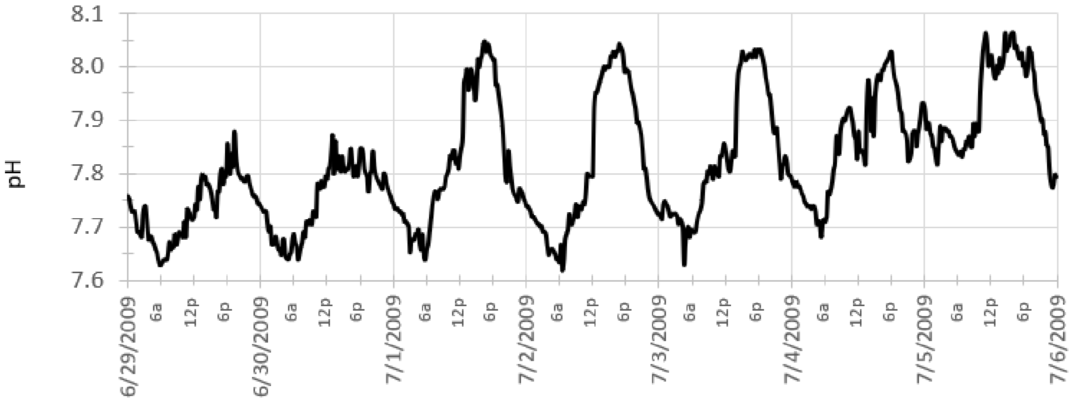


Figure A.7 – Water quality measurements.
One week of hatchery pH data (6/29 to 7/6/2009).

1. What patterns/trends do you notice in this data? (*It goes up and down every day, but it is steadily increasing over the course of the week.*)

2. At what time of day is pH the <u>lowest</u>? (*pH is the lowest around 6am.*)

3. At what time of day is pH the <u>highest</u>? (*pH is the highest around 5pm.)*)

4. What might explain these daily changes in pH? (*Photosynthesis could be taking CO_2 out of the water during the day, leading to the rise in pH. Then, at night, when plants aren't doing photosynthesis, respiration by marine organisms could cause the pH to drop until morning, when the sun comes out and photosynthesis begins again.*)

5. Larvae oysters generally do better when pH is higher. What time of day would you recommend the hatchery take water out of the bay to fill their tanks? (*They should fill their tanks between 3 & 5pm because this is when the pH is highest.*)

Some of our students suggested changes in human activity cause this pattern. They thought we might emit more CO_2 at night when we light our homes. CO_2 emissions vary on a daily cycle by level of urbanization. Emissions are generally higher during the daytime in urban areas. E.g., see Ueyama & Ando, (2016).

Figure A.8 - Data from summer 2009 at Whiskey Creek Shellfish Hatchery.shows water quality data from Whiskey Creek Shellfish Hatchery for the entire 2009 summer.

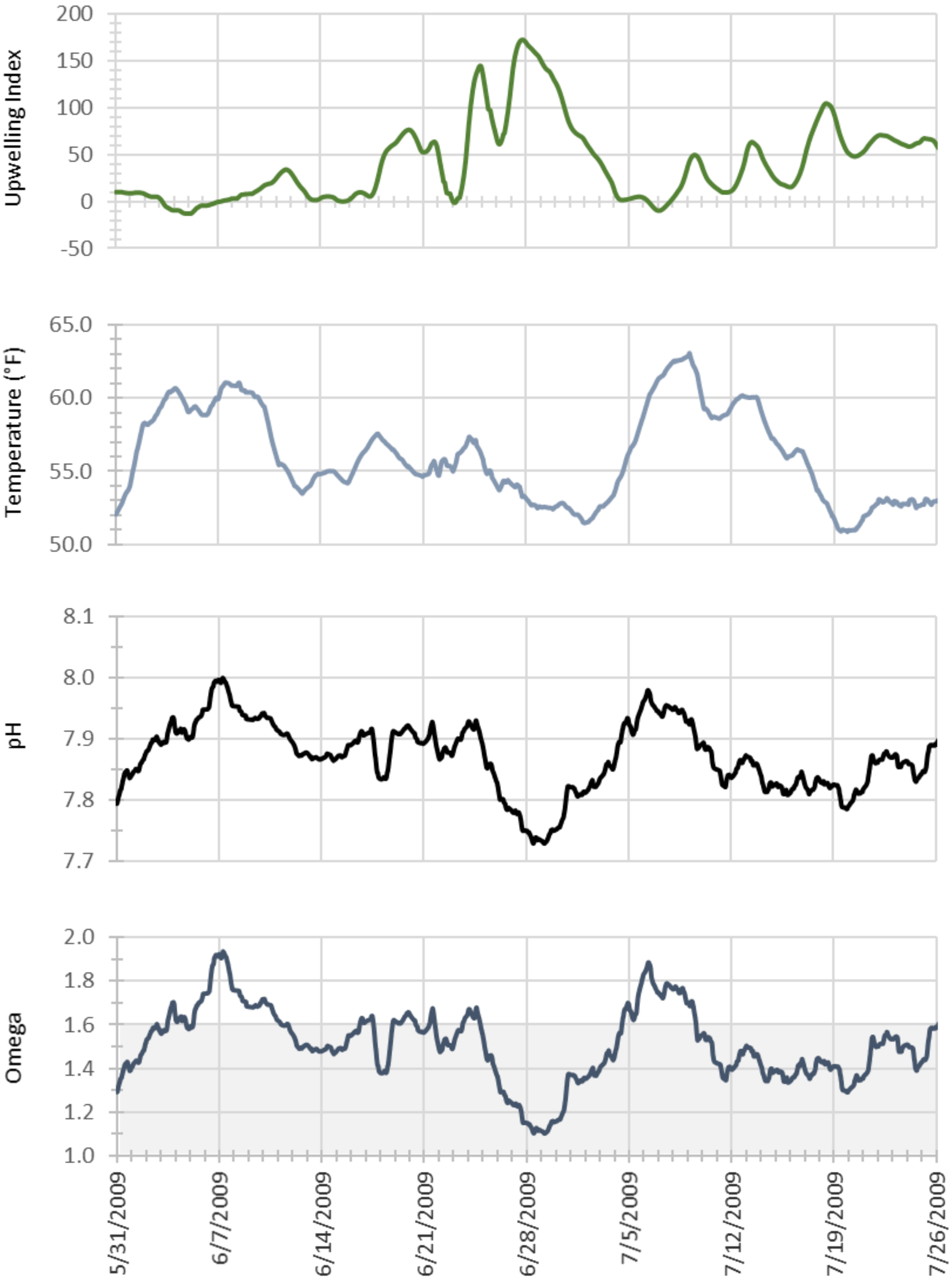


Figure A.8 - Data from summer 2009 at Whiskey Creek Shellfish Hatchery. Upwelling index is a measure of the strength of upwelling. More positive numbers reflect stronger upwelling. Omega is a measure related to calcium carbonate shell stability. Larger numbers mean it is easier (less energy is required) for organisms to build shells. When omega is below 1.6, oyster larvae die.

Help students work through the graph interpretation questions in their notes.

6. Based on the upwelling index graph, when was the strongest upwelling event in 2009? (*From 6/23 to 7/4.*)

7. Explain the relationship between upwelling and water temperature. (*When the upwelling index is higher, the temperature is generally lower. This makes sense because upwelling brings up cold water from the deep ocean.*)

8. Explain the relationship between upwelling and pH. (*pH is lower when upwelling is stronger. This is because deep ocean water is higher in* CO_2 *because there is a lot of respiration and decomposition in the deep ocean.*)

9. Larval oysters die when omega is below 1.6. Roughly how much of the summer was omega below 1.6? (*Most of the summer! There were only 16 or so days when omega was not below 1.6. This consistently low omega is why so many oysters died.*)

10. Why do you think scientists concluded that ocean acidification was causing the oysters to die? Wouldn't it make more sense to conclude that upwelling caused the deaths? *Hint*- *Upwelling occurs in Oregon every summer.* (*OA is a long-term decrease in pH and carbonate ion concentration. You cannot see it in a single year's data. The graph showing changes in* CO_2 *and pH over time (Figure A.3* - Changes in CO2 and pH.*) helped us see the steady decrease in pH that also includes seasonal ups and downs. Upwelling happens every summer on the Oregon coast, but because of OA, the extreme conditions (low pH and omega) are getting a little worse every year. So, OA is making it harder for some organisms to survive. Upwelling makes it even harder during Oregon summers.*)

This question is meant to get students to realize that, while the graphs show a drop in omega and pH during upwelling, OA caused these values to drop to lower than they had been in prior years. In essence, OA means these low pH/low omega days ("bad days" for larval oysters) are becoming more frequent and more extreme.

FINAL (CHALLENGE) QUESTION:

We have seen that ocean acidification is a small decrease in pH per year. If ocean acidification is a smaller change than what naturally happens over the course of days, weeks, and months, why are scientists so concerned about ocean acidification? (*While OA is only a small change each year, it is a steady decrease over time. Natural variation will continue to occur, but OA means pH will get lower and lower during those natural events.*)

It can be helpful for students to compare this situation to variation in weather. There is a natural range in temperature where you live (say 30-80°F). The temperature equivalent of OA would mean that this range slowly decreases, so it might be 25-75°F, then 20-70°F, and eventually 0-50°F. There is still variation, but the low temperatures are much lower than they used to be. If you cannot adapt to colder temperatures, you may struggle to survive.

LESSON 3 - WHAT ARE THE IMPACTS OF OCEAN ACIDIFICATION?

In this lesson, students conduct online research to explore how ocean acidification could impact marine ecosystems and the humans that rely on them. It seeks to avoid the overtly crisis tone and misconceptions that often accompany ocean acidification lessons, including notions that "all shells will dissolve," "pteropods will go extinct," and "the oceans will be inhospitable." Instead, students are responsible for finding out what it might mean and teaching each other about the possible impacts to ecosystems and people.

This lesson begins with a 4-minute video of scientists, shellfish hatchery workers, and marine resource managers describing what we know and don't know about the impacts of ocean acidification. Then, students explore possible impacts through independent research. Students present their findings to the class, and the lesson finishes by synthesizing what the students learned.

NOTE- *Online student research is a new addition to this latest edition of this module. In prior iterations, we found that students did not develop a broad understanding of what ocean acidification might mean for ecosystems. We'd love to hear your feedback (brian.erickson@oregonstate.edu) on this new approach to teaching the impacts of ocean acidification!*

ENDURING UNDERSTANDINGS

- Marine ecosystems, and the humans that rely on them, are interconnected.
- Human actions lead to changes in ecosystems.
- Changes in one portion of a system can lead to multiple changes in the rest of the system.

TIME

Two, 60-minute lessons

MATERIALS

- Copies of student handout (1 per student)
- Computer, projector & speakers
- Presentation slides and videos
- Computers with internet connection for student research

A prior version of this curriculum had students build an Oregon marine food web then use 4 research-based scenarios for a short but structured discussion of possible impacts of ocean acidification. See the Curriculum Appendix.

KEY POINTS

- There will be some winners and losers of ocean acidification (some organisms will benefit from ocean acidification while others will face negative consequences).
- Calcifiers, such as corals, shellfish, and some plankton, are especially vulnerable.
- Ocean acidification could have major impacts on marine ecosystems and the humans that rely on them for food, income, and well-being.

OBJECTIVES

Students will be able to:

- Describe some of the ways ocean acidification could impact organisms, food webs, and humans.
- Present research findings to the class.

SETUP

- Make copies of student handouts: *Researching Ocean Acidification Impacts* and *Learning about Ocean Acidification's Impacts* (1 per student).
- Open PowerPoint presentation and pre-load video.
- Reserve laptop cart/computer lab space for student research.

LESSON OUTLINE

Engage: Brainstorm

Ask students:

> What do you think the impacts of ocean acidification will be?

Encourage them to think of what they've previously heard about ocean acidification.

Write down student responses on chart paper so you can later compare their initial knowledge and what they learned from their research projects and presentations.

Explore: Ecosystem Impacts Video

Show Ecosystem Impacts video (3:30). Students answer questions in their notes.

> What does Mark mean when he says it is going to be a “timing issue”? (*ocean acidification will impact species that are trying to reproduce when the water is most acidic. In the Pacific Northwest, waters are currently most acidic during the summer due to upwelling. Mark insinuates that this period of “bad water” may expand with time.*)
>
> How does it feel to hear scientists say, “we don’t know what the impacts will be for ecosystems”? What does this make you think about and/or wonder? (*Student responses will vary.*)

Discuss student responses as a class.

Students in our study were reluctant to share how it felt to hear scientists say they didn't know what the impacts of ocean acidification would be. In their written notes, some students expressed fear/worry while others asked why it took researchers so long to figure this out. This point lead to the synthesis questions at the end of this lesson.

Interconnections Between Humans and the Ocean

Have students brainstorm ways that humans and marine ecosystems are interconnected. It is important to highlight both our dependence on the ocean and ways that we can change the ocean.

Framing a conversation about climate or ocean change with a focus on values, such as interconnections, can be an effective way to help individuals think about what is at stake and what can be done about an issue (Bales et al. 2015).

> In what ways do humans rely on the ocean? (*food, minerals, climate, transportation, shipping, recreation, well-being*)
>
> Does the ocean rely on humans for anything? (*Many students will say no, the ocean doesn't need humans. A few in each class say the ocean relies on humans to <u>avoid</u> polluting/ overharvesting*)

Researching Impacts of Ocean Acidification

Each student (or group of students) will be responsible for researching how ocean acidification is predicted to impact different marine organisms. After conducting internet research and recording their findings (on the student research handout or

For teachers without internet/classroom computers, you could print the Smithsonian OA or Seattle Times Sea Change Creatures page, give it to students and have them jigsaw their reading.

in their notebook), students prepare to present their findings to the class.

> Today we want to try to answer the question, "What are the possible impacts of ocean acidification?" To do so, each of you is going to research how ocean acidification is predicted to impact a specific organism. Our goal is to create a list of different possibilities for what it could mean for marine organisms and for people.

Direct students to look at their handout, "Researching Ocean Acidification's Impacts." Tell students:

See the student handout for a list of possible organisms and a link to the Seattle Times' Sea Change website: http://apps.seattletimes.com/creatures/

> You will research the potential impacts of ocean acidification on an organism of your choosing. You will be responsible for presenting your findings to the class. Our goal is to gain a broad understanding of the range of possible impacts ocean acidification might have.

A few recommendations:

- Have students sign up for organisms so you ensure a variety of different organisms are being researched. You could do this a number of ways, including: on the board, online, or on a sheet of paper that gets passed around.
- Make sure at least one student researches the possible benefits to photosynthesizers, like seagrass and diatoms.
- Students will be responsible for presenting their findings to the class in 1-2 minutes. They can be as creative as they'd like, but must provide the following info:
  - What organism did they look at?
  - How might it be impacted by ocean acidification?
  - What impact would this have on other creatures and/or humans?
  - Where did you find this information?

Some websites, like http://www.co2science.org may seem legitimate to students but are actually climate/ocean change denial websites. If students use this site, the teacher could lead a discussion about reliable vs. unreliable websites and information.

Allow students to research and prepare their presentation for the rest of the class period.

The Smithsonian's website http://ocean.si.edu/ocean-acidification might be a helpful reference.

Presentations: What are the Impacts?

At the beginning of the next class period, tell students:

> Today, we'll be learning from each other's research on the impacts of ocean acidification. Our goal is to better understand what it means for the ocean and for people.

Pass out the student handout, "Learning about Ocean Acidification's Impacts." Model how students should take notes during presentations. Since we've already talked about the Pacific oyster, use it as an example for how to fill out the table. You could prompt students to help you fill in the first row in their handout.

> **Organism:** oyster
>
> **Predicted impacts:** students should be able to explain that some larval oysters will die

If you have a document camera, you could fill out the first row based on what students tell you about the impacts of ocean acidification on oysters.

Show slide with image of four-day old larval oysters.

> Ask students what they notice when they compare the two oysters. (*the oyster on the right, grown in "bad," or acidified water, is smaller and deformed.*)
>
> So additional impacts are smaller and deformed oysters.

Not all oysters die from ocean acidification. Research at Whiskey Creek Shellfish Hatchery has shown that larval oysters that don't die can still be affected.

NOTE: Previous versions of this module used an analogy that compared larval oysters to cell phones. The message was that OA causes them to spend more energy, a key message often missing from OA instructional resources. We cut this analogy due to concerns about anthropomorphism. If students do not realize that OA means organisms will spend too much energy trying to build their shells, you might consider using this analogy.

> **How will this impact ecosystems and humans?**
> Fewer and smaller oysters could mean: less habitat for other organisms, less food for other organisms that eat oysters, murkier water (oysters filter the water). Hatchery owners might make less money or go out of business; oyster farmers might have a harder time finding seed (baby oysters), making them less productive; restaurants might not have as many oysters to sell or might have to charge more for them…

After giving this example of how to fill out the table, begin student presentations. While each student presents their research have all other students take notes in their handout.

Summary: The Big Picture (3 min)

After students finish their presentations, ask them to work in groups to summarize what they heard.

> Could ocean acidification benefit any organisms? (*Likely yes. Some plants might do better with extra* CO_2*. Some organisms may benefit from population changes in their predators and competitors.*)
>
> Could ocean acidification hurt any organisms? (*Absolutely. There is a whole range of organisms that may be harmed from ocean acidification, and the impacts go beyond shell dissolution.*)
>
> How would you answer our research question, “what are the possible impacts of ocean acidification?” (*Student answers will vary.*)

Ask students to share with the class what they discussed in groups. Then, present slides summarizing key points about the predicted impacts of ocean acidification. Did we bring up all these key points?

- Ecosystems are complex, and organisms could adapt, or they might not have enough time. It is very difficult to accurately predict what ocean acidification will mean.
- We know that some organisms will do better (like some seagrass, algae, and plants) while other organisms will do worse (especially calcifiers)

- There are many impacts beyond shell growth. And we're not just predicting that living things will die.
- Different life stages (young vs adults) respond differently

This may be a good point to revisit the ideas brought up in the video at the start of this lesson. You could have students discuss (in pairs to encourage everyone participates):

> Based on what you learned about the predicted impacts of ocean acidification, what do you think the scientists in the video meant when they said, “we don’t know what the impacts of ocean acidification will be?” (*The scientists were likely explaining that ecosystems are complex and it is hard to predict all the outcomes. It is also hard to translate lab experiments into the real world.*)
>
> How has your understanding of this changed after doing your own research and hearing from other students in your class? (*Answers will vary.*)

It is not that we know nothing; rather it is that we are unsure how the possible changes will interact and how bad the impacts might be.

Encourage students to consider how their thoughts have changed since the brainstorm at the start of this lesson. You could even bring the chart paper back out to prompt memories.

It is important to acknowledge that this lesson on the impacts of ocean acidification may have been dispiriting. Highlight that tomorrow we will begin thinking about what can be done about ocean acidification.

