Harmful Algal Blooms (HABs): Track them like a scientist

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Abstract

Marine phytoplankton comprise the foundation of oceanic food webs and generate most of the Earth's oxygen. Of the many phytoplankton species in the ocean, a few dozen produce potent toxins, and at high concentrations can form what are called Harmful Algal Blooms (HABs) or "red tides" that can discolor marine waters. Managers and scientists have been monitoring coastal waters and shellfish resources for HABs and their toxins to ensure seafood safety and understand why blooms occur. This educational activity focuses on a prominent HAB species that causes paralytic shellfish poisoning (PSP). Students will learn about the importance of HABs and PSP, as well as how scientists collect and use data to understand and predict blooms. Students will plot data on HAB species collected by scientists over multiple years of sampling. Students will plot results over time and across regions, report on observed patterns, and complete grade-appropriate calculations. Lastly, group discussion will focus on determining whether geographic patterns exist that might influence where shellfish beds are closed. This activity is timely given the widespread wildlife mortalities and beach closures due to Florida red tide, as well as recent dog deaths attributed to exposure to freshwater cyanobacteria (blue-green algae) blooms.

Keywords

Harmful Algal Bloom (HAB), red tides, dinoflagellate, Paralytic Shellfish Poisoning (PSP)

Background

Just like plants in terrestrial systems, there are plant-like organisms inhabiting our oceans that photosynthesize, thereby producing oxygen. In fact, a large percentage of the world's oxygen is produced by marine organisms that photosynthesize. Dinoflagellates are one of the major groups of phytoplankton (see vocabulary insert). They have two tail-like appendages called flagella (singular flagellum) that are used for locomotion (Figure 1; Figure 2a). These organisms are unicellular (one celled) but can form chains (Figure 2b), and are transported by ocean currents. Most dinoflagellates are not harmful, but a small number of species are capable of producing potent toxins (reviewed by Backer and McGillicuddy, 2006; Anderson et al. 2012). Marine organisms such as shellfish (oysters, clams, mussels, and scallops) as well as other invertebrates and fish can accumulate these toxins when they consume these red tide algae during filter feeding. This often occurs when conditions are favorable for dinoflagellate growth, leading to the formation of high algal densities, also known as a "bloom." These blooms can become visible and have been historically called "red tides" because the ocean water can be discolored by the large number of dinoflagellate cells. During harmful algal blooms, consumption of toxin-containing shellfish can be dangerous. However, when the bloom diminishes, shellfish will gradually excrete the toxin, and will once again be safe to eat.

New England waters are subject to several HAB problems, and the most prominent of these is Paralytic Shellfish Poisoning, or PSP, caused by the dinoflagellate *Alexandrium catenella*. PSP is a life-threatening illness associated with the consumption of shellfish that are contaminated with neurotoxins known collectively as saxitoxins. These toxins are concentrated in the body tissues of shellfish, and can be accumulated to levels that can cause illness in people who eat contaminated shellfish. Symptoms of PSP include numbness, tingling, dizziness, paralysis, as well as difficulty breathing and respiratory arrest. In severe cases, PSP can be fatal. The shellfish themselves can also be impacted by these toxins and will exhibit physiological and behavioral responses such as reduced feeding rates and impaired ability to burrow in sediment (Bricelj et al. 1996). Some species are more sensitive to saxitoxins then others, however. For example, mussels are comparatively insensitive to toxin exposure, and can thus accumulate extremely high toxin levels. In addition to impacting humans, the consumption of saxitoxin-carrying shellfish, fish, and invertebrates can sicken other organisms that eat them, such as marine mammals and birds (Landsberg et al. 2014).

In the U.S., PSP primarily impacts northern Atlantic and Pacific coasts, as well as Alaskan coastal waters, and is of particular concern in the Northeast, where PSP toxins and health risks have been a recurring problem for many years (Anderson et al. 2005, Anderson et al. 2014a, Bean et al. 2005). To protect human health, public health managers in shellfish-producing states impacted by PSP closely monitor shellfish for toxins to ensure that they are safe to eat. If toxins reach a certain level (0.8 ppm, or 80 μg 100 g^{-1} of shellfish meat), managers will close an area to shellfishing by posting signs along the impacted coastal areas where people may collect shellfish recreationally (Figure 3), and will circulate notices to notify commercial shellfishers, county and town offices, and seafood sellers. Closures are enacted well before toxins reach levels that might sicken human consumers. Managers will continue to monitor a particular area until toxin levels decrease to the point where shellfish is safe to eat, and only then will the closure be lifted.