> “While the last two days have likely been a little depressing, after all, we discussed quite a few mostly negative impacts to organisms and people, tomorrow we’ll be discussing possible solutions and what we and others could possibly do about ocean acidification.”

LESSON 4 - WHAT CAN WE DO ABOUT OCEAN ACIDIFICATION?

This lesson aims to leave students with a sense of hope. Students are reminded that carbon dioxide emissions from human activities are the primary cause of ocean acidification. After brainstorming possible actions that reduce CO_2 emissions and barriers to these actions, students are introduced to an analysis performed by psychologists that looks at how much of an impact various household changes could have on total U.S. energy use, and thus CO_2 emissions. This discussion leads into an analysis of the impacts of individual vs. collective action and leads into the final Call to Action project.

ENDURING UNDERSTANDINGS

- Marine ecosystems, and the humans that rely on them, are interconnected.
- Individual and collective actions are needed to effectively manage resources for all.

KEY POINTS

- There are ways to reduce future damage to ecosystems from ocean acidification.
- Even if people know what actions could reduce CO_2 emissions, there are many barriers to taking action.
- Some actions have larger impacts on reducing CO_2 emissions than others, and thus have greater potential to reduce ocean acidification.

OBJECTIVES

Students will be able to:
- Identify potential solutions to ocean acidification.
- Discuss the impact and feasibility of various actions to reduce ocean acidification.

TIME

1 60-minute lesson, plus final project

MATERIALS

- Copies of student handout (1 per student)
- Computer, projector & speakers
- Presentation slides and videos
- CO_2 reduction action cards
- Computers with internet for student research

SETUP

- Make copies of student notebook (1 per student).
- Open PowerPoint presentation and preload video.
- Prepare CO_2 Reduction Action Cards: Print 10 copies of CO_2 action cards (1 page each, see lesson materials), or enough for each group to have a set. Cut out a set of action cards for each pair/group of students. Use a paper clip to hold each set together. Laminate cards for long-term use.

LESSON OUTLINE

Engage: Solutions Video (5 min)

Present slide summarizing key ideas covered so far.

> "Today we're going to think about solutions to ocean acidification, things that people like you can do to reduce ocean acidification. I wanted to start with a short video clip."

Show the video (L4_Solutions) discussing the future of OA (2 min). Present slide of three main ways to address ocean acidification: dealing with the cause, buying time (seagrass restoration, sewage/runoff reduction), and learning more about the problem, this lesson focuses on dealing with the main cause, anthropogenic CO_2.

Cutting CO_2 Emissions (10 min)

BRAINSTORMING ACTIONS AND BARRIERS

Show slide. Students take 2 minutes to list actions that could be taken to reduce CO_2 emissions in the U.S. and things that might prevent people from taking these actions.

Make a T-chart on the board: left side says "Actions," right side says "Barriers."

Students share out responses to possible actions. Teacher/student volunteer writes these under the Actions heading. Students share out possible barriers. Record answers under the Barriers heading.

> You've just listed several actions that could be taken to reduce CO_2 emissions, and thus reduce ocean acidification since we said anthropogenic CO_2 was the main cause of the problem. You've also come up with numerous explanations for why people, even people who care and want to do something, might not take action.

Maximizing Impact (15 min)

> Now we are going to go beyond just thinking of possible actions and move toward being strategic about prioritizing which actions to take. It's not very common to talk about the impact of different CO_2 reduction actions. Usually we talk about what would be easy, or inexpensive, or what's in our control, we don't often talk about how much CO_2 is removed or prevented by actions.

COMMIT & TOSS: Tell students to take out a blank piece of paper. Do not put their name on it! They are going to write an honest answer on the paper. Once finished writing, crumple up your answer into a ball and toss it around the room. We'll then read the answers out loud and make an anonymous list.

This commit and toss activity was added to increase student discussion.

Have them answer the following question on a piece of paper:

> What is the most effective thing you could do to conserve energy? (Write **ONE** action)

Once students have written a response, they crumple their paper and throw it into the air (not directly at someone). After brief chaos, have students grab a paper ball from the floor. On the board write "Most effective actions…" and then list the answers students read (use tally marks for answers that are listed multiple times).

Show slide.

> Back in 2008 there was a research study published that sorted through possible actions American households could take and came up with a list of 9 low-cost actions that would have the largest impact. We are going to explore some of the ideas from this paper. We are trying to think about how we can get the most bang for our buck, or in other words, how we can be sure that the actions we are taking make a difference.

Tossing balls of paper will not be appropriate in all classrooms. You could have students "toss" their ball into a basket, shake it, and pull one ball out.

Show slide. Each group will get a stack of cards. Each card lists an action you could take to reduce household co2 emissions. With your group, organize the cards from the most effective to least effective actions to reduce energy use (in other words, from most to least energy saved). Give student groups 3-5 minutes for the initial card sort.

Present slides.

> Now that you have an initial guess, I wanted to show you some data about how households use energy.

"Turn off lights" and "watch less TV" are energy saving actions that are commonly mentioned but that have little impact on energy use. These actions were initially included to make the point that they were commonly thought of but very low impact. We found that students remembered these low-impact actions but not that they had limited impact. To focus students on high-impact actions, we removed these two action cards from the deck

Students are given 1-2 minutes to adjustment the order of their cards based on the new information. Present slide showing the ordered list of actual impact of the different actions (See Table A.3 - Energy saving actions rankings.). Possible discussion points include:

- How does your list compare to the order of actions the researchers found? (*Student answers will vary.*)
- Were you surprised by anything from this activity? (*Answers will vary)*)
- Do you notice anything about the actions at the top vs. bottom of this list? (*Answers will vary. Many top actions deal with efficiency, bottom actions are daily habits/behaviors.*)
- How many of the actions listed involve one-time improvements to the efficiency of an energy-using appliance and how many involve an on-going choice in how much/how intensely an item is used? (*Efficiency- 6; Daily Choice- 6*)

e.g. buying a fuel-efficient vehicle is a choice that will lead to large savings every time the car is used. In contrast, washing with cold water, line drying clothes, turning out lights, etc. are choices that have to be made on an ongoing basis.
.

Table A.3 - Energy saving actions rankings.
Ordered list of impacts of various household actions on energy use.

Action	Energy Saved (%)
1. Buy a more fuel-efficient vehicle	13.5
2. Adjust your driving habits	8.3
3. Insulate your attic	7.0
4. Install a more efficient heater/AC unit	5.1
4. Maintain your vehicle	5.1
6. Carpool to school with one other person	4.2
7. Replace 85% of incandescent lightbulbs with LEDs	4.0
8. Replace old windows with high-efficiency ones	3.7
9. Use less heat/ air conditioning	3.4
10. Wash clothes in cold water	1.2
11. Install a more efficient washing machine	1.1
11. Line dry clothes 5-months of the year	1.1

The Short List (5 min)

Pass out the Short List Infographic.

> While it is helpful to have an ordered list, for me this is still a bit overwhelming. Also, many of the actions seem expensive. What low-cost actions lead to the biggest reduction in CO_2? Look at the infographic. Notice the left column shows low-cost actions that could be done now, the right column shows more expensive actions with big impacts on emissions.

*Students calculate the impact of a family, county, and state taking action. Then discuss with their neighbor, then as a class:

> What do you think about the actions listed in this table? How many seem doable? (*Answers will vary.*) Do you think they would have an impact on ocean acidification? Why or why not? (*Answers will vary.*) What's missing from this list that you expected to see? (*Answers will vary; but energy generation and policy measures were not included in this household-focused activity.*)

Present slides on the impact of planting trees versus changing light bulbs.

A NOTE ON PLANTING TREES: While trees do remove CO_2 *from the atmosphere for photosynthesis, the impact of planting one young tree is likely not as great as students expect. Estimates of* CO_2 *absorption by trees varies. One estimate suggests a young conifer removes 10 lbs of* CO_2*/year per tree planted and kept alive, an average life of 30 years. In contrast, changing one 43-watt incandescent bulb to a 9-watt LED saves about 66 lbs of* CO_2*/year* (EPA, 2017).

Installing solar panels isn't on there because it is high cost and this analysis was focused on saving energy, not generating it. Similarly, commonly listed actions like turning off the lights were not included because they are considered low-impact.

Personalizing the Message

Have students calculate their own carbon footprint and look through the various actions they could take to reduce their impact (This could be done as homework if you are running short on class time).

Several curricula recommend this action.

Students go to the Cool Climate Calculator (http://coolclimate.berkeley.edu/calculator). After completing the questions, they are presented with a long list of actions. Students record their CO_2 footprint and identify the area where they generate the most CO_2. Then, they choose 3 actions they'd be most likely to take, explain why they chose those actions and consider how challenging it will be for them to make the change. This activity primes students for the final project.

We recommend Berkeley's Cool Climate Calculator because it allows students to easily analyze different possible actions and adjust the assumptions to show the relative impact of various actions more clearly.

FINAL PROJECT: A CALL TO ACTION

This final project was added to the curriculum to help students process what they've learned and attempt to influence those who they think should be taking action. Some of our students felt that "everyone" should be taking action while others thought people with money, power, and knowledge should be the ones leading the way. This project allows students to determine who they feel should be doing more and try to convince these people to act.

This final project could be a great way to connect with an English classroom to work on crafting persuasive messages/arguments.

> To reduce OA and its impacts, action will be needed by many different individuals, groups, and governments. Your task for this final project is to create something that will convince others to take action. You get to choose who you target, what action(s) you try to get them to take, and how you try to convince them. In addition to letting you try your hand at persuading others, this final project is also designed so you can showcase what you learned/know about OA.

Main Features:

> **Target audience:** Who are you trying to convince to take action? Why did you choose them? (You might try to convince someone in government, or the president, because you think they have the most power to change things. You might target your friends and family because you know them. You might target your classmates or school, your sports team, or someone else entirely. But you have to communicate who you are trying to persuade and why.)
>
> **Method:** You can be as creative as you want in your means of persuasion. (Ideas include: letter, Op-Ed piece for a newspaper, flyer, Public Service Announcement, video, grassroots action campaign, speech, etc.)
>
> **Argument:** Make a persuasive argument that shows that you understand ocean acidification.
>
> **Overcoming barriers:** Demonstrate that you thought about what barriers might prevent your audience from taking action and explain how you tried to get around these barriers

It might also be worthwhile to have students show that they looked into what their audience is already doing, especially if they are writing to government officials.

SUPPLIES LIST

The following list summarizes materials needed for the curriculum. It is a repeat of the list found at the start of each lesson. Note- a computer, projector, and speakers, as well as student handouts, are needed for every lesson

Lesson 1

No additional supplies needed.

Lesson 2

- Soda Stream
- Universal indicator
- Dropper/pipette (for adding indicator to solution)
- Aquarium tubing (~1-2 feet)
- 3x 300 mL Erlenmeyer flasks
- Water (distilled preferred; tap water okay)
- Soda ash
- Stirring rod/spoon
- Measuring spoon (to scoop soda ash)
- Floating candles
- Lighter/matches
- 2 clear salad bowls/aquaria
- Distilled water
- Computers with internet access for student homework

Bromothymol blue and cabbage juice also work but have a more limited pH range. See Educator Background.

Lesson 3

- Computers with internet access for student research.

Lesson 4

- CO_2 reduction cards

Make enough sets to have 1 per group of 2-4 students.

Paperclips and envelopes would help with organization. Laminating the CO_2 reduction cards would extend their life.

EDUCATOR BACKGROUND

LESSON 1- EDUCATOR BACKGROUND

Ocean Acidification

Ocean acidification is the change in ocean chemistry due to increasing amounts of carbon dioxide (CO_2) in the atmosphere as a result of human activities, primarily the combustion of fossil fuels (e.g., oil, coal, gasoline, natural gas), land use changes (e.g., deforestation), and cement production (Doney et al., 2009). Ocean acidification can be described with the following explanatory chain (Bales et al., 2015): i) human activities release CO_2 into the atmosphere; ii) the ocean absorbs roughly 25% of these human created CO_2 emissions; iii) the chemistry of the ocean changes; iv) one result is that dissolved carbonate ions, something shellfish need to build their shells, becomes more scarce, making it more difficult for shellfish like oysters and mussels to build shells; (v) carbonate, used for shell building, becomes less available and it takes more energy to make shells, leading to fewer & smaller shellfish; (vi) shellfish filter water so fewer shellfish could lead to cloudier water, making it harder for seagrasses to do photosynthesis; (vii) seagrass beds are important habitat for young fish so less seagrass could mean fewer fish to catch; (viii) this could impact humans who rely on fish for food & jobs.

Since the mid-1700s, human activities, mostly the burning of fossil fuels, have led to dramatic increases in the concentration of CO_2 in the atmosphere (Tans, 2009). Current concentrations of atmospheric CO_2 are higher than they have been at any point in at least the past 800,000 years (Ciais et al., 2013). This buildup of anthropogenic, or human generated, CO_2 creates a concentration gradient between the atmosphere and the surface ocean, which leads to the absorption of CO_2 from the atmosphere into the surface ocean. It is estimated that roughly 25% of anthropogenic CO_2 emitted is absorbed by the ocean, another 25% is absorbed by land plants, and the rest remains in the atmosphere.

When CO_2 enters the ocean, a series of acid-base equilibrium reactions occur, changing the ocean chemistry. While ocean acidification was traditionally defined as, “the pH reduction associated with the long-term ocean uptake of anthropogenic CO_2,”(Caldeira & Wickett, 2003) it can be helpful to think of it as a suite of chemical changes, not just a decrease in pH.

Ocean Acidification is an Active Area of Research

Ocean acidification is a relatively recent phenomenon in ocean research despite roots stretching back across most of the 20th century. Researchers knew for decades that the ocean played a key role in absorbing heat and carbon dioxide from the atmosphere; however, it wasn’t until the 21st century when the potential environmental problems were fully realized (Brewer, 2013). There has been tremendous growth in research on ocean acidification since the mid-2000s. A Web of Science© search (May 2018) for “ocean” AND “acidification” returns 5,461 publications dating back to 1990. The pace of research and publication has quickly accelerated such that 93% of all papers on ocean acidification have been published since 2010. In fact, 1 in 5 papers on “ocean acidification” have been published since the start of 2017. This means knowledge about ocean acidification is relatively new and ever expanding. Despite the pervasiveness of ocean acidification in scientific publications over the past decade, surveys suggest the American public remains largely unaware of ocean acidification (Bales et al., 2015; The Ocean Project, 2012).

Changes in Ocean Acidification Understanding

Much of the “early” (pre-2010) work on ocean acidification described a global phenomenon, mentioned that the average pH of ocean surface waters had fallen by 0.1 units from 8.2 to 8.1 since the Industrial Revolution, and projected decreases in average pH of 0.3-0.4 by 2100 (Richard Feely, Doney, & Cooley, 2009; Orr et al., 2005). As recently as 2013, ocean acidification was described by some researchers as an “open-ocean” issue (Duarte et al., 2013). Thus, less than five years ago, ocean acidification was considered by some to be a global ocean problem that would have future impacts largely away from where humans lived and worked. While this understanding is generally correct, research in the past few years has revealed that some coastal ecosystems are already being impacted by ocean acidification, some “hotspots” will be impacted sooner and more severely, and different organisms exhibit varying responses to ocean acidification.

Major developments in the past few years, as revealed in literature review and expert interviews, include: discovery of impacts of ocean acidification on shellfish larvae (Barton et al., 2012; Waldbusser, Hales, Langdon, Haley, Schrader, Brunner, Gray, Miller, & Gimenez, 2015; Waldbusser, Hales, Langdon, Haley, Schrader, Brunner, Gray, Miller, Gimenez, et al., 2015); expansion of the discussion of impacts beyond pH to also include omega and other pieces of the carbonate system (see

Lesson 2- Educator Background for more information); a shift towards identifying hotspots and geographic/spatial patterning and away from global averages (Gruber, 2011; Mabardy et al., 2015; Strong et al., 2014); a shift in the timescale of anticipated impacts from 2100 to 2025; expansion of ecosystems impacted from just coral reefs and open oceans to include many other marine ecosystems, including nearshore and estuarine ecosystems along the Pacific Northwest coast; and a dramatic increase in the number of published studies, including several meta-analyses (papers that analyze several papers on the same subject to identify larger patterns, conclusions, and gaps in knowledge).

Shellfish in the Pacific Northwest

Shellfish harvesting has occurred in the Pacific Northwest for thousands of years. Commercial harvests began during the San Francisco gold rush in the late 1800s (Shabica et al., 1976). Overharvesting greatly reduced the naturally occurring populations of oysters, and over time the industry shifted to growing non-native Pacific oysters, *Crassostrea gigas*, as the primary farmed species in the region. Today there are a few naturally reproducing populations of Pacific oyster, mostly in Willapa Bay and parts of Puget Sound, Washington, but their success is not reliable enough to maintain the shellfish industry. Since the 1970s, the industry has become increasingly reliant on hatcheries for their larvae, and there are currently three major commercial hatcheries that provide seed to support the majority of the nearly $270 million per year shellfish industry (Barton et al., 2015). One of these hatcheries, Whiskey Creek Shellfish Hatchery, provides seed to ~70% of independent oyster growers throughout the West Coast.

Pacific Oyster Hatchery Failures

Starting in 2007, hatcheries saw persistently high levels of larvae mortality (Barton et al., 2015). Initially, it was suspected that a bacterium, *Vibrio tubiashii*, was responsible for the die offs at Whiskey Creek Shellfish Hatchery; however, problems remained even after installation of a $180,000 filtration system eliminated the pathogen. This led hatchery managers in search of another explanation. In 2008, they began exploring water chemistry as a possible culprit. By 2009, monitoring of water chemistry began, and it was determined that changes in water chemistry were to blame. Thanks to industry-researcher collaborations, hatcheries installed water monitoring and buffering systems and changed their behaviors so that the worst water for larval oysters could mostly be avoided or adjusted.

Currently, the industry manages the effects of ocean acidification in their controlled environment. Their ability to continue dealing with water conditions into the future is an ongoing question. Betting that conditions in the Pacific Northwest will become less favorable in the future, one hatchery has already moved from Washington to Hawaii, where ocean acidification's impacts are projected to be less severe in coming decades (Welch, 2013).

The hatchery failures in the mid-2000s, sometimes called the "Pacific oyster seed crisis" in popular news accounts, were a surprise to many researchers. They helped highlight that ocean acidification is a current problem occurring in coastal oceans, not an open-ocean problem that would not show impacts until the century's end. They also highlighted the need for careful research that considers the full chemistry of ocean systems, as it turned out that the oyster larvae die-offs were not specifically a result of pH changes. Instead, they were due to changes in the carbonate saturation state of the water (Barton et al., 2012; Waldbusser et al., 2015).