To learn more about why and when blooms occur, scientists routinely collect both seawater and sediment samples to quantify concentrations of dinoflagellate cells, as well as their resting stages (similar to a seed, called "cysts"). Samples can be collected from shore, using small boats, or during surveys aboard larger research vessels. These data are used to determine when and where blooms occur, identify the conditions that might promote bloom formation, and to develop models of bloom dynamics that can be used to predict blooms. These data have also been used to identify locations of cyst "seedbeds"; e.g., extremely high concentrations of cysts that might initiate blooms in subsequent years (McGillicuddy et al. 2005). To visualize these data, scientists may construct what resembles a "heatmap" depicting dinoflagellate concentrations across a study region (Figure 4 depicts dinoflagellate cysts in the Gulf of Maine region). Note that the map's color coded shading is based on dinoflagellate concentrations, and is not related to the temperature/heat measured in the region.

Dinoflagellate life cycle

The life cycle of the dinoflagellate *Alexandrium catenella* is complicated and includes an asexual phase (during which organisms reproduce by binary fission) and a sexual phase (during which two cells fuse to form a planozygote that has a mix of genetic material from both parents), followed by a resting cyst phase (Figure 5). The cyst stage is an inactive life cycle stage during which the dinoflagellate remains dormant in ocean sediments, and this enables them to survive unfavorable conditions (e.g., low temperature). When conditions are suitable for growth (increased light availability and water temperature), the cyst germinates and commences cell division. This organism can reproduce quickly during the asexual phase, and under certain conditions can form blooms.

Introduction

This activity focuses on a particular species of bloom-forming dinoflagellate that can produce toxins that are harmful to humans and wildlife, and depicts how scientists collect and interpret data to better understanding bloom dynamics. The purpose is to engage students in plotting data over a large geographic area and over time to identify potential locations where HABs are prevalent, which is important information for managers charged with protecting citizens from PSP. Students will plot real data (Figure 6) to determine where and when high accumulations of dinoflagellate cysts are found and develop their own ideas about sampling strategies. There are modifications for the visually impaired. The sketches are provided with thick black lines with high visual contrast that can be seen by students who have some vision, and/or can be printed out on a Pictures in a Flash (PIAF) machine, which elevates black ink when printed on a special paper. Students can then feel the outline (Figure 7).

Vocabulary

bivalve – a type of mollusk such as a clam, mussel, oyster, or scallop

cyst stage – an inactive or resting life cycle stage of an organism

dinoflagellate – a type of phytoplanktonic organism in aquatic systems.

flagellum – appendage that allows microorganisms to swim

harmful algal bloom – rapid growth of a particular algal species, leading to toxic or harmful effects on people, shellfish, fish, marine mammals, and birds

invertebrate – an animal without a vertebral column (backbone)

phytoplankton – passively drifting photosynthetic organisms such as dinoflagellates

saxitoxin – neurotoxin produced by *Alexandrium* and the best-known paralytic shellfish toxin

shellfish – general term including a variety of species of clams, mussels, oysters, scallops, crab, lobster, shrimp, and sea urchins.

shellfisher – person who harvests shellfish to eat (recreational shellfisher) or sell (commercial shellfisher)

unicellular organism – an organism that is only one cell

Standards

Middle-school standards are provided below, although this activity has been shared with high school students as well.

Next Generation Science Standards (NGSS Lead States 2013)

<u>MS-LS1-6 From Molecules to Organisms: Structures and Processes</u>

Construct a scientific explanation based on evidence for the role of photosynthesis in the cycling of matter and flow of energy into and out of organisms.

MS-LS2 Ecosystems: Interactions, Energy, and Dynamics

Performance Expectations: MS-LS2-4. Construct an argument supported by empirical evidence that changes to physical or biological components of an ecosystem affect populations.

Science and Engineering Practices: MS-LS2-1: Interdependent relationships in ecosystems.

Crosscutting Concepts: MS-LS2.5: Science addresses questions about the natural and material World.

MS-LS2-1 Ecosystems: Interactions, Energy, and Dynamics

Analyze and interpret data to provide evidence for the effects of resource availability on organisms and populations of organisms in an ecosystem.

Grade:

Middle School (6-8)

MS-LS2-3 Ecosystems: Interactions, Energy, and Dynamics

Develop a model to describe the cycling of matter and flow of energy among living and nonliving parts of an ecosystem.

Grade:

Middle School (6-8)

MS-LS2-4 Ecosystems: Interactions, Energy, and Dynamics

Construct an argument supported by empirical evidence that changes to physical or biological components of an ecosystem affect populations.

Grade:

Middle School (6-8)

MS-LS2-5 Ecosystems: Interactions, Energy, and Dynamics

Evaluate competing design solutions for maintaining biodiversity and ecosystem services.

Grade:

Middle School (6-8)

MS-LS4-1; HS-PS1-2: Patterns: Observed patterns in nature guide organization and classification and prompt questions about relationships and causes underlying them.