LESSON 1- TEACHING NOTES

General Comments

Discussions of ocean acidification can become chemistry heavy. An emphasis on the chemical equations involved in ocean acidification may prevent students from seeing the larger picture and possible impacts of the issue. In hopes of introducing the topic, building emotional investment, and providing a broad understanding before diving into the chemical details, this curriculum begins by introducing a story of how ocean acidification is currently impacting the shellfish industry in the Pacific Northwest.

Throughout this curriculum, videos from interviews with hatchery personnel and scientists help tell the story of ocean acidification. They give students examples of ocean acidification's current impacts and provide a starting point to explore additional possible ecosystem and human impacts.

Avoiding Misconceptions

One goal of this curriculum is to avoid reinforcing student misconceptions about ocean acidification. In preparation for building this curriculum, existing teaching materials, published journal articles, interviews with ocean acidification "experts" (current ocean acidification researchers at Oregon State University), and public communications research were compared to uncover differences between how researchers discuss ocean acidification and how the public/teachers typically hear about the issue. Several common misconceptions were identified. This module attempts to avoid the following ocean acidification related common misconceptions:

- The ocean will become acidic (below pH = 7)
- The ocean will be inhospitable to all ocean life
- All shelled organisms will dissolve
- Ocean acidification only involves a decrease in pH
- CO_2 is natural, so it cannot be bad

Because of this conscious and active effort to avoid misconceptions, this curriculum avoids one of the most common demonstrations used to teach ocean acidification: putting shells/chalk (calcium carbonate) in vinegar or another acid and watching bubbles form. This is an engaging visualization; however, we believe it reinforces the idea that all shelled organisms and all life stages of shelled organisms will dissolve. While there is evidence of dissolution in some organisms, this does not seem to be the case across the board. Different life stages seem to exhibit different abilities to avoid dissolution and repair shells, with adults often showing increased resilience. Additionally, different organisms show varying susceptibility based on the composition of their shells (see day 3 Educator Background for more information). While these caveats can be explained to students, the researcher felt it would be best to find other ways to help students think through the possible impacts of ocean acidification. This “shells in acid” demonstration was used as part of a research project that accompanied the development of this curriculum, and survey data suggested a reinforcement of misunderstandings following this lab.

Misconceptions to Avoid in this Lesson

Misconception: Ocean Acidification Only Involves a Decrease in pH

While ocean acidification does cause a decrease in pH (an increase in the hydrogen ion concentration), several other characteristics of seawater chemistry also change simultaneously (see day 2, carbonate chemistry). Thus, ocean acidification is about more than just a change in pH.

Misconception: CO_2 is Natural, so it Cannot be Bad

Research conducted by FrameWorks Institute (Bales et al., 2015) focusing on how to talk about climate and ocean change revealed that many people see carbon dioxide as a natural part of life and assume natural things cannot also be a problem. It is important for students to realize that too much of anything, natural or unnatural, can throw a system out of balance. Making a distinction between natural and anthropogenic CO_2 seems to help people organize information that could otherwise conflict with how they think about the world.

LESSON 2- EDUCATOR BACKGROUND

The pH Scale

pH is a concept that is seemingly straightforward and familiar. Most individuals of the public have some notion of pH as a measure of “acidity.” Additionally, the pH of a solution is fairly easy to observe, just ask anyone with a pH test strip or a pool. However, pH is hard to measure accurately and precisely, and interpretation of pH values is complicated (Galster, 1991). There are multiple definitions of acids and bases, multiple pH scales, and pH measurements are sensitive to environmental conditions including temperature, salinity, and pressure. Furthermore, ocean acidification happens at the rate of 0.001 pH units/year, while almost all pH measuring instruments measure to 0.1 or 0.01 levels of accuracy, when properly calibrated. Also, the difference between commonly used pH scales is ~0.2, which is within the range of predicted changes in pH due to ocean acidification by 2100. Additionally, pH can naturally vary over 0.5 units in some marine systems over short time scales (hours to weeks). Thus, without precise measurements it is difficult to distinguish the small, persistent long-term trend (ocean acidification) from the larger short-term cycles. *This does not mean that ocean acidification is not happening; it simply means ocean acidification is hard to measure.*

Thus, while pH is a familiar concept, changes with the absorption of CO_2 into the ocean, and impacts some organisms directly, it might be more accurate to consider pH change as an indicator of larger ocean chemistry changes and possible organism responses rather than the driver of change.

Carbonate Chemistry

There are three major inorganic forms of dissolved carbon dioxide in seawater: free aqueous carbon dioxide (CO_2 (aq)), bicarbonate (HCO_3^-), and carbonate (CO_3^{2-})(Zeebe, 2012). These chemical species are known collectively as dissolved inorganic carbon or simply "DIC." When gaseous CO_2 is absorbed by the ocean, the concentration of dissolved CO_2 in seawater (pCO_2) increases. This dissolved carbon dioxide reacts with water molecules and undergoes a series of near-instantaneous, reversible equilibrium reactions:

$$CO_2 \text{ (g)} \leftrightarrow CO_2 \text{ (aq)}$$

$$CO_2 \text{ (aq)} + H_2O \leftrightarrow H_2CO_3$$

$$H_2CO_3 \leftrightarrow H^+ + HCO_3^-$$

$$H^+ + CO_3^{2-} \leftrightarrow HCO_3^-$$

Under today's oceanic conditions, bicarbonate (HCO_3^-) is favored, and when bicarbonate is formed through the dissociation of the carbonic acid (H_2CO_3), a hydrogen ion (H^+) is released. Since $pH = -\log[H^+]$, adding CO_2 to seawater increases the $[H^+]$, which can be described as "making it more acidic" or "decreasing the pH." However, the equations above do not make it clear that the reaction also consumes, instead of forms, carbonate ions (CO_3^{2-}) under typical oceanic conditions. A net chemical reaction helps clarify additional changes in the carbonate system:

$$CO_2 + H_2O + CO_3^{2-} \rightarrow 2HCO_3^-$$

By combining information from the first four equations into the net chemical reaction, we see that the overall result of the ocean absorbing CO_2 from the atmosphere is an increase in the pCO_2, $[H^+]$, $[CO_2 \text{ (aq)}]$, $[H_2CO_3]$, and $[HCO_3^-]$ and a decrease in pH and $[CO_3^{2-}]$.

Carbonate Saturation State

An additional concept of importance to marine calcifying organisms, those that build shells or hard parts out of calcium carbonate, is the carbonate saturation state (Ω, "omega"), which is defined as:

$$\Omega = [Ca^{2+}]\,[CO_3^{2-}] / K^*_{sp}$$

Carbonate saturation state is the product of the calcium ion concentration times the carbonate ion concentration divided by the apparent solubility constant (K^*_{sp}). Carbonate saturation states > 1 indicate conditions where solid calcium carbonate is thermodynamically favored while carbonate saturation states < 1 indicate thermodynamically unfavorable conditions for solid calcium carbonate. In other words, at $\Omega > 1$, shell formation is favored, and at $\Omega < 1$, shell formation is not favored (instead, dissolution is favored). This does not, however, say anything about the rate of reaction, and therefore, does not mean that shells immediately and completely dissolve when $\Omega < 1$.

A Complicated Experiment

Ultimately, it is worth keeping in mind that ocean acidification represents what could be considered a complicated experiment. As science teachers, we begin by teaching our students to design experiments so that only one variable changes. With ocean acidification, when CO_2 is added to seawater, carbon dioxide enters the carbonate system and at least six additional variables change at the same time. Thus, if a researcher were to try to simulate future surface ocean conditions by adding CO_2 to seawater, it would be difficult without careful controls of seawater chemistry to know if an organism that responds to a change was responding to the increase in CO_2, decrease in pH, decrease in Ω, or one of the other chemical changes that co-occurred when CO_2 was absorbed. Additionally, depending on the conditions of the seawater (temperature, salinity, pressure, total alkalinity, etc.) being tested, the amount of change in the carbonate system per unit CO_2 added would differ. This reality makes the scientific study of ocean acidification complicated, and in the mind of the author, much more exciting. It also, however, makes it difficult to reach conclusions about cause and effect when pH or pCO_2 are manipulated without controlling for and reporting other aspects of the carbonate system.

Seawater Chemistry Varies Naturally

In temperate coastal marine ecosystems, there can be large variation in seawater conditions over short time scales (hours to weeks). While there are several factors that contribute to fluctuations in coastal ecosystems, two processes are of primary importance in coastal ecosystems in the Pacific Northwest: net community metabolism (or the balance between photosynthesis and respiration) and seasonal upwelling.

The amount of natural variation in pH is not constant across the ocean (see Figure A.9 - pH variation by ecosystem.). Temperate kelp forests (e.g., the Pacific Northwest) have larger variation, tropical coral reefs (e.g., French Polynesia) are relatively stable throughout the year, and polar oceans show large variations during summer (peak productivity) and small variation in winter (when productivity decreases) (Kapsenberg et al., 2015).

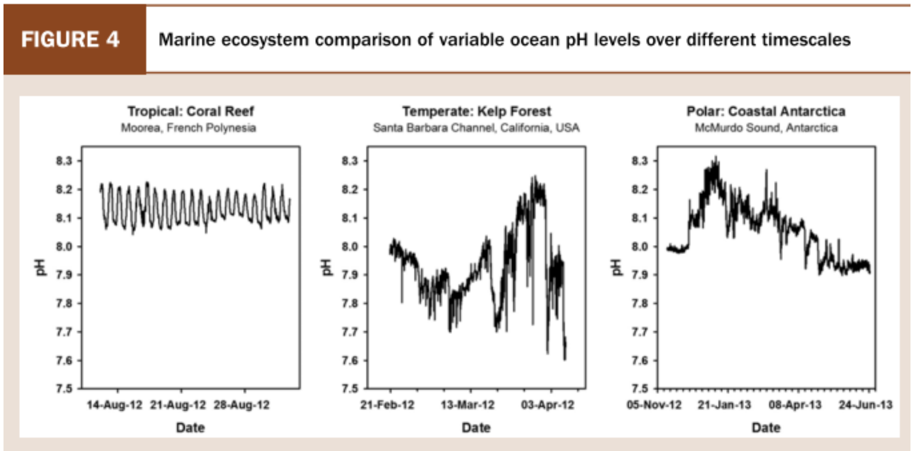


Figure A.9 - pH variation by ecosystem.
From: Kapsenberg et al. 2015. Exploring the complexity of ocean acidification: an ecosystem comparison of coastal pH variability. *Sci Scope*. November 2, pp. 51-60.

Net Community Metabolism

Net community metabolism describes the balance between photosynthesis and respiration. Photosynthesis and respiration are processes with opposite effects with respect to carbon dioxide. Photosynthesis removes CO_2 from seawater while respiration adds CO_2 to seawater:

$$\text{Photosynthesis (simplified): } CO_2 + H_2O \rightarrow CH_2O + O_2$$

$$\text{Respiration (simplified): } CH_2O + O_2 \rightarrow CO_2 + H_2O$$

Photosynthesis, however, only occurs during the daytime while respiration is continuous. Additionally, photosynthesis only occurs in the upper 50-200m, where sunlight is sufficient to fuel the process, while respiration occurs throughout the ocean. Measurements of water chemistry in areas with large populations of primary producers show pH levels fluctuations of 0.3-0.5 pH units over the course of a day (Kapsenberg et al., 2015), rising as photosynthesis removes CO_2 during daylight hours and falling overnight as respiration continues releasing CO_2 back into the environment.

Upwelling

Upwelling also contributes to seasonal changes in water conditions. In the Pacific Northwest, summer winds blow from the north, directing surface waters offshore. Cold, nutrient rich, deep water comes up from depths to replace the displaced surface water. This upwelled water has naturally elevated carbon dioxide levels because the water that upwells in Oregon has been below the surface for roughly 50 years (Richard a Feely, Sabine, Hernandez-Ayon, Ianson, & Hales, 2008). While the deeper waters were away from the surface, where CO_2 exchange and photosynthesis occurs, respiration continued adding CO_2 to the water.

Additionally, upwelling often triggers summer algal blooms. These blooms reduce CO_2 levels in the short term, creating temporary relief from decreased pH and Ω levels, but once the bloom dies, the organisms sink to the shelf and decompose, thus elevating CO_2 levels at depth.

LESSON 2- TEACHING NOTES

Data from Whiskey Creek Shellfish Hatchery in 2009 helps put the chemistry of ocean acidification into context. Students can see how pH and Ω co-vary, the pattern between larval success and Ω, and the impacts of photosynthesis and respiration on local water conditions over short time scales. Less intuitive is why small changes in ocean chemistry (ocean acidification) would matter given the context of widely varying oceanic conditions over shorter time scales (seasonal upwelling and net community metabolism). The key idea is that of changing baselines: while organisms in coastal ecosystems may be adapted to living in highly varying environments, ocean acidification adds a consistent downward trajectory to pH and Ω values. This longer-term trend could cause organisms to experience extreme conditions more often, beyond the conditions to which they've evolved. Additional impacts will be addressed in Day 3.

Adding CO_2 to Seawater Demo

The version of the demo included in this lesson is the author's favorite because it removes several possible factors that might lead students to unintended conclusions. It uses pure CO_2, setup is simple (attach a tube to the soda stream, add indicator to water), and connections to student's real life can be made (soda and other carbonated drinks contain CO_2, which is at least partially responsible for the drinks being acidic). Additionally, this lesson also reverses the reaction (raising the pH by adding a base). Most versions of this demonstration do not include this final step even though the reversibility of the reaction is a key concept that allows students to make connections to lessons on acid-base chemistry and helps explain the existing natural variation in pH.

Teachers might not have access to a Soda Stream, and many alternatives exist to show that adding CO_2 to water lowers the pH. All involve a way to observe pH change (indicators are most commonly used, but pH test strips and probes also work) and some way to add CO_2. Variations include:

- Blow through a straw into a beaker containing water and indicator (bromothymol blue).
    - The simplicity of this demo is wonderful. The potential confusion here is that many students do not realize that their breath is a mix of multiple gases. While this introduces a great teachable moment, it also requires students to trust that the thing in their breath that is changing the pH is the CO_2 and not one of the other gases. How do students know the O_2 in their breath isn't responsible for the pH change? Additionally, younger students may have a hard time controlling blowing vs. sucking on a straw and could accidentally inhale the indicator solution, which can be toxic. Some write ups recommend puncturing a hole in the straw to avoid this.
- Add dry ice (solid CO_2) to a beaker with water and indicator.
    - This demo has the excitement of bubbling dry ice, and an opportunity to talk about sublimation (going from solid to gas). Complications with this experiment are obtaining dry ice and maintaining lab safety (gas pressure from dry ice can build quickly and cause explosions in closed containers). Dry ice is often available at grocery stores, but it is not always convenient to acquire the day you need it. Using a Soda Stream, in the author's mind, seems like an easier up-front purchase that allows for demonstrations whenever needed, as opposed to day-of purchasing of materials.
- Use a CO_2 bike pump instead of a Soda Stream.
    - These are cheaper and smaller than a Soda Stream; however, slightly more work is required to connect the tubing to the pump. If you have the right parts, setup and use seem simple.
- Burn a candle and transfer CO_2 generated to a separate beaker filled with indicator.
    - This makes a great connection between combustion of fossil fuels releasing CO_2 and changing ocean pH. However, the setup is more involved and, like blowing through a straw, it relies on students trusting that combustion releases CO_2 and that this CO_2 is

the cause for the pH change. This might be a great extension for students to synthesize several concepts learned throughout this curriculum.

- Mix baking soda and vinegar and capture the CO_2 generated.
    - This simple setup allows students to quickly and safely generate CO_2 through a reaction they are already familiar with (but may not have previously known which gas is generated in the process). A variation of this method involves using TUMS.
- Use alternate indicators, pH test strips, or pH probes
    - Any indicator in the range of pH 5-9 should work for this demo. In the author's opinion, universal indicator works better than bromothymol blue because the former includes a wider range of colors and therefore it is easier to show pH changes in both directions; however, universal indicator is slightly less common in school laboratories. You can make an indicator out of red cabbage, although this process can be time intensive and a bit smelly. Additionally, if you have pH probes or test strips in your lab, these work, too. Ultimately, you just need a way to show that the pH changed.

Misconceptions to Avoid in this Lesson

Students could conclude that the decreased pH dissolved larval oyster shells, killing larval oysters. In reality, the situation was a bit more complicated. Larval oysters rely on egg energy reserves when building their first shell. There is essentially a 6-hour window in which larvae need to create their shells. If they are unable to do so, they die. With acidification, the decrease in saturation state causes larvae to expend more of their initial energy reserves in the shell building phase. Some larvae do not complete their shell within the allotted time and perish. Those that do make the 6-hour time window finish with lower energy reserves, which impacts subsequent growth and development. Thus, for larval oysters, ocean acidification creates an energy bottleneck; it does not directly dissolve their shells.

LESSON 3- EDUCATOR BACKGROUND

There are thousands of papers, meta-analyses (papers that synthesize findings from many papers on the same subject), and white papers (non-peer reviewed documents, usually written by government agencies or non-profits) looking at the possible impacts of ocean acidification. Most of the experiments described in the literature are short-term (days to weeks) laboratory experiments where organisms are exposed to elevated CO_2/low pH conditions. Not surprisingly, results vary depending on the organism used, developmental life history stage of organisms, experimental conditions, and research methods. Early experiments often exposed organisms to extreme conditions well beyond what would be expected in the coming decades to century (Browman, 2016). When these studies showed negative impacts, results were extrapolated to suggest that ocean acidification was an impending ocean calamity. As research continues, there are more reports on the nuances of responses to ocean acidification, and very recently (2016), there has been an increased effort to publish results showing little to no impact to help round out our understanding (Browman, 2016).

While it is easy to get lost in the research literature, some generalizations are clear:

- There will be winners and losers. Calcifiers (organisms that build calcium carbonate skeletons and hard parts) and organisms that are less able to regulate internal body chemistry will likely be more severely impacted by ocean acidification (Kroeker et al., 2013). In contrast, it seems that some macroalgae, phytoplankton, and seagrasses may actually benefit from increases in CO_2 concentrations (R. Feely, Klinger, Newton, & Chadsey, 2012). However, this benefit will likely depend on availability of other limiting nutrients and will vary by species.
- Ocean acidification has differing impacts on different life stages. Experiments in Pacific Northwest hatcheries helped show that some life stages (e.g., young larvae) are extremely susceptible to carbonate chemistry while other life stages (adults) seem largely resistant to these chemical changes. While larval stages of some organisms do appear susceptible to ocean acidification, in other instances with different organisms, larvae show no response to acidification. This is equally true for adults.
- Ocean acidification has impacts beyond calcification and shell building. Other documented responses include changes in: growth, reproduction, survival, energy use, predator detection, hearing, and other behavioral changes.
- It is difficult to study the effects of ocean acidification in the field and within ecosystems (in contrast to single organism laboratory studies). Currently, in instances where field measurements exist, data sets are often too short to allow for conclusions on whether there are changes over time. Even if changes are observed, it will be hard to determine whether they are due to ocean acidification or some other environmental change or stressor (e.g., temperature, nutrients, human use, etc.).