MS-ESS3-3 Earth and Human Activity: Apply scientific principles to design a method for monitoring and minimizing a human impact on the environment.

National Science Education Standards (National Research Council 1996):

Life Science

Characteristics of organisms

Organisms and environments

Mathematics through the National Council of Teachers of Mathematics

(http://www.nctm.org/Standards-and-Positions/Principles-and-Standards/Principles,-Standards,-and-Expectations/)

Grades 6-8

Understand numbers, ways of representing numbers, relationships among numbers, and number systems

Develop meaning for integers and represent and compare quantities with them.

Understand measurable attributes of objects and the units, systems, and processes of measurement

Understand both metric and customary systems of measurement;

Solve problems involving scale factors, using ratio and proportion;

Formulate questions that can be addressed with data and collect, organize, and display relevant data to answer them

Formulate questions, design studies, and collect data about a characteristic shared by two populations or different characteristics within one population;

Select, create, and use appropriate graphical representations of data, including histograms, box plots, and scatterplots;

Select and use appropriate statistical methods to analyze data;

Find, use, and interpret measures of center and spread, including mean and interquartile range;

Discuss and understand the correspondence between data sets and their graphical representations, especially histograms, stem-and-leaf plots, box plots, and scatterplots.

Develop and evaluate inferences and predictions that are based on data

Use observations about differences between two or more samples to make conjectures about the populations from which the samples were taken;

Make conjectures about possible relationships between two characteristics of a sample on the basis of scatterplots of the data and approximate lines of fit;

Ocean Literacy Principles (National Marine Educators Association 2013)

Principle 5: The ocean supports a great diversity of life and ecosystems

5F. Ocean ecosystems are defined by environmental factors and the community of organisms living there. Ocean life is not evenly distributed through time or space due to differences in abiotic factors such as oxygen, salinity, temperature, pH, light, nutrients, pressure, substrate, and circulation. A few regions of the ocean support the most abundant life on Earth, while most of the ocean does not support much life.

Principle 6. The ocean and humans are inextricably interconnected.

6D. 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, nonpoint 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.

6G. Everyone is responsible for caring for the ocean. The ocean sustains life on Earth and humans must live in ways that sustain the ocean. Individual and collective actions are needed to effectively manage ocean resources for all.

Climate Literacy Principle

Principle Seven: Climate change will have consequences for the Earth system and human lives.

Materials List

- Printout of Figure 2 and Figure 5 to show students
- Plush toys or 3D printed models of dinoflagellates (The code for producing 3D models is publicly available here: https://sites.google.com/site/drjeffreywkrause/diatom-models)
- Activity sheet (provided below; one per person)
- Colored pencils (1 package per group)
- Printout of heatmaps after students complete their own
- Raised print PIAF handout (optional)

Supplemental material for visually impaired students

- Braille writer and paper if students
- Stick-on gems for students to place data points on the graph

Note that the 3D printed models and raised print figures were designed to accommodate visually impaired students, but were appreciated by sighted students and teachers so were included in the materials list above.

Safety

Students will be handling paper and pencils and any models the teacher has available. Some objects might be sharp, smelly (shells), or heavy.

Procedure

Time requirement: approximately one class period (50 min) unless more background is provided or assigned at the beginning.

Before beginning the activity, the teacher may want to ask students some background questions to gauge what they already know about photosynthesis and its importance, such as:

- What kinds of organisms photosynthesize?
- Why is it important?
- Do you know any marine plants that photosynthesize?
- Do you know that there are microscopic organisms called plankton, specifically phytoplankton, that photosynthesize (they probably know the word "plankton" from the cartoon Spongebob Squarepants)?

Distribute some of the examples of dinoflagellates such as:

a copy of Figure 2; plush toy; or model from 3D printer (Figure 2 is approximately 5,000 times larger than actual dinoflagellate size). Share any of the information provided in the Background section before getting started.

Follow along with the instructions provided in the HAB Handout. In brief, students will be working in groups of 2-3 and answering questions after making a heat map using actual data provided by scientists monitoring the Gulf of Maine. They will then generate a line graph using the time series of data from four of the sites from 2006-2011.

Observation and Discussion

This activity was tested on both sighted and visually impaired students. It was designed to be accessible to visually impaired students through modifications using raised features (Picture in a Flash tactile graphic maker), gem stickers (Figure 8) and/or braille writers (Figure 9) to produce the graphs. The time needed to complete the activity depends on the visual acuity and dexterity of the students, but should be 1-2 class periods. We received positive comments from teachers regarding the use of real data and the opportunity for student participants to generate their own models, as this is often excluded from activities for the visually impaired. Examples of the graphs students produced are in Figures 10 and 11.