- Ocean acidification is not happening in isolation. While scientists study ocean acidification, the oceans are also warming, decreasing in oxygen, rising, being polluted, and some species are being overharvested. These multiple problems can have effects that intersect, building on each other or partially cancelling out effects.
- The impacts of co-occurring stressors (e.g., increasing temperatures and ocean acidification) are contentious and difficult to accurately study. For example, some studies suggest ocean acidification accelerates coral bleaching, a phenomenon primarily related to seawater temperature, while other studies suggest there is no impact of elevated CO_2 on bleaching events, at least down to pH 7.5 (Cooley, Mathis, Yates, & Turley, 2012).
- Short-term (days to weeks) studies are largely unable to comment on longer scale (decades) changes because they provide little to no insight on whether organisms will be able to acclimate (get used to changes in ocean chemistry), adapt (undergo genetic changes due to natural selection allowing them to survive under new conditions), or go extinct. There is some evidence that, depending on the context, organisms could respond in one or more of these ways (acclimation, adaptation, extinction).

LESSON 3- TEACHING NOTES

This lesson makes an explicit choice to avoid an overtly crisis tone when discussing the possible effects of ocean acidification. Instead of listing all possible impacts or confusing students with lists of conflicting findings, this lesson has students explore some of the many possible responses to ocean acidification. It introduces some uncertainty to show students that there are still unknowns. The overall message is that marine ecosystems consist of many interconnected pieces. Students consider how changes to one organism could impact other organisms in the ecosystem and the people who rely on the ocean. Extinction is not the only possible response to ecosystem change. It is, however, an intuitive response for many students. Hopefully students walk away from this lesson understanding that it appears that ocean acidification will create largely negative changes in marine ecosystems; we just don’t know exactly what these changes will be or what they will mean for humans.

Misconceptions to Avoid for this Lesson

- The oceans will become inhospitable to all life

- All organisms will be negatively impacted by ocean acidification
- Ocean acidification does not impact humans

LESSON 4- EDUCATOR BACKGROUND

With changing water chemistry already impacting the US. West Coast shellfish industry (Barton et al., 2015) and field samples revealing severe dissolution in pteropods in the California Current System (Manno et al., 2017), the notion that ocean acidification is a future problem that will begin to show impacts in 50-100 years appears outdated, at least in ocean acidification hotspots.

Discussing Solutions to Inspire Action

Upon hearing about ocean acidification for the first time, many students will likely ask or wonder, "is there anything that can be done about it?" Some research suggests that when individuals hear of an environmental problem, but do not hear of any solutions, they fill in the gap and conclude that there is little that can be done to address the problem (Bales et al., 2015). Other theories of psychological coping behavior suggest that for individuals to take action to fix a problem (called problem-focused coping), they must think there is a problem and there is something they can do to fix the problem. In contrast, if they don't think they can control the threat, they will respond with emotion-focused coping strategies, which seek to reduce one's feelings through responses such as denying, ignoring, or dismissing the threat. This final day of the module argues that there are things that students can do to reduce ocean acidification. The challenge is to present solutions that seem within a high school student's locus of control while also encouraging collective actions that could lead to broader impacts.

The primary cause of ocean acidification is anthropogenic carbon dioxide emissions. Thus, solutions to ocean acidification, meaning actions that could be taken to reduce ocean acidification, should focus on reducing anthropogenic CO_2 emissions and/or removing CO_2 from the ocean/atmosphere. Many students have already heard of ways to reduce human CO_2 emissions. When they are reminded that anthropogenic CO_2 is the primary cause of ocean acidification, students are able to brainstorm possible actions. Many of these actions, however, are either outside of their immediate control (e.g., regulating industry, increasing government funding) or they are low impact actions that would do little to decreases the amount of anthropogenic CO_2 emitted (e.g., planting one tree). Research suggests the public does not know which actions would best reduce their home energy use (Attari et al., 2010; Gardner & Stern, 2008). This suggests that to attain meaningful reductions in energy use and fossil fuel consumption, individuals need better awareness of the payoffs of different actions not just that actions would reduce energy/fossil fuel consumption.

The question switches from "what could be done to reduce anthropogenic CO_2 emissions" to "what would be the most effective actions for us to take to reduce our CO_2 emissions?" While national policy efforts and technological advancements would certainly help reduce anthropogenic CO_2 emissions, these often take decades to fully implement. Research from the field of conservation psychology has identified household actions that could be taken today, many at little or no cost, that could reduce household energy consumption by up to 30%, or 11% of total U.S. energy consumption (Dietz, Gardner, Gilligan, Stern, & Vandenbergh, 2009; Gardner & Stern, 2008; Stern, Dietz, Gardner, Gilligan, & Vandenbergh, 2010).

Seagrass Restoration as Possible Mitigation

In addition to increasing energy efficiency and decreasing consumption, other actions are being discussed that could be taken to remove CO_2 from the ocean and atmosphere. One idea that holds promise but still requires testing is that of seagrass and kelp restoration (See Oregon Field Guide's 8-minute video, "A Greener Future for Oysters?" http://tinyurl.com/y9p7oz3t). We know that photosynthesizers like seagrass and kelp take in CO_2 during the day. In theory, these organisms could help reduce the amount of CO_2 in the ocean through an increase in photosynthetic biomass. This could potentially improve local water chemistry in seasonal to multiyear timescales (Cooley et al., 2012). This idea is similar, but not identical, to the notion of Blue Carbon, which seeks to capture carbon in plants. Both ideas hinge on a few key factors. For example, would the daytime decrease in CO_2 be more beneficial than the likely increase in daily variation (areas with vegetation see greater daily cycles in pH/CO_2 than comparable areas without substantial vegetation)? How do plant life cycles impact restoration benefits? If a plant dies in the same season it was planted/created, the net CO_2 removal would be 0. Thus, longer living plants, like some seagrasses and kelps, seem to have potential to help with local water chemistry, but these results are tentative (Smith, 2016).

Ocean Buffering with Chemicals

When discussing ways to reduce the impacts of ocean acidification, the notion that the ocean could be buffered through the addition of chemicals is sometimes raised. This idea makes some intuitive sense: the ocean is naturally buffered over hundreds of thousands of years through a balance of volcanism and weathering, and hatcheries can improve conditions by buffering seawater with soda ash (sodium carbonate). Unfortunately, it would take vast amounts of calcium carbonate (limestone) to buffer the global ocean. In fact, for an annual application to buffer global ocean pH, it would require more than 30x the limestone currently mined by humans (Cooley et al., 2012). This increased level of mining is likely unachievable and would certainly involve substantial carbon dioxide emissions of its own.

Reducing Additional Environmental Stressors

Another area of potential for ocean acidification mitigation is to address other co-stressors (pollution, deoxygenation, temperature increases, etc.). In some locations, runoff from sewers and farms adds excess nutrients to waterways, including estuaries. These nutrients cause eutrophication, or excessive growth of aquatic plants due to nutrient enrichment. The initial result is to stimulate phytoplankton and algal growth, which temporarily reduces CO_2 levels; however, these blooms die within a few weeks. When they die, the organisms sink and decompose. This decomposition releases CO_2 into the water and reduces O_2 levels. When blooms occur in shallow waters, acidification and hypoxia can be considerable. Thus, in places where runoff is substantial, tackling runoff and eutrophication can improve local water quality and reduce ocean acidification.

LESSON 4- TEACHING NOTES

Most teaching resources on ocean acidification do not fully engage students in thinking about solutions to the problem. Of the few that do address solutions, often students are asked to brainstorm ways to reduce emissions for 5-10 minutes at the end of a lesson, and occasionally they are told to use a carbon footprint calculator to see how much they could reduce. In contrast, this curriculum attempts to make students think more critically about actions to reduce CO_2 emissions. It tries to have students evaluate the impact of various actions and consider what might prevent people from taking action (it isn't just about whether someone "cares" about the problem). The Call to Action project allows students to try to persuade whoever they think should do more to take action on OA while simultaneously cementing their own understanding.

ADDITIONAL READING:

There are many sources of information on ocean acidification available. We find the following two resources especially helpful:

> Cooley, S.R. et al., 2012. Frequently Asked Questions about Ocean Acidification. *US Ocean Carbon and Biogeochemistry Program and the UK Ocean Acidification Research Programme. Version 2*, p.28.
>
> Washington State Blue Ribbon Panel on Ocean Acidification, 2012. *Ocean Acidification: From Knowledge to Action, Washington State's Strategic Response.* H. Adelsman & L. W. Binder, eds., Olympia, WA: Washington Department of Ecology.

STANDARDS ADDRESSED

NEXT GENERATION SCIENCE STANDARDS

Performance Expectations

HS-ESS2-6. Develop a quantitative model to describe the cycling of carbon among the hydrosphere, atmosphere, geosphere, and biosphere.

HS-ESS3-4. Evaluate or refine a technological solution that reduces impacts of human activities on natural systems.

HS-LS2-6. Evaluate the claims, evidence, and reasoning that the complex interactions in ecosystems maintain relatively consistent numbers and types of organisms in stable conditions, but changing conditions may result in a new ecosystem.

HS-LS2-7. Design, evaluate, and refine a solution for reducing the impacts of human activities on the environment and biodiversity.

Science and Engineering Practices

Constructing Explanations and Designing Solutions

- Design, evaluate, and refine a solution to a complex real-world problem, based on scientific knowledge, student-generated sources of evidence, prioritized criteria, and tradeoff considerations. (HS-LS2-7), (HS-ESS3-4)

Engaging in Argument from Evidence

- Evaluate the claims, evidence, and reasoning behind currently accepted explanations or solutions to determine the merits of arguments. (HS-LS2-6)
- Construct an oral and written argument or counterarguments based on data and evidence. (HS-ESS2-7)

Disciplinary Core Ideas

ESS2.D: Weather and Climate

- Changes in the atmosphere due to human activity have increased carbon dioxide concentrations and thus affect climate. (HS-ESS2-6)

Crosscutting Concepts

Cause and Effect

- Empirical evidence is required to differentiate between cause and correlation and make claims about specific causes and effects. (HS-LS2-8), (HS-LS4-6)

Stability and Change

- Much of science deals with constructing explanations of how things change and how they remain stable. (HS-LS2-6), (HS-LS2-7)

COMMON CORE STANDARDS

9-10.RST.1. Cite specific textual evidence to support analysis of science and technical texts, attending to the precise details of explanations or descriptions.

9-10.RST.2. Determine the central ideas or conclusions of a text; trace the text's explanations or depiction of a complex process, phenomenon, or concept; provide an accurate summary of the text.

9-10.SL.1. Initiate and participate effectively in a range of collaborative discussions (one-on-one, in groups, and teacher-led) with diverse partners on grades 9–10 topics, texts, and issues, building on others' ideas and expressing their own clearly and persuasively.

9-10.WHST.10. Write routinely over extended time frames (time for reflection and revision) and shorter time frames (a single sitting or a day or two) for a range of discipline specific-tasks, purposes, and audiences.

OCEAN LITERACY PRINCIPLES

6. The ocean and humans are inextricably interconnected.

- **B.** The ocean provides food, medicines, and mineral and energy resources. It supports jobs and national economies, serves as a highway for transportation of goods and people, and plays a role in national security.
- **D.** 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 leads to pollution (point source, non-point source, and noise pollution) changes to ocean chemistry (ocean acidification), and physical modifications (changes to beaches, shores, and rivers). In addition, humans have removed most of the large vertebrates from the ocean.
- **E.** Changes in ocean temperature and pH due to human activities can affect the survival of some organisms and impact biological diversity (coral bleaching due to increased temperature and inhibition of shell formation due to ocean acidification).
- **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 collection actions are needed to effectively manage ocean resources for all.

OREGON ENVIRONMENTAL LITERACY STRANDS

1 Systems thinking. Students study systems and issues holistically, striving to understand the relationships and interactions between each system's parts. They use the knowledge gained to assess the effects of human choices on economic, ecological, and social systems, and to optimize outcomes for all three systems.

B. Habits of systems thinking. Understand the habits of systems thinking, and identify opportunities to apply them.

- Recognize the impact of time delays on cause-and-effect relationships.
- Consider short- and long-term consequences of actions.
- Notice how system elements change over time, generating patterns and trends.
- Identify where unintended consequences emerge.

C. Strategic responsibilities of systems thinking. Apply the habits and techniques of systems thinking to decision-making.

- Explain how human action or inaction affects the systems in which we live.
- Consider the effects of human choices on economic, ecological, and social systems.

3 Interconnectedness of people and the Environment. Students understand the interdependence of humans and the environment, and appreciate the interconnectedness of environmental quality and human well-being.

B. Interrelationships between the environment and human activities. Analyze how environmental changes affect human systems; how human activities and systems change the environment; and the connection between environmental quality and human well-being.

- Analyze how environmental changes affect political, social, cultural, economic and health systems.
- Analyze how human activities and systems change Earth's physical systems (e.g., atmosphere, ocean, climate, soil, landforms) and living systems (e.g., ecosystems, biodiversity, carrying capacity).

5 Investigate, plan, and create a sustainable future. Students apply civic action skills that are essential to healthy, sustainable environments and communities.

D. Demonstrate effective decision-making and citizen action. Analyze options, plan actions, evaluate outcomes, and reach evidence-based conclusions.

Evaluate the need for action:

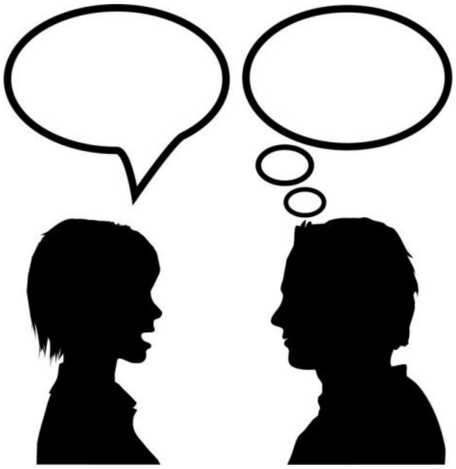
- Decide whether action is warranted, based on available evidence about the issue and proposed solutions; the scale of the concern; the legal, social, economic, and ecological consequences; and alternatives to citizen action.

- Identify options for citizen action, including consumer choices; resource use choices; writing letters to the editor; drafting legislation, ordinances, or policies; environmental stewardship projects; and communicating with decision-makers.
- Speculate on the probable effects of specific actions and the likelihood that they will resolve the problem.
- Decide whether to take personal action, based on their own values, skills, resources, and commitments.

APPENDIX B: Student Handouts

Name: *Lesson 1- What is ocean acidification?*

Period:



Students in Mrs. James' class are discussing ocean acidification. They have different ideas on what causes it.

James: I think ocean acidification is caused by litter in the ocean.

Tonya: I think ocean acidification is caused by chemicals spilling into the ocean.

Leslie: I think ocean acidification is caused by carbon emissions from cars.

Mark: I think ocean acidification is caused by animals breathing.

Jessica: I think ocean acidification is caused by acid rain.

Which student do you agree with? ________________________ Explain why you agree with this student and disagree with the others.

____

____

____

____

____

____

____

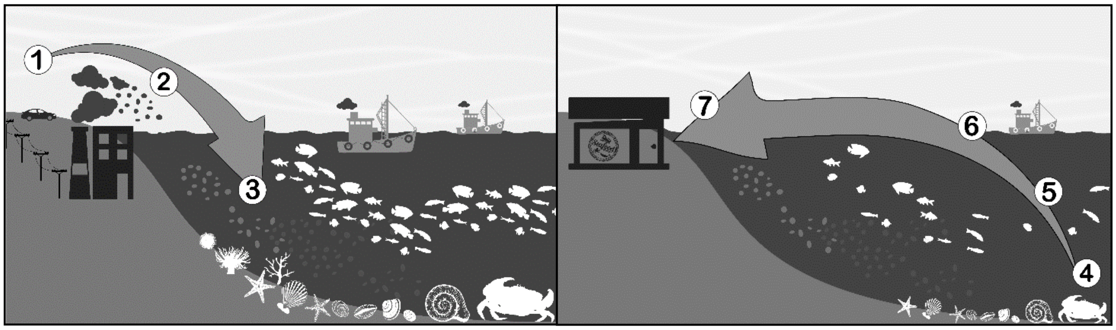
____

VIDEO QUESTIONS: POSTCARD FROM THE OREGON COAST

1. What do they grow at Mark & Sue’s hatchery?
2. What happened at the hatchery in 2007
3. Why does ocean acidification affect baby oysters?
4. How often are conditions currently favorable for shell formation?
5. How might this change in the future?

POST-VIDEO QUESTION:

6. Nearly 70% of oyster farms along the US West Coast rely on Mark & Sue for their baby oysters. What could happen to these farmers, and the restaurants they supply, if Mark and Sue’s hatchery cannot cope with ocean acidification?



OCEAN ACIDIFICATION EXPLAINED

The Process:

1. Human activities ____________________ CO_2.
2. The ocean _____________________ ~25% of anthropogenic CO_2.
3. Ocean chemistry ________________________.