Conclusions

Students learned about the importance of HABs and how they impact human health, as well as how coastal waters are routinely monitored to ensure the safety of the seafood we eat. The data plotting exercises familiarize students with different ways that scientists visualize and interpret data, and illustrate the importance of adequate temporal and spatial sampling. Students learned from making both types of graphs and were proud of their accomplishment. They enjoyed the creative element of making the heatmap especially since they were constructed from "real" data collected by scientists studying and modeling HABs in the Gulf of Maine. The students also enjoyed comparing their heat map with those generated by students for other sampling years, which helps to illustrate patterns in cyst distribution that were consistent over time and across geography.

Extensions

Students interested in researching the topic further can prepare a brochure on the topic as described in Fogleman and Curran (2006). Another activity about toxic algae, with details chemistry including photosynthesis (Curran and Robertson, forthcoming). Students who are more interested in the socioeconomic aspect of the problem of HABs could create a mock townhall meeting similar to one described in Williams et al. (2016). This activity enables students to pick or be assigned different stakeholders as they try to resolve a problem that impacts people's livelihoods. Students could also research what government entities are responsible for monitoring the safety of the environment or the exploited resources. In this activity, data were only presented using metric units. If teachers feel that more background is needed on the metric system, they could incorporate the activity described in Curran (2003) or add an exercise converting imperial units to metric ones.

Other activities with modifications for the visually impaired include Curran et al. (2019), Sukkestad and Curran (2012), Thompson et al. (2016), and Curran et al. (2017).

Acknowledgments

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Biosketches

Mary Carla Curran is a Full Professor in the Department of Marine and Environmental Sciences at Savannah State University. She is an active member of the National Marine Educators Association and has extensive experience translating scientific research into peer-reviewed K-12 activities. She is passionate about outreach activities and hopes to encourage students to remain interested in the sciences. Her areas of research include fish biology, parasite-host interactions, and estuarine ecology.

Mindy Richlen is a Research Specialist at the Woods Hole Oceanographic Institution. Her research interests focus on the ecology, physiology, and molecular biology of phytoplankton taxa responsible for harmful algal blooms (HABs). In addition to her research, she is actively engaged in coordinating the interests of HAB stakeholders at the national level through her involvement in the U.S. National Office for Harmful Algal Blooms and the National HAB Committee. As lead of the Community Engagement Core for the Woods Hole Center for Oceans and Human Health, she is involved in fostering data sharing and communication, and translating research findings for diverse audiences.

HAB Handout
Harmful Algal Blooms (HABs): Track them like a scientist

Work in groups of 2 or 3 to complete the heat map you are assigned. The teacher will assign you each with one of the years in Table 1 below. Additional paper may be required to answer the questions.

1. Match the site letters below to the locations on the map (Figure A). Fill in the box for each site with the cyst abundance value for the year you were assigned.

   - Use colored pencils to fill in the scale bar below the map.
   - Locate all sites with 0-149 cysts/cm. Color the circles at these sites blue to match the scale bar.
   - Find all sites with 150-299 cysts/cm. Color the circles at these sites green to match the scale bar.
   - Repeat this process for yellow, orange and red.
   - Find the sites with the most cysts that you colored red. Draw a large red circle or oval that encompasses these sites and shade it in. Your teacher can show you an example if you need more help
   - Draw an orange shape surrounding each of the sites within that concentration range. Fill this in.
   - Draw a yellow shape surrounding your other shapes which also includes any yellow points nearby.
   - Repeat for green and blue.

   Table 1. Cyst concentrations (per cubic centimeter) of dinoflagellate *Alexandrium catenella* in the sediment for three different years in the Gulf of Maine

Site	2006	2009	2011
A	9	25	18
B	84	38	15
C	46	5203	546
D	140	755	557
E	119	183	106
F	590	4205	912
G	668	4080	2115
H	116	78	86
I	25	73	68
J	205	220	243
K	30	65	43
L	18	75	50
M	504	1280	1100
N	28	3315	145

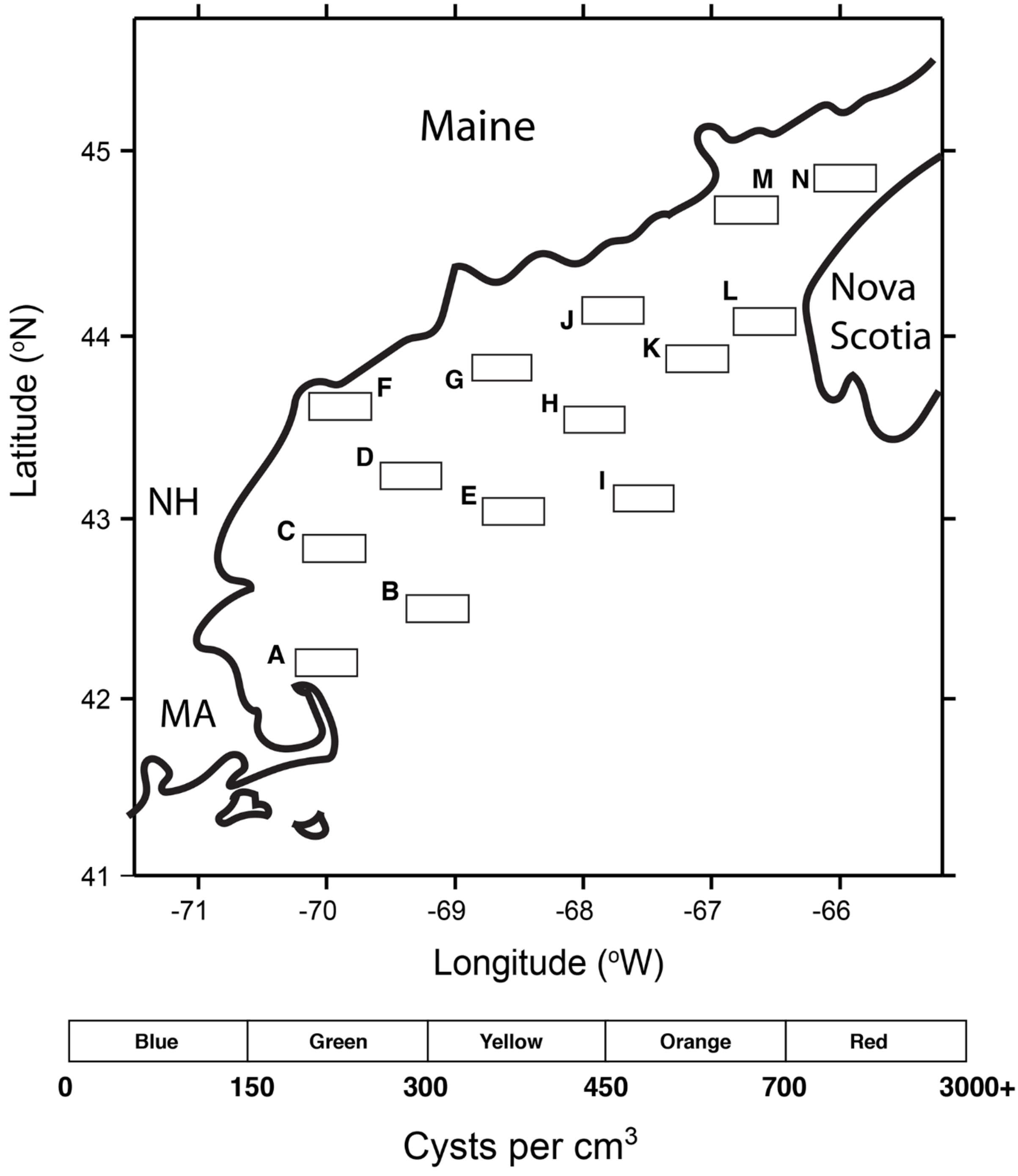


Figure A. Heat map of the cyst concentrations (per cubic centimeter) of the dinoflagellate *Alexandrium catenella* in the sediment in the Gulf of Maine. The term "heat map" is used to describe a scale of, in this case, concentrations from low values (cool colors like blue) to high values (hot colors like red).

2. Which sites have the most *Alexandrium catenella* cysts (red color)? _______________
   Where are there the least (blue color)? _______________

3. Now look at your partner's heat map. At what sites are there the most cysts?
   ________________ and where are there the least? _______________
   What are some other similarities and differences?

4. Now compare your results with the actual heat map provided by your teacher. Note that your teacher's heat map included data from over 30 sites, while yours only had 13 sites. What details did your teacher's map show that yours did not have? In other words, how would having data from more locations change your map? Which of the heat maps that you created was most similar to the heat map constructed by the scientists?

5. Figure B below shows the concentration of cysts in the sediment samples collected from 2006-2011. Site B is already plotted for you. Plot the data for the three other sites provided in Table 2. Use a different symbol (and/or color) for each of these sites and then connect the points for each of the sites using a separate line for each. What differences do you see across years within a site? What differences do you see across the four sites? In other words, is there a benefit to monitoring more than one site or over multiple years? How does that help scientists understand what is happening?