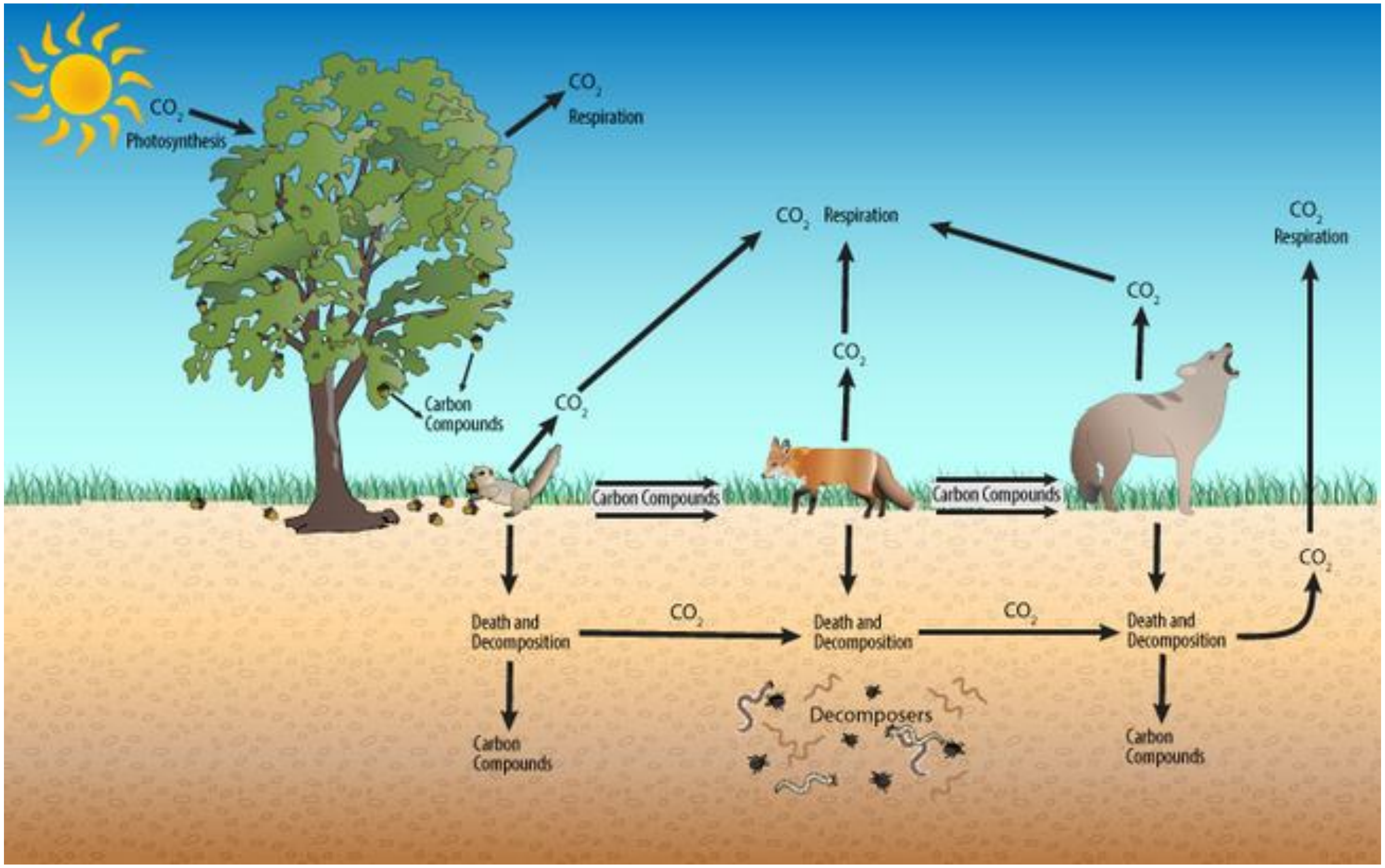
An example:

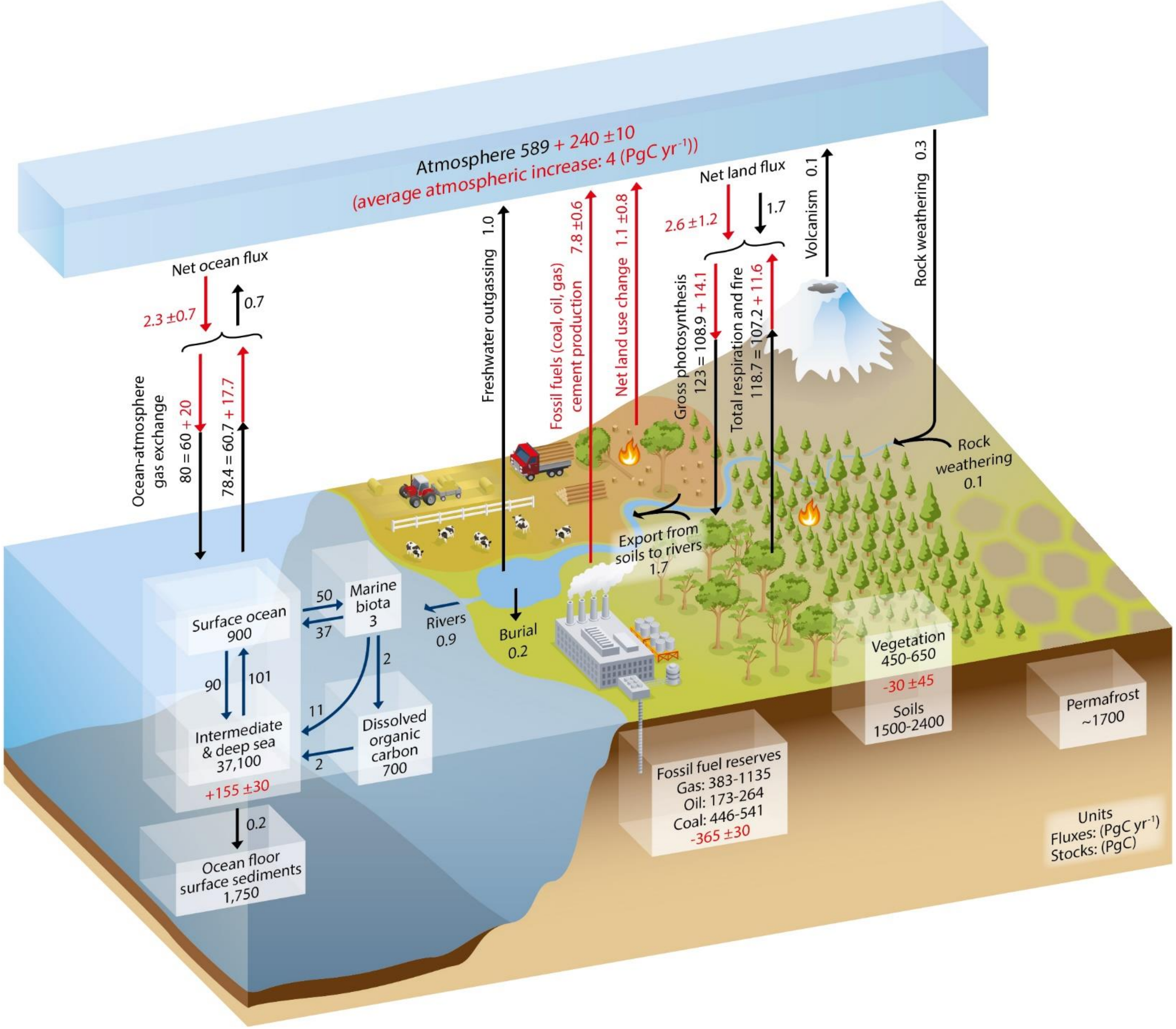
4. Carbonate, used for shell building, becomes less available. It takes _________________________ to make shells, leading to _____________________ & ___________________ shellfish.
5. Shellfish filter water. Fewer shellfish could lead to _______________________________________. Cloudy water makes it harder for seagrasses to do photosynthesis. Seagrass beds are important habitat for young fish.
6. Less seagrass could mean _____________________________ to catch.
7. This could impact humans who rely on fish for food & jobs.

KEY TERMS:

Ocean acidification: ____
____

Anthropogenic: ____


CO_2
Photosynthesis
CO_2
Respiration
Carbon Compounds
CO_2
CO_2 Respiration
CO_2
CO_2
CO_2
Respiration
Carbon Compounds
Carbon Compounds
CO_2
Death and Decomposition
CO_2
Death and Decomposition
CO_2
Death and Decomposition
Carbon Compounds
Decomposers
Carbon Compounds


Atmosphere 589 + 240 ±10
(average atmospheric increase: 4 (PgC yr^{-1}))
Net ocean flux
2.3 ±0.7
0.7
Ocean-atmosphere gas exchange
80 = 60 + 20
78.4 = 60.7 + 17.7
Freshwater outgassing 1.0
Fossil fuels (coal, oil, gas) cement production 7.8 ±0.6
Net land use change 1.1 ±0.8
Net land flux
2.6 ±1.2
1.7
Gross photosynthesis 123 = 108.9 + 14.1
Total respiration and fire 118.7 = 107.2 + 11.6
Volcanism 0.1
Rock weathering 0.3
Rock weathering 0.1
Export from soils to rivers 1.7
Surface ocean 900
50
37
Marine biota 3
Rivers 0.9
Burial 0.2
90
101
2
11
Intermediate & deep sea 37,100
+155 ±30
Dissolved organic carbon 700
2
0.2
Ocean floor surface sediments 1,750
Vegetation 450-650
-30 ±45
Soils 1500-2400
Permafrost ~1700
Fossil fuel reserves
Gas: 383-1135
Oil: 173-264
Coal: 446-541
-365 ±30
Units
Fluxes: (PgC yr^{-1})
Stocks: (PgC)

Name: *Lesson 1-Homework*

Period:

PART 1: SEEING CHANGES IN AN INVISIBLE GAS

Watch: NASA A year in the Life of Earth's CO_2 (https://youtu.be/x1SgmFa0r04)

1. Describe what happened in the simulation to carbon dioxide over the course of a year. How did it change? Why did it change?

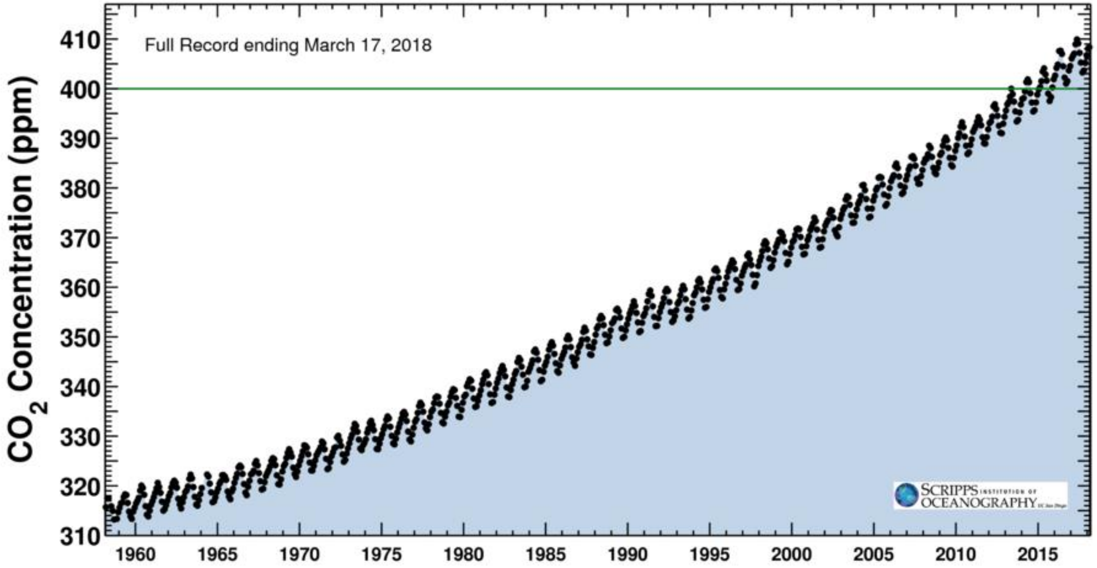
PART 2: INTERPRETING GRAPHS

Use the three graphs on the next page to help answer questions 2-5.

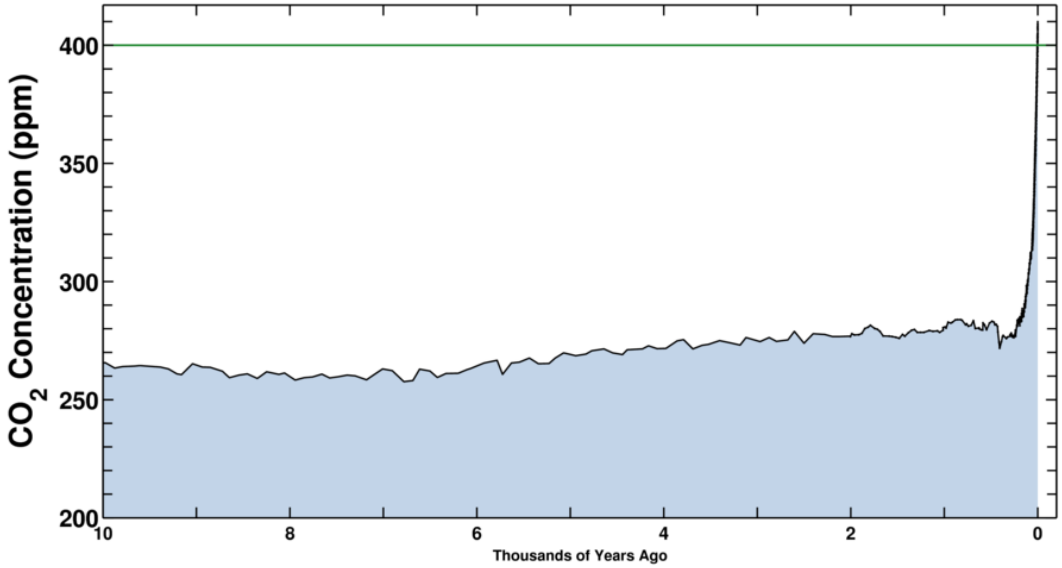
2. What is shown on the y-axis for each graph? How is the range of values on each graph?

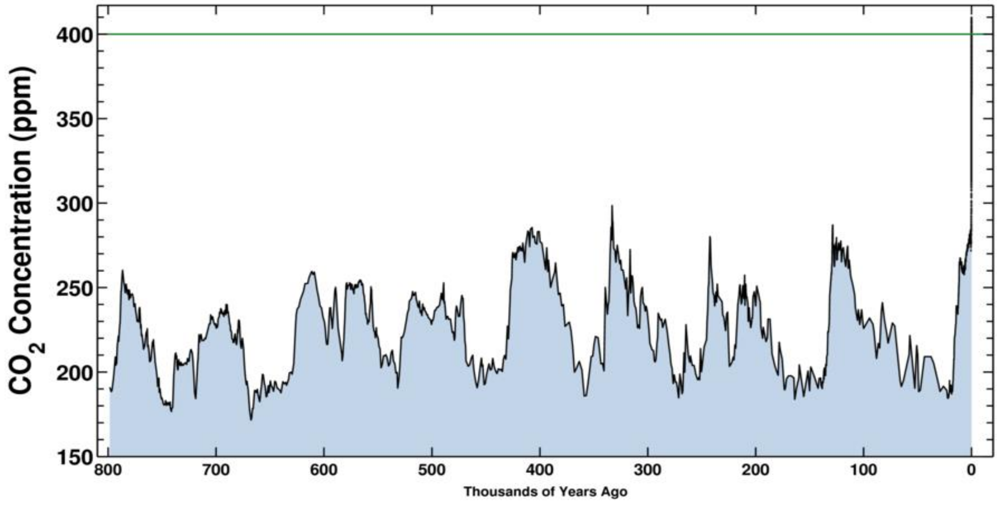
3. What is shown on the x-axis? How does this measure vary between graphs?

Carbon dioxide concentration at Mauna Loa Observatory



Ice-core data before 1958. Mauna Loa data after 1958.





4. Describe what you observe in each graph. Do you see any patterns or trends?
    a. Top graph-

    b. Middle graph-

    c. Bottom graph-

5. How does the time scale shown (60 years, 10,000 years, 800,000 years) influence the conclusions you would make about CO_2 in Earth's atmosphere?

PART 3: FINAL SYNTHESIS QUESTIONS

6. What parts of the simulation and graphs could be used as evidence for natural variation in atmospheric CO_2 levels?

7. What parts of the simulation and graphs could be used as evidence for human-caused (anthropogenic) variation in atmospheric CO_2 level

Name: *Lesson 2, part 1- Chemistry of OA*

Period:

DEMO: CO_2 IN WATER

Describe what happened to the pH of water throughout the demonstration. Try to incorporate the following vocabulary: acidic, basic, carbon dioxide, pH.

DEFINING ACIDS AND BASES

There are multiple definitions of acids and bases. Record how we are defining acids and based below.

Acids:

Bases:

Complete the following equation.

$CH_3COOH \rightleftharpoons$ _____________ + _____________

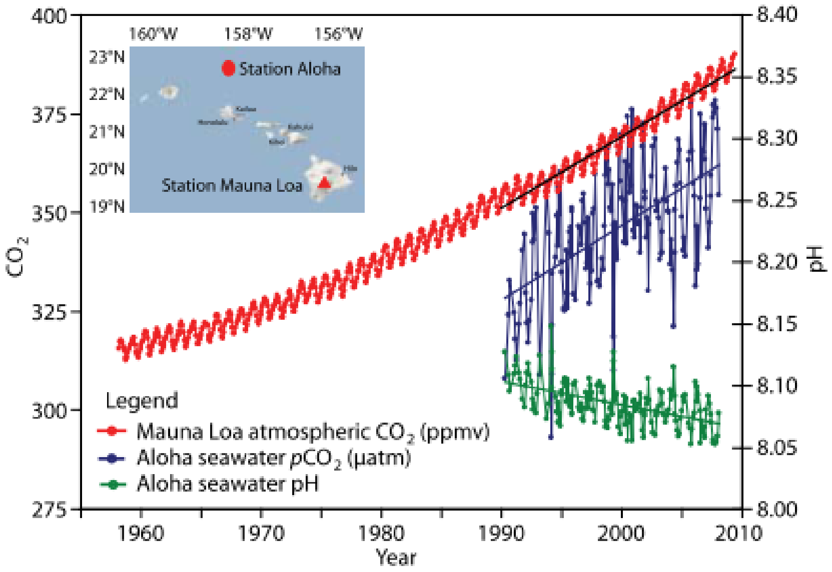
(Vinegar)

(Acetic acid)

HOW DOES EXTRA CO_2 IN THE ATMOSPHERE LEAD TO OCEAN ACIDIFICATION?

Chemical equations	Describe, in words, what the equation says:
1. $CO_2\ (g) \leftrightarrow CO_2\ (aq)$	
2. $CO_2 + H_2O \leftrightarrow H_2CO_3$ (Carbonic acid)	
3. $H_2CO_3 \leftrightarrow$ ________ + ______________	

Using the graph below, discuss the following questions with your partner:



1. In what ways does this graph connect to the equations above?

2. How does the SodaStream demo connect with this graph and the equations?

3. Look at the pH values on the graph. Is seawater currently acidic, neutral, or basic?

4. Scientists predict an average ocean pH of 7.8-7.9 by 2100. Will the ocean be acidic then?

5. Considering your answers to #3-4, why do you think we call it ocean acidification?

ONLINE ACTIVITY: ON THE MOLECULAR LEVEL, WHAT IS THE DIFFERENCE BETWEEN ACIDS AND BASES?

Procedure:

1. Access the simulation by going to: http://tinyurl.com/mc4m4b3/
2. Watch this video to orient you to this lesson: http://tinyurl.com/y7cbqee3
3. You'll begin by working in the Micro section. Double click on the Micro tab.

As the video shows, follow these steps:

4. Choose 1 chemical (coffee, for example).
5. Write down the pH, the [H_3O^+] and the [OH^-] in your data table (next page).
    - *Remember: [brackets] means "concentration."*
6. With a calculator, multiply those numbers together. Write down your data.
7. Make a dilute solution of your chemical (i.e., add water). Repeat steps 5 and 6.
8. Repeat this process for 3 more chemicals (a total of 4 different chemicals) and their dilutions.
9. Finally, add a ninth row to your table… Repeat steps 1-4 for pure water.