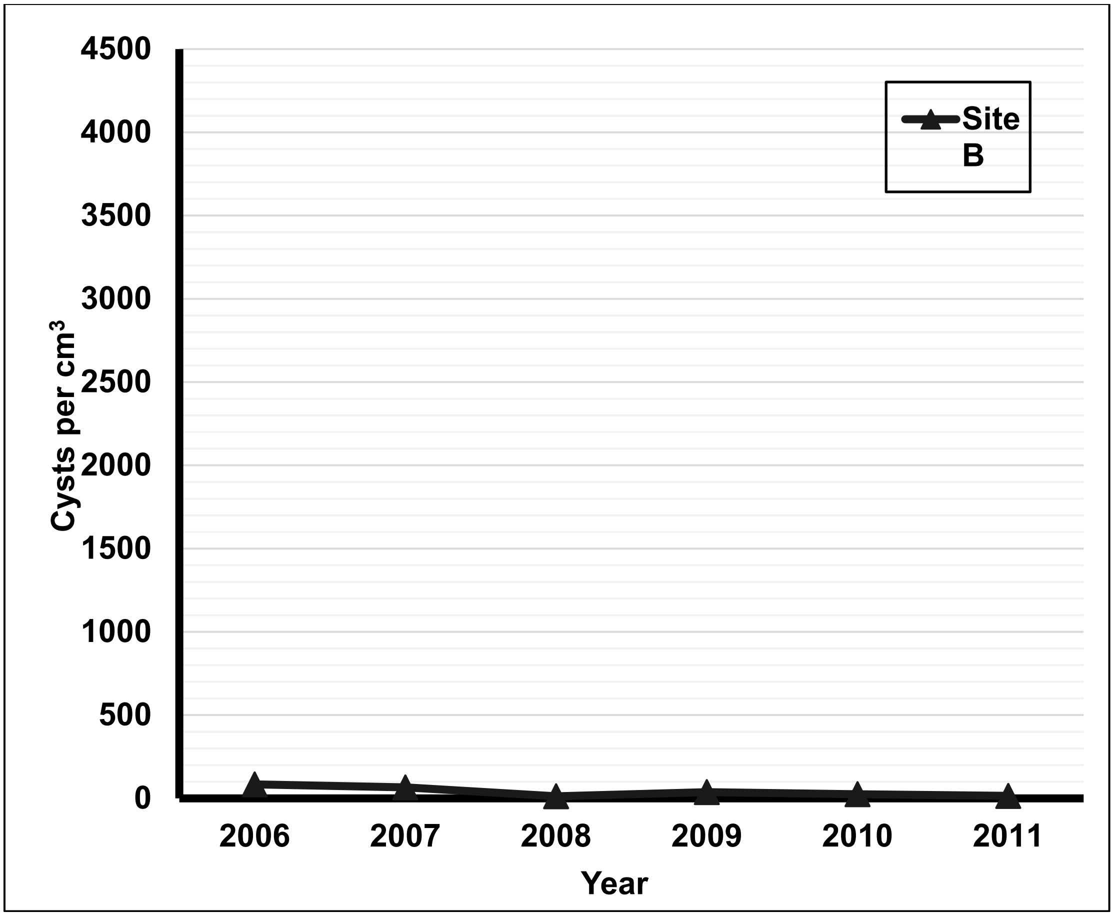


Figure B. Plot the three other sites (G, H, N) using the instructions above. Site B is already plotted for you.

Table 2. Cyst concentrations (per cubic centimeter) of the dinoflagellate *Alexandrium catenella* at a depth of 0-1 cm in the sediment at four different sites (B, G, H, and N) for three different years in the Gulf of Maine.

Site	2006	2007	2008	2009	2010	2011
B (already plotted)	84	66	13	38	25	15
G	668	792	1040	4080	1365	2115
H	116	418	160	78	968	86
N	28	370	200	3315	670	145

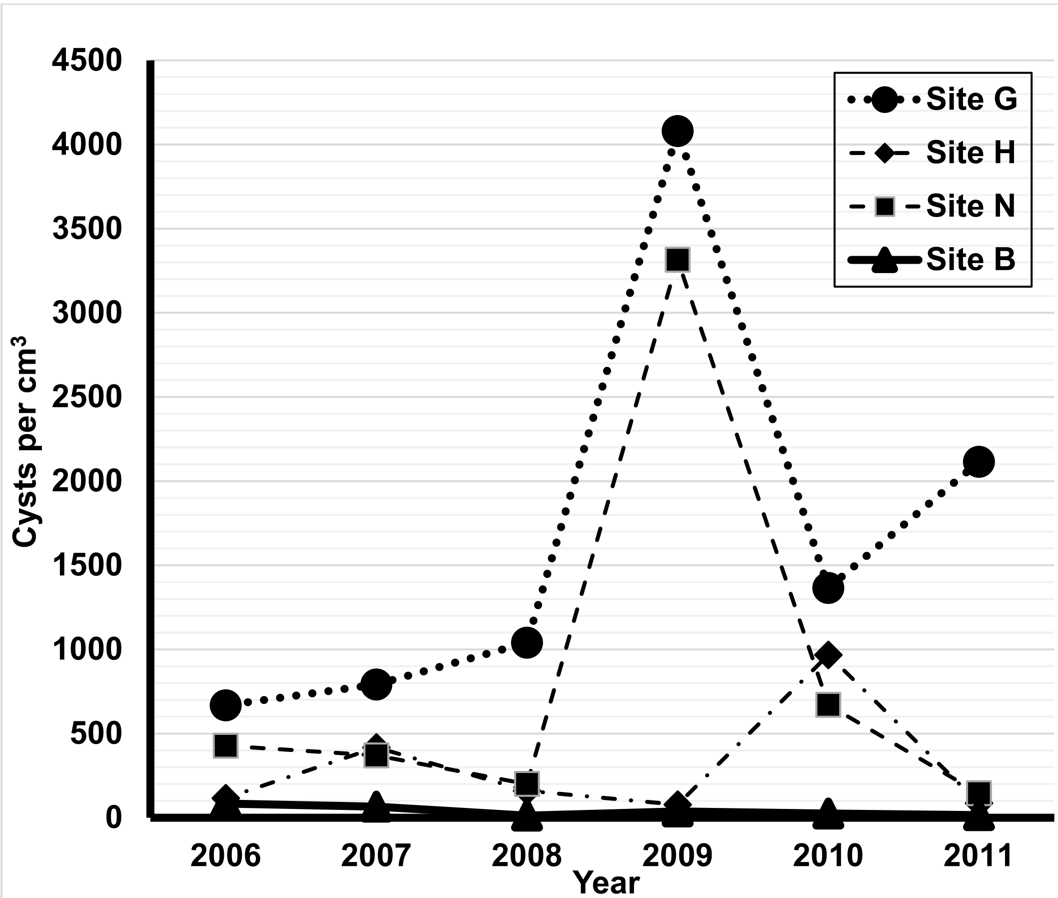
7. The numbers above were presented in cysts per cm3 in order to have a standardized unit that is comparable across studies so that scientists can identify areas with particularly high values. Usually 5 cm^3 of sample is obtained. Given that, what is the highest number of cysts found? What was the lowest number? Time permitting, or as homework, calculate the average value for each year, along with the minimum and maximum value. What is the purpose of calculating the mean value and why was it helpful to monitor 4 sites?

8. These organisms are photosynthesizers and therefore play a role in creating the world's oxygen supply. Discuss how thy are important in food webs and therefore their overall contribution to the cycling of matter.

Answer Key

Question 1. See Figure 4A-C for heat maps produced by scientists.

Question 5. See below.



Original data from Anderson et al. (2014b)

Question 7.

Site	2006	2007	2008	2009	2010	2011
B	420	330	65	190	125	75
G	3340	3960	5200	20400	6825	10575
H	580	2090	800	390	4840	430
N	140	1850	1000	16575	3350	725

Yearly average	1120.0	2057.5	1766.3	9388.8	3785.0	2951.3
Minimum	140	330	65	190	125	75
Maximum	3340	3960	5200	20400	6825	10575