After you have completed steps 4-9 for a total of 4 chemicals (coffee plus 3 additional ones), answer the questions below:

1. Describe the difference between an acid and a base on the molecular level.

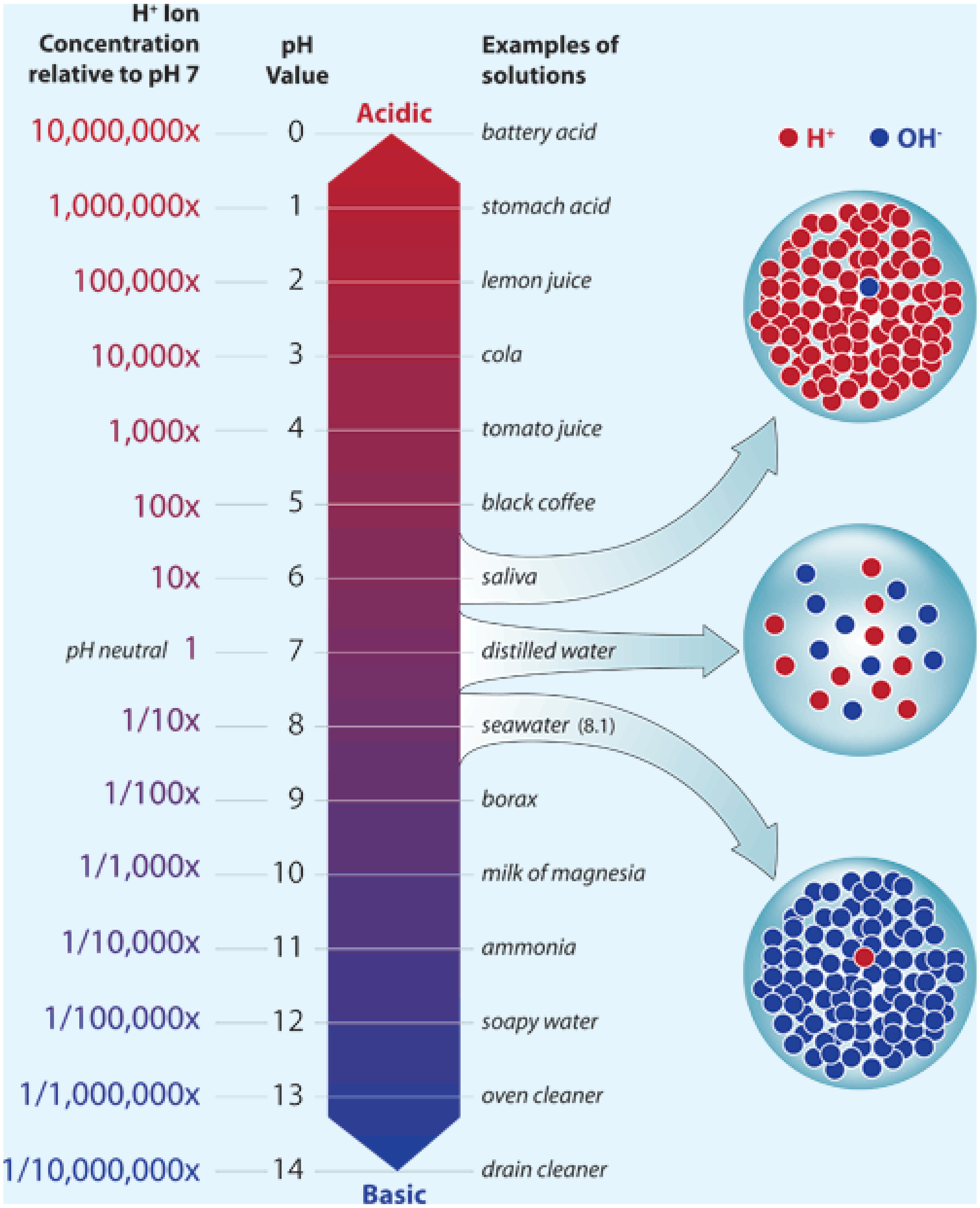
2. What is the product of [H_3O^+] x [OH^-]?

3. What happens to pH as [H_3O^+] increases? Decreases?

4. What happens to pH as [OH^-] increases? Decreases?

5. What do you notice about the relationship between [H_3O^+], [OH^-], and pH for pure water?

6. Examine the image on the next page. Based on this image and what you learned from the online simulation, describe the relationship between pH and H^+ concentration:


H+ Ion Concentration relative to pH 7
pH Value
Examples of solutions
Acidic
Basic
● H+
● OH-
10,000,000x
1,000,000x
100,000x
10,000x
1,000x
100x
10x
pH neutral 1
1/10x
1/100x
1/1,000x
1/10,000x
1/100,000x
1/1,000,000x
1/10,000,000x
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
battery acid
stomach acid
lemon juice
cola
tomato juice
black coffee
saliva
distilled water
seawater (8.1)
borax
milk of magnesia
ammonia
soapy water
oven cleaner
drain cleaner

Chemical	**pH**	**H_3O^+ Count**	**OH^- Count**	**Product of $[H_3O^+] \times [OH^-]$**
Coffee				
Dilute coffee				
Pure water				

Name: *Lesson 2, part 2- Chemistry of OA*

Period:

DEMO: FLOATING CANDLES

1. Explain with pictures and words what happened in this demo? In what ways does it show ocean acidification? In what ways is it different from ocean acidification?

OCEAN ACIDIFICATION CHEMICAL REACTIONS

Name	Chemical Formula
Carbonic Acid	H_2CO_3
Bicarbonate	HCO_3^-
Carbonate	CO_3^{2-}

2. Compare the molecules in the table above. What do you notice?

3. Fill in the blanks below:

$$CO_2\ (g) \leftrightarrow CO_2\ (aq)$$

$$CO_2\ (aq) + H_2O \leftrightarrow \underline{\hspace{4cm}}$$

$$H_2CO_3 \leftrightarrow \underline{\hspace{4cm}} + HCO_3^{2-}$$

There's another reaction that happens due to ocean acidification:

$$H^+ + CO_3^{2-} \leftrightarrow \underline{\hspace{5cm}}$$

4. What does this suggest happens to the $[CO_3^{2-}]$?

WHAT IS HAPPENING TO WHISKEY CREEK SHELLFISH HATCHERY'S WATER?

We have introduced several concepts over the past few days. Each of these influences the water chemistry. We are now going to use real water quality data that was collected at Mark & Sue's shellfish hatchery (named Whiskey Creek) in 2009, and we are going to try to figure out why ocean acidification was blamed for the die-offs.

5. In the table below, summarize what we've learned about ocean acidification by circling the word the describes how each measure changes.

Measure	How it changes
$[H^+]$ "hydrogen ion concentration"	Increase or Decrease?
pH	Increase or Decrease?
$[CO_3^{2-}]$ "carbonate ion concentration"	Increase or Decrease?

The equation below shows a simplified formula for photosynthesis:

$$CO_2 + H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2$$

"carbon dioxide + water forms glucose (sugar) + oxygen"

6. Based on the equation above, would photosynthesis by aquatic plants cause the concentration of carbon dioxide in the water to increase or decrease? Explain.

7. What would this change in $[CO_2]$ do to the water's pH? Explain.

8. During what time of day would you expect plant and phytoplankton photosynthesis to influence the $[CO_2]$ and pH of seawater? *Hint: When does photosynthesis occur?*

The equation below shows a simplified formula for respiration:

$$C_6H_{12}O_6 + 6O_2 \rightarrow CO_2 + H_2O$$

"glucose (sugar) + oxygen forms carbon dioxide + water"

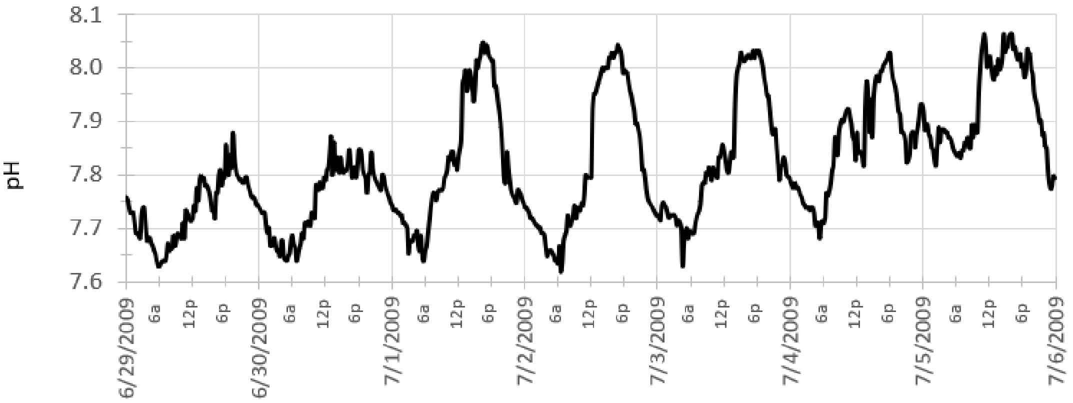
9. Based on the equation above, would respiration cause the [CO_2] to increase or decrease? Explain.

10. What would this change in [CO_2] do to the water's pH? Explain. *Hint- think about the Soda Stream demo*.

11. What types of organisms carry out respiration?

12. During what time of day does respiration occur?

The graph below shows pH at Whiskey Creek Shellfish Hatchery over the course of one week in July 2009. Use the graph to answer the questions that follow:



13. What patterns/trends do you notice in this data?

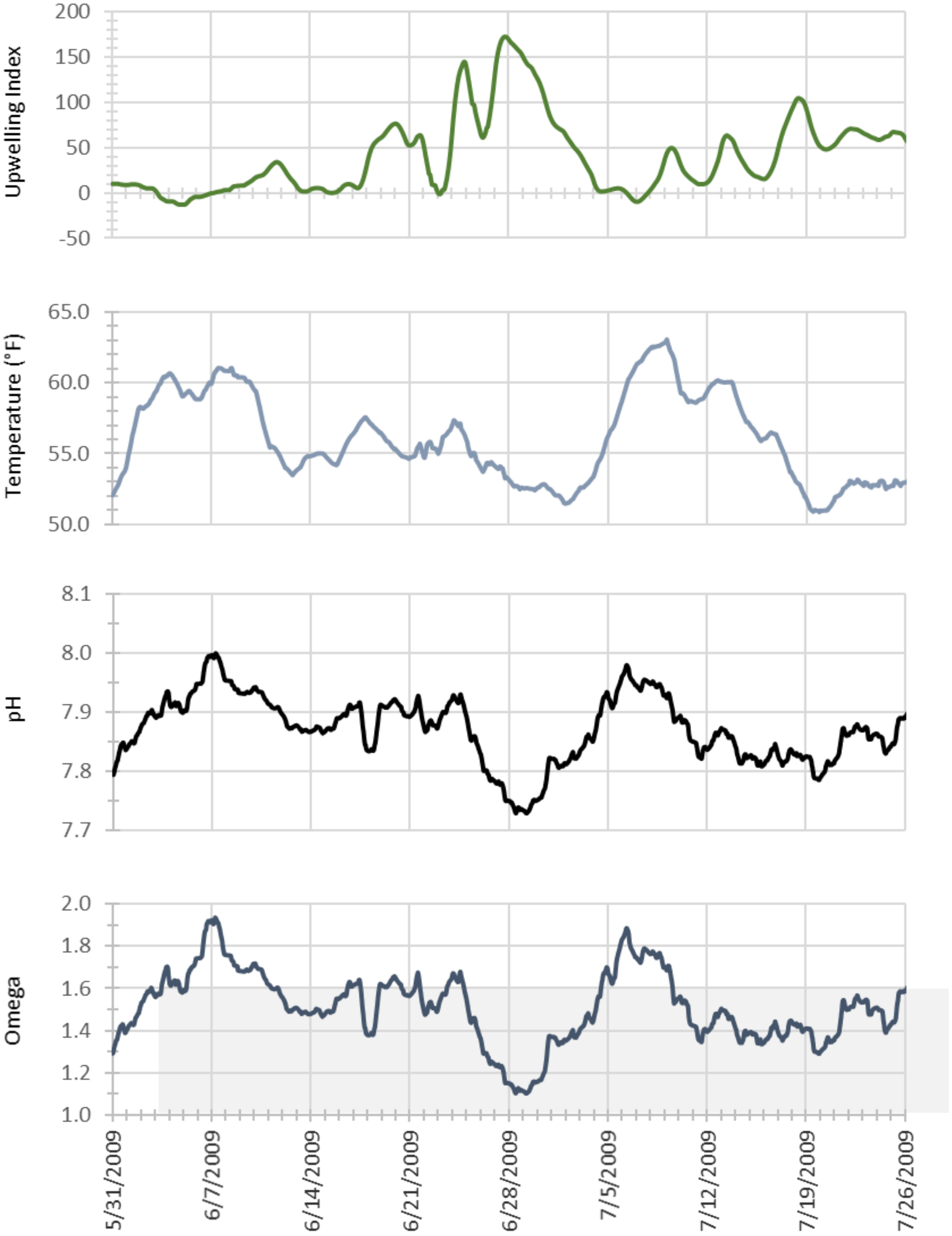
14. At what time of day is pH the lowest?

15. At what time of day is pH the highest?

16. What might explain these daily changes in pH

17. Larvae oysters generally do better when pH is higher. What time of day would you recommend the hatchery take water out of the bay to fill their tanks?

The graphs on the next page show water quality data from Whiskey Creek Shellfish Hatchery for the entire 2009 summer. Use these graphs to answer the questions that follow.


Upwelling Index
200
150
100
50
0
-50
Temperature (°F)
65.0
60.0
55.0
50.0
pH
8.1
8.0
7.9
7.8
7.7
Omega
2.0
1.8
1.6
1.4
1.2
1.0
5/31/2009
6/7/2009
6/14/2009
6/21/2009
6/28/2009
7/5/2009
7/12/2009
7/19/2009
7/26/2009

18. Based on the upwelling index graph, when was the strongest upwelling event in 2009?

19. Explain the relationship between upwelling and water temperature.

20. Explain the relationship between upwelling and pH.

21. Larval oysters die when omega is below 1.6. Roughly how much of the summer was omega below 1.6?

22. Why do you think scientists concluded that ocean acidification was causing the oysters to die? Wouldn’t it make more sense to conclude that upwelling caused the deaths? *Hint-Upwelling occurs in Oregon every summer.*

Name: *Lesson 3- Researching Ocean Acidification’s Impacts*
Period:

Today we are going to research the various possible impacts of ocean acidification on marine organisms and humans. You will 1) pick an organism to research, 2) research your organism, and 3) teach the class what you learned.

STEP 1: CHOOSE AN ORGANISM YOU WANT TO RESEARCH.

My Organism: ______________________________________

Your first step is to pick an organism that you want to research. There is more known about some creatures than others. The Seattle Times has a website (http://apps.seattletimes.com/creatures/) that provides a starting point for many creatures:

- Brittlestars
- Clams
- Clownfish (Nemo)
- Corals
- Blue Crab
- Red King Crab
- Damselfish
- Jellyfish
- Krill
- Mussels
- Oysters
- Pteropods
- Seagrass
- Sea urchins
- Walleye pollock
- Walrus

There are many other organisms where researchers have looked at the possible impacts of ocean acidification. These include (but might be more challenging to research):

- Blue-green algae (cyanobacteria)
- Coccolithophores
- Copepods
- Coralline algae
- Diatoms
- Dungeness Crab
- Foraminifera
- Other fish (e.g., herring)
- Pink Shrimp
- Salmon
- Squid
- Starfish
- Whales

STEP 2: RESEARCH YOUR ORGANISM.

Use at least 2-3 websites in your research. Record the websites below and the key information you gathered from them in the table on the next page.

Source 1: Organization (who runs the website?): ___________________________________
Website URL: https://____
Author (if available): ____
Why do you trust this source?

Source 2: Organization (who runs the website?): ___________________________________
Website URL: https://____
Author (if available): ____
Why do you trust this source?

Source 3: Organization (who runs the website?): ___________________________________
Website URL: https://____
Author (if available): ____
Why do you trust this source?

Source 4: Organization (who runs the website?): ___________________________________
Website URL: https://____
Author (if available): ____
Why do you trust this source?

Which organism are you researching? (*Describe / draw it*)	How will this organism be affected by ocean acidification?
How could this impact other organisms in the food web?	How could this impact people?

STEP 3: PRESENT YOUR FINDINGS

You will give a 1-2 minute presentation to the class on what you learned. Your presentation should cover the four key points in the table above.

Name: *Lesson 3- Research Presentations*

Period:

LEARNING ABOUT OCEAN ACIDIFICATION'S IMPACTS

Today you will learn from your classmates about the potential consequences of ocean acidification. Take notes in the table below (or separately in your notes).

Organism	**Predicted impacts**	**How will this impact ecosystems <u>and</u> humans?**
e.g. Oysters		

Organism	**Predicted impacts**	**How will this impact ecosystems and humans?**

Name: *Lesson 4- Household Actions to Address OA*

Period:

REDUCING THE PROBLEM

Brainstorm responses to the following questions:

What actions could be taken to reduce CO_2 emissions in the U.S.?	What might prevent someone from taking one or more of the actions you listed?
• • • • •	• • • • •

CARD SORT ACTIVITY REFLECTION

1. How does your list compare to the order of actions the researchers found?

2. Were you surprised by anything from this activity?

3. Do you notice anything about the actions at the top vs. bottom of this list?

4. How many of the actions listed involve one-time improvements to the efficiency of an energy-using appliance and how many involve an on-going choice in how much/how intensely an item is used?

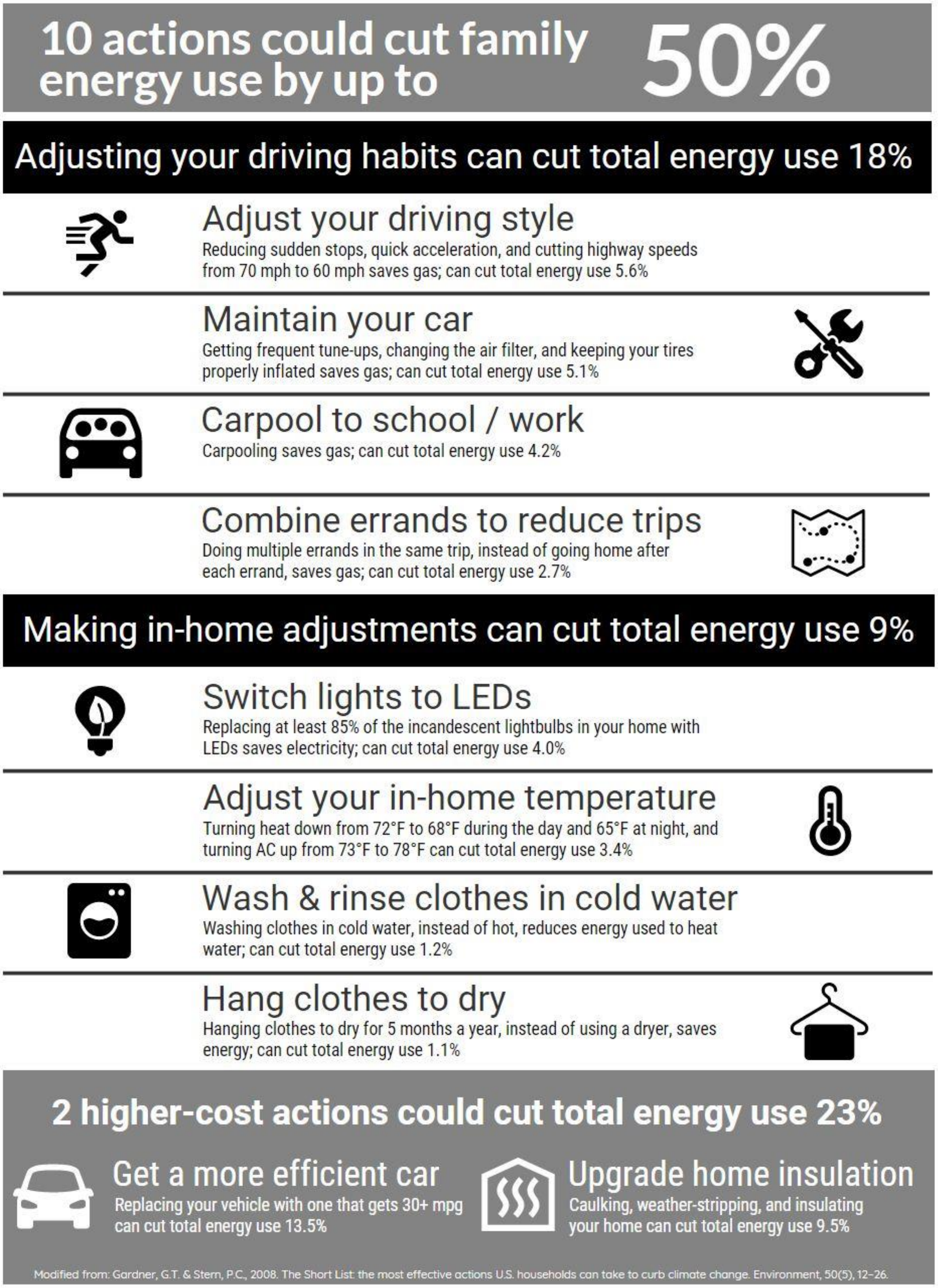
WHAT IS YOUR CARBON FOOTPRINT?

Go to the Cool Climate Calculator (http://coolclimate.berkeley.edu/calculator). After completing the questions, you will be presented with a long list of actions that could help reduce your carbon footprint.

5. What was your CO_2 footprint?

6. Look at the graph of your results. What part of your lifestyle generates the most CO_2 emissions?

7. Look through the list of possible actions to reduce your carbon footprint (Clicking on the title reveals more details). Of the actions listed, what 3 actions would you be most likely to take? Explain why you chose these actions and describe how challenging you think it would be for you to make these changes.



10 actions could cut family energy use by up to 50%

Adjusting your driving habits can cut total energy use 18%

Adjust your driving style

Reducing sudden stops, quick acceleration, and cutting highway speeds from 70 mph to 60 mph saves gas; can cut total energy use 5.6%

Maintain your car

Getting frequent tune-ups, changing the air filter, and keeping your tires properly inflated saves gas; can cut total energy use 5.1%

Carpool to school / work

Carpooling saves gas; can cut total energy use 4.2%

Combine errands to reduce trips

Doing multiple errands in the same trip, instead of going home after each errand, saves gas; can cut total energy use 2.7%

Making in-home adjustments can cut total energy use 9%

Switch lights to LEDs

Replacing at least 85% of the incandescent lightbulbs in your home with LEDs saves electricity; can cut total energy use 4.0%

Adjust your in-home temperature

Turning heat down from 72°F to 68°F during the day and 65°F at night, and turning AC up from 73°F to 78°F can cut total energy use 3.4%

Wash & rinse clothes in cold water

Washing clothes in cold water, instead of hot, reduces energy used to heat water; can cut total energy use 1.2%

Hang clothes to dry

Hanging clothes to dry for 5 months a year, instead of using a dryer, saves energy; can cut total energy use 1.1%

2 higher-cost actions could cut total energy use 23%

Get a more efficient car

Replacing your vehicle with one that gets 30+ mpg can cut total energy use 13.5%

Upgrade home insulation

Caulking, weather-stripping, and insulating your home can cut total energy use 9.5%

Modified from: Gardner, G.T. & Stern, P.C., 2008. The Short List: the most effective actions U.S. households can take to curb climate change. Environment, 50(5), 12–26.

APPENDIX C: Student Baseline Survey

The following survey was used to gauge student baseline knowledge and attitudes for an experiment that accompanied the development of this curriculum.

Directions: Read each question carefully and answer to the best of your ability. This first page is designed to find out what you already know about ocean acidification. You will have another opportunity when we finish to demonstrate what you learned. This is not a test and you are not being graded.

1) How much, if anything, would you say you know about ocean acidification? (*check <u>one</u> answer*)
   - ☐ I have not heard of ocean acidification
   - ☐ I have heard of ocean acidification, but I know almost nothing about it
   - ☐ I know just a little about ocean acidification
   - ☐ I know a fair amount about ocean acidification
   - ☐ I know a great deal about ocean acidification

2) Which, if any, do you think is the **main cause** of ocean acidification? (*check <u>one</u> answer*)
   - ☐ Carbon dioxide in the atmosphere that is naturally-occurring being absorbed by the ocean
   - ☐ Carbon dioxide in the atmosphere from human activities being absorbed by the ocean
   - ☐ Increased sea water temperatures from climate change
   - ☐ Normal cycles of change in ocean chemistry
   - ☐ Over-fishing (catching too many fish) leading to disruption of ocean food chains
   - ☐ Pollution, such as from oil spills and discharge of waste
   - ☐ None of these
   - ☐ I don’t know

3) Which, if any, do you think are **possible consequences** of ocean acidification? (*check <u>all</u> that apply*)
   - ☐ Worse conditions for some larger marine organisms (including fish)
   - ☐ Better conditions for some larger marine organisms (including fish)
   - ☐ Worse conditions for some small marine organisms
   - ☐ Better conditions for some small marine organisms
   - ☐ The ocean will become acidic (below pH = 7)
   - ☐ Coral reefs will grow more slowly
   - ☐ Most living marine animals will have their shells completely dissolve
   - ☐ Making and repairing shells will require more energy
   - ☐ Making and repairing shells will require less energy
   - ☐ There will be problems, such as decreased profits, for people who make a living from the sea
   - ☐ People spending long periods of time at sea, such as fishermen, will have skin damage
   - ☐ The metal hulls of ships will be damaged
   - ☐ None of the above
   - ☐ I don’t know

Directions: Read each question carefully and answer honestly. The following questions ask how you think and feel, so there are no right or wrong answers.

Definition: *An "estuary" is a water passage where ocean tides meet a river. Examples include Yaquina Bay, Siletz Bay, and Alsea Bay*.

4) How concerned, if at all, are you about ocean acidification? (*check one answer*)
- ☐ Not at all concerned
- ☐ Not very concerned
- ☐ Fairly concerned
- ☐ Very concerned
- ☐ I don't know

Read each statement and show how much you agree or disagree by ***circling one number*** for each statement.

		Strongly disagree	**Somewhat disagree**	**Neither agree nor disagree**	**Somewhat agree**	**Strongly agree**	**I don't know**
5)	Ocean acidification is happening in my **local estuary**	1	2	3	4	5	0
6)	Ocean acidification is happening along the **U.S. West Coast**	1	2	3	4	5	0
7)	Ocean acidification is happening **globally**	1	2	3	4	5	0
8)	The ocean is **too big** to be harmed by humans	1	2	3	4	5	0
9)	Ocean acidification is a **threat** to overall ocean health	1	2	3	4	5	0
10)	Ocean acidification has consequences for people **today**	1	2	3	4	5	0
11)	Ocean acidification will have consequences for people within **my lifetime**	1	2	3	4	5	0
12)	Ocean acidification will have consequences for **me** within **my lifetime**	1	2	3	4	5	0
13)	Ocean acidification will have consequences for **future generations**	1	2	3	4	5	0

Read each statement and show how much you agree or disagree by ***circling <u>one</u> number*** for each statement.

		None at all	**Very little**	**A moderate amount**	**A lot**	**A great deal**	**I don't know**
14)	How much control do you feel that **you, alone**, have in reducing ocean acidification in your **local estuary**?	1	2	3	4	5	0
15)	How much control do you feel that **you, alone**, have in reducing ocean acidification in the **global ocean**?	1	2	3	4	5	0
16)	How much control do you feel that **you, working with others**, have in reducing ocean acidification in your **local estuary**?	1	2	3	4	5	0
17)	How much control do you feel that **you, working with others**, have in reducing ocean acidification in the **global ocean**?	1	2	3	4	5	0

Read each statement and show how much you agree or disagree by ***circling <u>one</u> number*** for each statement.

		Strongly disagree	**Somewhat disagree**	**Neither agree nor disagree**	**Somewhat agree**	**Strongly agree**	**I Don't Know**
18)	Reducing ocean acidification is the **right thing** to do	1	2	3	4	5	0
19)	**People** should be taking action to reduce ocean acidification	1	2	3	4	5	0
20)	**I** should be taking action to reduce ocean acidification	1	2	3	4	5	0

21) Which people, if any, do you think should be taking action to reduce ocean acidification?

____

22) Explain why you think these people, in particular, should be taking action.

____

____

23) **List actions** someone **could take** to reduce ocean acidification. Then, **circle** the number that shows how often you **currently** do each action.

Action	I **never** do this	I **rarely** do this	I **sometimes** do this	I **regularly** do this
	0	1	2	3
	0	1	2	3
	0	1	2	3
	0	1	2	3
	0	1	2	3

24) Do you have any final comments?

____

____

____

____

____

Thank you!

APPENDIX D: Student Post Survey

The following survey was used to gauge student knowledge and attitudes post instruction for an experiment that accompanied the development of this curriculum.

Directions: Read each question carefully and answer to the best of your ability. This first page is designed to find out what you already know about ocean acidification. You will have another opportunity when we finish to demonstrate what you learned. This is not a test and you are not being graded.

1) Were you present for the following classes? (check <u>all</u> that apply)

☐ Day 1: Introduction to ocean acidification	[insert date]
☐ Day 2: Chemistry of ocean acidification	[insert date]
☐ Day 3: Impacts of ocean acidification	[insert date]
☐ Day 4: Experiment: Shells in acid / Solutions to ocean acidification	[insert date]

2) How much, if anything, would you say you know about ocean acidification? (*check <u>one</u> answer*)
   - ☐ I have not heard of ocean acidification
   - ☐ I have heard of ocean acidification, but I know almost nothing about it
   - ☐ I know just a little about ocean acidification
   - ☐ I know a fair amount about ocean acidification
   - ☐ I know a great deal about ocean acidification

3) Which, if any, do you think is the **main cause** of ocean acidification? (*check <u>one</u> answer*)
   - ☐ Carbon dioxide in the atmosphere that is naturally-occurring being absorbed by the ocean
   - ☐ Carbon dioxide in the atmosphere from human activities being absorbed by the ocean
   - ☐ Increased sea water temperatures from climate change
   - ☐ Normal cycles of change in ocean chemistry
   - ☐ Over-fishing (catching too many fish) leading to disruption of ocean food chains
   - ☐ Pollution, such as from oil spills and discharge of waste
   - ☐ None of these
   - ☐ I don’t know

4) Which, if any, do you think are **possible consequences** of ocean acidification? (*check <u>all</u> that apply*)
   - ☐ Worse conditions for some larger marine organisms (including fish)
   - ☐ Better conditions for some larger marine organisms (including fish)
   - ☐ Worse conditions for some small marine organisms
   - ☐ Better conditions for some small marine organisms
   - ☐ The ocean will become acidic (below pH = 7)
   - ☐ Coral reefs will grow more slowly
   - ☐ Most living marine animals will have their shells completely dissolve
   - ☐ Making and repairing shells will require more energy
   - ☐ Making and repairing shells will require less energy
   - ☐ There will be problems, such as decreased profits, for people who make a living from the sea
   - ☐ People spending long periods of time at sea, such as fishermen, will have skin damage
   - ☐ The metal hulls of ships will be damaged
   - ☐ None of the above
   - ☐ I don’t know

Directions: Read each question carefully and answer honestly. The following questions ask how you think and feel, so there are no right or wrong answers.

Definition: *An "estuary" is a water passage where ocean tides meet a river. Examples include Yaquina Bay, Siletz Bay, and Alsea Bay*.

5) How concerned, if at all, are you about ocean acidification? (*check* <u>*one*</u> *answer*)
   ☐ Not at all concerned
   ☐ Not very concerned
   ☐ Fairly concerned
   ☐ Very concerned
   ☐ I don't know

Read each statement and show how much you agree or disagree by ***circling <u>one</u> number*** for each statement.

		Strongly disagree	**Somewhat disagree**	**Neither agree nor disagree**	**Somewhat agree**	**Strongly agree**	**I don't know**
6)	Ocean acidification is happening in my **local estuary**	1	2	3	4	5	0
7)	Ocean acidification is happening along the **U.S. West Coast**	1	2	3	4	5	0
8)	Ocean acidification is happening **globally**	1	2	3	4	5	0
9)	The ocean is **too big** to be harmed by humans	1	2	3	4	5	0
10)	Ocean acidification is a **threat** to overall ocean health	1	2	3	4	5	0
11)	Ocean acidification has consequences for people **today**	1	2	3	4	5	0
12)	Ocean acidification will have consequences for people within **my lifetime**	1	2	3	4	5	0
13)	Ocean acidification will have consequences for **me** within **my lifetime**	1	2	3	4	5	0
14)	Ocean acidification will have consequences for **future generations**	1	2	3	4	5	0

Read each statement and show how much you agree or disagree by ***circling <u>one</u> number*** for each statement.

		None at all	**Very little**	**A moderate amount**	**A lot**	**A great deal**	**I don't know**
15)	How much control do you feel that **you, alone**, have in reducing ocean acidification in your **local estuary**?	1	2	3	4	5	0
16)	How much control do you feel that **you, alone**, have in reducing ocean acidification in the **global ocean**?	1	2	3	4	5	0
17)	How much control do you feel that **you, working with others**, have in reducing ocean acidification in your **local estuary**?	1	2	3	4	5	0
18)	How much control do you feel that **you, working with others**, have in reducing ocean acidification in the **global ocean**?	1	2	3	4	5	0

Read each statement and show how much you agree or disagree by ***circling <u>one</u> number*** for each statement.

		Strongly disagree	**Somewhat disagree**	**Neither agree nor disagree**	**Somewhat agree**	**Strongly agree**	**I Don't Know**
19)	Reducing ocean acidification is the **right thing** to do	1	2	3	4	5	0
20)	**People** should be taking action to reduce ocean acidification	1	2	3	4	5	0
21)	**I** should be taking action to reduce ocean acidification	1	2	3	4	5	0

22) Which people, if any, do you think should be taking action to reduce ocean acidification?

____

23) Explain why you think these people, in particular, should be taking action.

____

____

24) **List actions** someone **could take** to reduce ocean acidification. Then, **circle** the number that shows how often you **currently** do each action.

	Currently…				In the future…			
Action	I **never** do this	I **rarely** do this	I **sometimes** do this	I **regularly** do this	I **never** plan to do this	I plan to do this **rarely**	I plan to do this **sometimes**	I plan to do this **regularly**
	0	1	2	3	0	1	2	3
	0	1	2	3	0	1	2	3
	0	1	2	3	0	1	2	3
	0	1	2	3	0	1	2	3
	0	1	2	3	0	1	2	3

25) Do you have any final comments?

____

____

____

____

____

Thank you!

APPENDIX E: Student Follow-up Survey

The following survey was used to gauge student knowledge and attitudes 10-weeks after instruction for an experiment that accompanied the development of this curriculum.

Directions: Read each question carefully and answer to the best of your ability. This first page is designed to find out what you already know about ocean acidification. You will have another opportunity when we finish to demonstrate what you learned. This is not a test and you are not being graded.

1) How much, if anything, would you say you know about ocean acidification? (*check* <u>*one*</u> *answer*)
   - ☐ I have not heard of ocean acidification
   - ☐ I have heard of ocean acidification, but I know almost nothing about it
   - ☐ I know just a little about ocean acidification
   - ☐ I know a fair amount about ocean acidification
   - ☐ I know a great deal about ocean acidification

2) Which, if any, do you think is the **main cause** of ocean acidification? (*check* <u>*one*</u> *answer*)
   - ☐ Carbon dioxide in the atmosphere that is naturally-occurring being absorbed by the ocean
   - ☐ Carbon dioxide in the atmosphere from human activities being absorbed by the ocean
   - ☐ Increased sea water temperatures from climate change
   - ☐ Normal cycles of change in ocean chemistry
   - ☐ Over-fishing (catching too many fish) leading to disruption of ocean food chains
   - ☐ Pollution, such as from oil spills and discharge of waste
   - ☐ None of these
   - ☐ I don't know

3) Which, if any, do you think are **possible consequences** of ocean acidification? (*check* <u>*all*</u> *that apply*)

   - ☐ Worse conditions for some larger marine organisms (including fish)
   - ☐ Better conditions for some larger marine organisms (including fish)
   - ☐ Worse conditions for some small marine organisms
   - ☐ Better conditions for some small marine organisms
   - ☐ The ocean will become acidic (below pH = 7)
   - ☐ Coral reefs will grow more slowly
   - ☐ Most living marine animals will have their shells completely dissolve
   - ☐ Making and repairing shells will require more energy
   - ☐ Making and repairing shells will require less energy
   - ☐ There will be problems, such as decreased profits, for people who make a living from the sea
   - ☐ People spending long periods of time at sea, such as fishermen, will have skin damage
   - ☐ The metal hulls of ships will be damaged
   - ☐ None of the above
   - ☐ I don't know

Directions: Read each question carefully and answer honestly. The following questions ask how you think and feel, so there are no right or wrong answers.

Definition: *An "estuary" is a water passage where ocean tides meet a river. Examples include Yaquina Bay, Siletz Bay, and Alsea Bay*.

4) How concerned, if at all, are you about ocean acidification? (*check one answer*)
   - ☐ Not at all concerned
   - ☐ Not very concerned
   - ☐ Fairly concerned
   - ☐ Very concerned
   - ☐ I don't know

Read each statement and show how much you agree or disagree by ***circling one number*** for each statement.

		Strongly disagree	**Somewhat disagree**	**Neither agree nor disagree**	**Somewhat agree**	**Strongly agree**	**I don't know**
5)	Ocean acidification is happening in my **local estuary**	1	2	3	4	5	0
6)	Ocean acidification is happening along the **U.S. West Coast**	1	2	3	4	5	0
7)	Ocean acidification is happening **globally**	1	2	3	4	5	0
8)	The ocean is **too big** to be harmed by humans	1	2	3	4	5	0
9)	Ocean acidification is a **threat** to overall ocean health	1	2	3	4	5	0
10)	Ocean acidification has consequences for people **today**	1	2	3	4	5	0
11)	Ocean acidification will have consequences for people within **my lifetime**	1	2	3	4	5	0
12)	Ocean acidification will have consequences for **me** within **my lifetime**	1	2	3	4	5	0
13)	Ocean acidification will have consequences for **future generations**	1	2	3	4	5	0

Read each statement and show how much you agree or disagree by ***circling <u>one</u> number*** for each statement.

		None at all	**Very little**	**A moderate amount**	**A lot**	**A great deal**	**I don't know**
14)	How much control do you feel that **you, alone**, have in reducing ocean acidification in your **local estuary**?	1	2	3	4	5	0
15)	How much control do you feel that **you, alone**, have in reducing ocean acidification in the **global ocean**?	1	2	3	4	5	0
16)	How much control do you feel that **you, working with others**, have in reducing ocean acidification in your **local estuary**?	1	2	3	4	5	0
17)	How much control do you feel that **you, working with others**, have in reducing ocean acidification in the **global ocean**?	1	2	3	4	5	0

Read each statement and show how much you agree or disagree by ***circling <u>one</u> number*** for each statement.

		Strongly disagree	**Somewhat disagree**	**Neither agree nor disagree**	**Somewhat agree**	**Strongly agree**	**I Don't Know**
18)	Reducing ocean acidification is the **right thing** to do	1	2	3	4	5	0
19)	**People** should be taking action t reduce ocean acidification	1	2	3	4	5	0
20)	**I** should be taking action to reduce ocean acidification	1	2	3	4	5	0

21) Which people, if any, do you think should be taking action to reduce ocean acidification?

____

22) Explain why you think these people, in particular, should be taking action.

____

____

23) **List actions** someone **could take** to reduce ocean acidification. Then, **circle** the number that shows how often you **have done** each action **in the past 3 months** (since learning about ocean acidification in class) and how often you **plan to do** each action in the future.

	In the past 3 months…				**In the future…**			
Action	I **never** did this	I **rarely** did this	I **sometimes** did this	I **regularly** did this	I **never** plan to do this	I plan to do this **rarely**	I plan to do this **sometimes**	I plan to do this **regularly**
	0	1	2	3	0	1	2	3
	0	1	2	3	0	1	2	3
	0	1	2	3	0	1	2	3
	0	1	2	3	0	1	2	3
	0	1	2	3	0	1	2	3

24) Do you have any final comments?

Thank you!

APPENDIX F: The Case of the Dying Oysters Readings

THE CASE OF THE DYING OYSTERS

NOTE- This reading is a modified, edited version of paragraphs from the following three articles: Geiling (2015); Gilles (2013); Grossman (2011).

The sun chips away at the clouds on a quickly warming May morning. On the estuary's muddy banks, people dressed in knee-high rubber boots dig in the dark sludge for clams, while throughout the bay other aquatic farmers dredge for their prize: oysters.

Oysters have been grown commercially on the West Coast since the mid-to-late 1800s, thriving in the shallow, cool estuaries along the Pacific Coast. By the 1890s, oystermen were pulling 200,000 bushels a year out of the Puget Sound. But the boom was followed by bust, as over-harvesting and declining water quality devastated the native population of Olympia oysters (*Ostrea lurida*). In the 1920s, as a way of saving their industry, the West Coast oyster growers began importing Pacific oysters (*Crassostrea gigas*) from Japan. The Pacific oysters thrived, and oyster farmers began growing the species in large numbers.

But unlike the native Olympia oyster, the Pacific oyster was never able to reproduce quite as successfully in the wild – so in the 1970s, the shellfish industry began installing hatcheries along the Pacific Coast, in order to supply oyster farmers with the larvae needed to sustain their businesses. In 1978, the Whiskey Creek Shellfish Hatchery set up shop next to Netarts Bay, five miles southwest of Tillamook, Oregon. A family-run business, it now supplies Pacific oyster larvae to 70 percent of the West Coast's oyster farms stretching from Canada to South America.

In 2007, Pacific oyster larvae at Whiskey Creek started dying en masse… At first, the only thing anyone knew was that something was horribly wrong.

"We had three or four months when we had zero production. We'd never seen anything like it," says Mark Wiegardt, who owns a small oyster farm on the bay's south end and whose wife, Sue Cudd, has owned and operated Whiskey Creek since 1997.

"We had two awful years in a row," said Alan Barton, Production Manager at Whiskey Creek. "And this is a small business, so that's almost the end."

Whiskey Creek might be a small business, but it's a crucial link in the $270 million Pacific shellfish industry. As the second-largest commercial shellfish hatchery on the West Coast, it provides hundreds of small to medium-sized oyster farms with the microscopic larvae they need to make their operations work.

"If we don't produce larvae then there's farms that go out of business and thousands of jobs gone in those rural communities," Barton said.

References:

Geiling, N., 2015. How Washington Transformed Its Dying Oyster Industry into a Climate Success Story. *Think Progress*. [Accessed July 8, 2017].

Gilles, N., 2013. The Whiskey Creek Shellfish Acid Tests: Ocean acidification and its effects on Pacific oyster larvae. *Confluence*, pp.3–8.

Grossman, E., 2011. Northwest Oyster Die-offs Show Ocean Acidification Has Arrived. *Yale Environment 360*. [Accessed August 7, 2017].

CHALLENGE READING: THE CASE OF THE DYING OYSTERS

NOTE- This challenge reading is a modified version of Barton et al. (2015).

Shellfish have been harvested in the Pacific Northwest for thousands of years, and commercial oyster farming has been an important cultural and economic part of coastal communities in the Northwest since the late 1800s. Today, shellfish farming supports over $270 million in economic activity and over 3,000 family wage jobs in rural areas throughout the region. Although shellfish farms can be found throughout Oregon, Washington, Alaska, California, and Hawaii, most of the oysters harvested in the Pacific Northwest are produced in Washington. Large farms in Willapa Bay and southern Puget Sound make up the majority of the industry, and have existed in these areas for several generations.

Shellfish species farmed in the Pacific Northwest include Manila clams (*Venerupis philippinarum*), geoduck clams (*Panopea generosa*), mussels (*Mytilus trossulus* and *M. galloprovincialis*), and several species of oysters. Although Kumamoto oysters (*Crassostrea sikamea*), eastern oysters (*Crassostrea virginica*), and the native Olympia oyster (*Ostrea conchaphila*) represent important niche markets, the Pacific oyster (*Crassostrea gigas*) is the predominant species farmed in the region, comprising >80% of the industry's total annual shellfish production by live weight.

Pacific oysters from Japan were first brought to the United States in the early twentieth century, and naturalized populations became established in portions of Puget Sound and in Willapa Bay. Natural recruitment of seed oysters from these spawning populations helped support the industry for several decades, supplementing the supply of imported seed from Japan. In the 1970s, the cost of importing seed became prohibitively expensive, and it became clear that growers could not rely solely on inconsistent natural spawning events (Dumbauld et al., 2011) to support their burgeoning industry (Gordon and Blanton, 2001).

By the late 1970s, successful commercial hatcheries were established in the Pacific Northwest and began supplying billions of "eyed" (setting size) larvae to growers each year. The three major commercial hatcheries that currently supply larvae to the West Coast shellfish industry are Whiskey Creek Shellfish Hatchery (Netarts Bay, OR), Taylor Shellfish Hatchery

(Dabob Bay, WA), and Coast Seafoods Hatchery (Quilcene Bay, WA). These hatcheries combine with smaller hatcheries in Washington and Hawaii to produce 40-60 billion eyed larvae each year, and their 30 years of consistent production has helped build today’s $270 million per year shellfish industry.

High levels of larval mortality at the Whiskey Creek Shellfish Hatchery began in July 2007 and persisted to the end of the growing season in October. Some month-to-month variability in hatchery production is normal, but the magnitude and duration of the 2007 mortality events were unprecedented in the hatchery’s 30-year history… Overall production at Whiskey Creek in 2008 was approximately 2.5 billion eyed larvae, about 25% of a normal season’s production. Whiskey Creek is the primary supplier of larvae to many independent growers throughout the Pacific Northwest, and the shortage of larvae from the hatchery, combined with several consecutive years of poor natural recruitment of larvae from spawning populations in Willapa Bay (Dumbauld et al., 2011), generated concern among growers across the entire West Coast shellfish industry.

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READING QUESTIONS: THE CASE OF THE DYING OYSTERS

What problem occurred Whiskey Creek Shellfish Hatchery from 2007-2009?

In a separate interview about the dying oysters, Mark Wiegardt said, "if [we] go out of business [we're] taking a bunch of people with [us]." What did he mean by this?

What might be wrong at Whiskey Creek? Write 3-5 possible causes for the hatchery's problems on the left side of the table (below). Then, on the right side of the table, list one way you could test each idea to see if it is correct.

Possible Causes	Possible Tests

APPENDIX G: Oregon Marine Food Webs

The following food web activity was used in prior versions of this curriculum and is modified from one used in the Channel Islands National Park/National Marine Sanctuary's "Ocean Acidification Curriculum," lesson 1. All uncited photos are from the Channel Islands curriculum's food web.

PREPARE FOOD WEB CARDS: Print 10 copies of food web cards (2 pages each, see lesson materials), or enough for each group to have a set. Cut out a set of food web cards for each pair/group of students. Place these cards into an envelope to simplify distribution and storage. Laminate cards for long-term use.

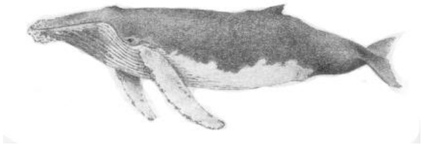
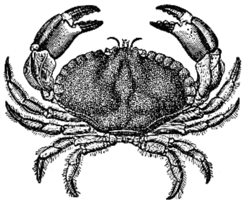
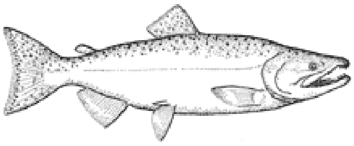
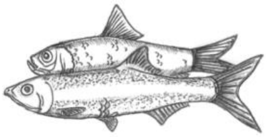
Students build an Oregon marine food web using organism cards. Introduce food webs to your students.

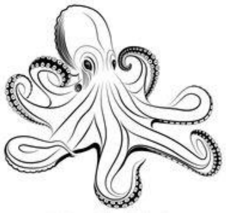
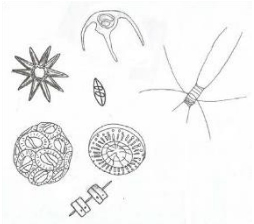
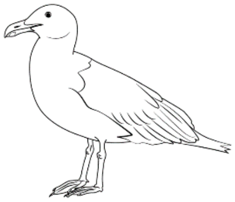
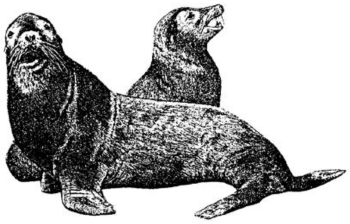
> "What does a food web show? (*the flow of energy in an ecosystem; interconnection between organisms*)
>
> Food webs can be drawn in many ways. I find it easier if the producers, or photosynthesizers (like plants and algae), are on the bottom. Food webs are an oversimplification of a very complex environment. But, they help show how species are interconnected."

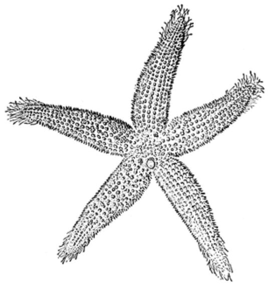
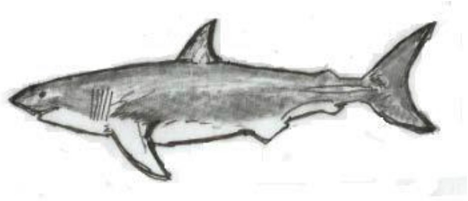
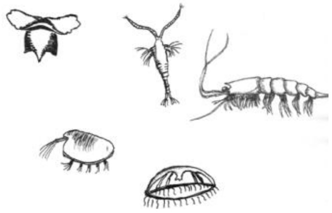
Divide students into groups of 2-4. Each group receives a stack of Marine Food Web cards. Explain that these cards represent a simplified version of the organisms that can be found in Oregon's nearshore waters.

You are going to build a food web based on the information provided on the cards. (Students organize cards into a food web. Students draw their food web in their notes. *Note- arrows should point from the thing being eaten (prey) toward the animal that is eating (predator)*)

Some students interpreted this literally and drew pictures of all food web organisms

Algae  http://www.fao.org/docrep/005/ac860e/AC860E01.htm	There are many types of algae in the ocean, including build calcium carbonate skeletons. Algae use the sun for photosynthesis.
Baleen whales 	These whales (e.g., Humpbacks) take in huge amounts of water and filter it to catch food. Baleen whales eat phytoplankton, zooplankton (especially krill), and small fish.
Crabs ($)  https://goo.gl/D9qzEe	Crabs eat many things including phytoplankton, zooplankton, algae, kelp, sea stars, small fish, and dead organisms.
Fish (carnivorous) $  https://goo.gl/DELJiF	Eat other fish, zooplankton, snails, etc.
Fish (omnivorous) $ 	Eat algae, kelp, phytoplankton, and zooplankton
Kelp $ 	Kelp use the sun for photosynthesis

Mussels ($) 	Mussels filter ocean water to catch phytoplankton, zooplankton, and other tiny particles to eat.
Octopuses  https://goo.gl/MNNv9S	Eat many things including crabs, mussels, and some fish.
Phytoplankton 	Phytoplankton are microscopic plants and plantlike organisms. They use the sun for photosynthesis
Sea birds  https://goo.gl/xxRTRn	Eat a variety of things including fish, mussels, squid, and sea urchins.
Sea lions 	Sea lions eat squid, octopus, and fish.

Sea stars  https://goo.gl/uP3Ufk	Eat sea urchins, mussels, and snails.
Seals 	Eat fish, octopuses, and squids.
Sharks 	Eat fish, octopuses, seals, sea lions, whales, other sharks, and dead animals.
Zooplankton 	These are animals that use water currents to drift in the ocean. They eat phytoplankton.

APPENDIX H: Scenarios: Impacts of Ocean Acidification

The following activity was used in prior versions of this curriculum immediately following the food web activity.

Prepare scenario cards: Print 10 copies of scenario cards (2 pages each, see lesson materials below), or enough for each group to have a set. Cut out a set of scenario cards for each pair/group of students. Place these cards into the food web envelope to simplify distribution and storage. Laminate cards for long-term use.

Once students complete their food web, they use scenario cards to examine a few possible impacts of ocean acidification. Students discuss each scenario as a group.\sidenote{student post surveys showed very little change in the number of students that thought OA would be a benefit to small or large organisms, despite the first scenario presenting information saying seagrass could benefit from OA.

Discuss scenario questions as a class (5 min).

In practice, after doing the card sort, students weren't very interested in reading and discussing scenarios. I can imagine a few ways to try to fix this:

Teacher-led: Direct students to read the first scenario, then lead a discussion as a class. Repeat for scenarios 2-4.

Allow student groups to choose one scenario. Have students present the scenario (remind students that other groups have not read their scenario, so they must summarize it) and what they discussed to the rest of the class. (*I tried this, and it somewhat worked, but it could have been setup better. Perhaps give students a table they have to complete while listening to other students discussing their scenarios.)

Scenario Cards

Scenario 1 - Impacts on primary producers

Some seagrasses and algae, like kelp, seem to benefit when the concentration of CO_2 in seawater increases. Certain studies have shown an increase in growth when the amount of CO_2 increases.

Discuss with your group:

- If ocean acidification meant seagrasses and kelp grew more in the future, what could be some possible impacts of this growth on the food web you created?
- Ocean acidification might also cause these plants to not make chemicals that deter predators. How might this decrease in toxin production affect their survival?
- How would an increase in ocean plants change local water chemistry?

Scenario 2 - Impacts on mussels

Mussels are a keystone species in Oregon rocky intertidal ecosystems. They occupy large areas and are home to many other organisms. Mussel beds also lessen the power of waves, protecting coast lines from erosion. Additionally, mussels are an important food source for many organisms, as you saw in your food web. Experiments have shown that larval mussels respond to ocean acidification in the same way that larval oysters do: they spend more energy building their shells and have similar sensitivities to carbonate saturation state.

Additionally, mussels use strings, called byssal threads, to hold onto rocks. These threads seem to dissolve with ocean acidification. If these strings dissolve, mussel beds could be swept away by strong waves.

Discuss with your group:

Imagine that, because of ocean acidification, the number of mussels in an area decreases by 50%.

- Which organisms eat mussels (in your food web)? How would they be impacted by a 50% decrease in mussels? How might they respond?
- What do mussels eat? If the number of mussels decreases, what could happen to these organisms?

Scenario 3 – Impacts on fishing

Pteropods, a type of zooplankton, are an important food source for Pink Salmon in the Gulf of Alaska. At certain times of year, a Pink Salmon's diet is 45% pteropods. Some research suggests that pteropods will become less nutritious due to ocean acidification because they will spend more energy on shell repair. The researchers conclude that juvenile Pink Salmon will grow slower, which will delay when they start eating larger food, like squid. Ultimately, the researchers think Pink Salmon will come back to rivers weighing less because they ate smaller food for a longer period of time. Salmon are an important source of income and food for many people. Fishermen are usually paid by the pound for the fish they catch.

Discuss with your group:

- What would a decrease in Pink Salmon weight because of ocean acidification mean for a fisherman's income?
- What are some ways fishermen might respond to catching lighter salmon?

Scenario 4- Impacts on coral reefs

Corals are an animal that build reefs out of calcium carbonate. Since ocean acidification decreases the amount of carbonate in the water, corals might have a harder time building their skeleton, the coral reef. There is some indication that reefs could start to dissolve in the future.

Additionally, some research suggests that ocean acidification could make coral bleaching worse. Coral bleaching occurs when algae that live in the skin of corals abandon the coral because the water gets too hot. Bleaching means corals have less available food and often leads to coral death. Ocean acidification might make corals less able to handle temperature changes, leading to more coral bleaching.

Coral reefs are home to many organisms, and loss of a reef means loss of a home and feeding grounds. Humans also rely on coral reefs for food, tourism, protection from strong waves, and well-being.

Discuss with your group:

- How might an increase in coral bleaching impact tourism?
- What would this change mean to people who rely on tourism for employment?

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