List of Figures

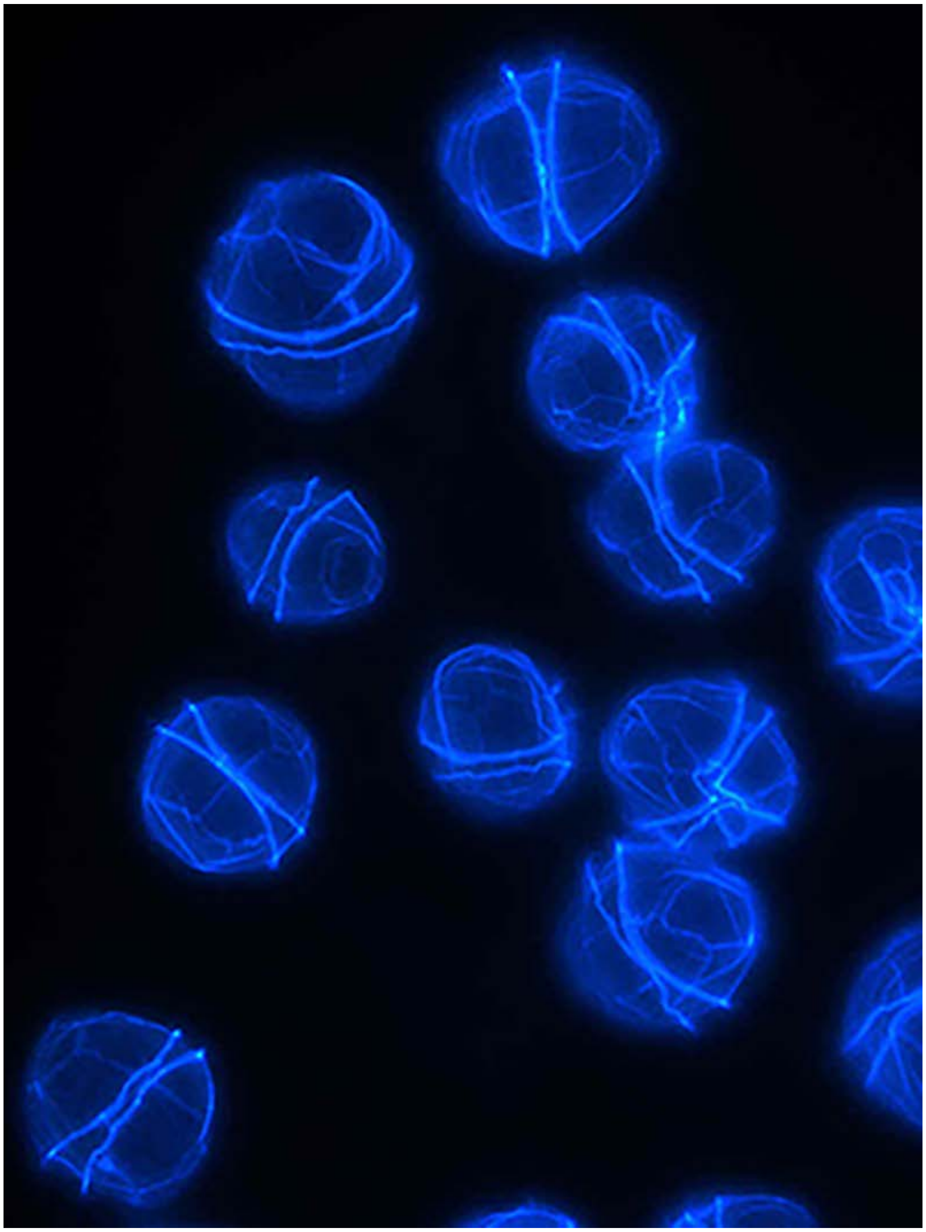


Figure 1. Fluorescent microscope image of *Alexandrium catenella* cells. Photo courtesy of G. Usup.

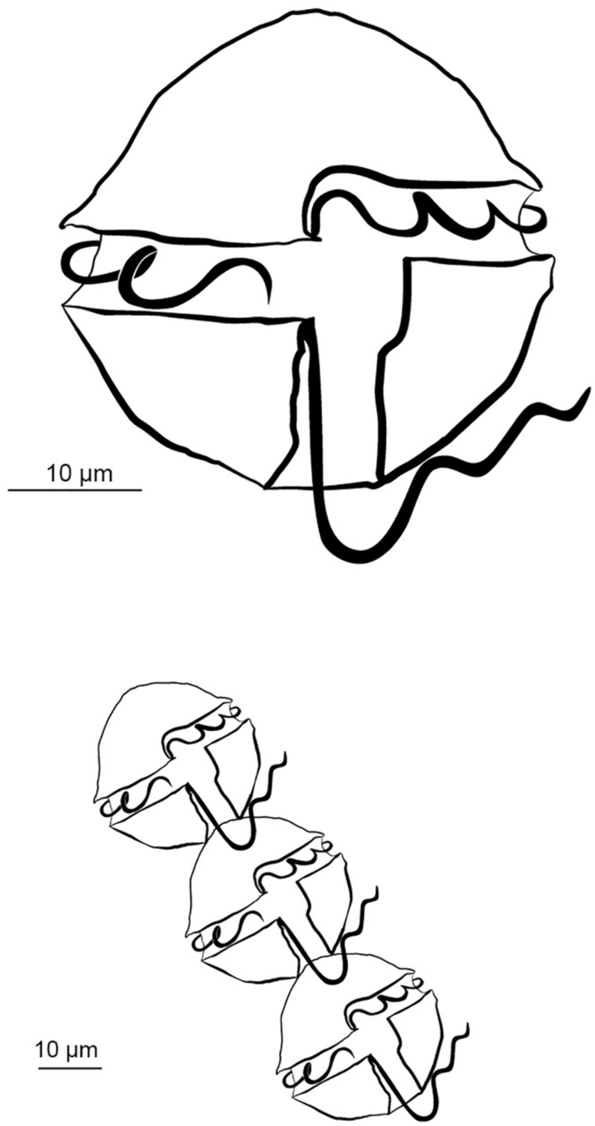


Figure 2. Diagram of a dinoflagellate as a single cell (A) and as a chain (B).

Figure 3. A) Example of signage used for shellfish bed closures and beach closure due to marine and freshwater harmful algal blooms, respectively. Shellfish bed closure photo courtesy of J. Kleindinst; beach closure photo taken by M. Richlen.

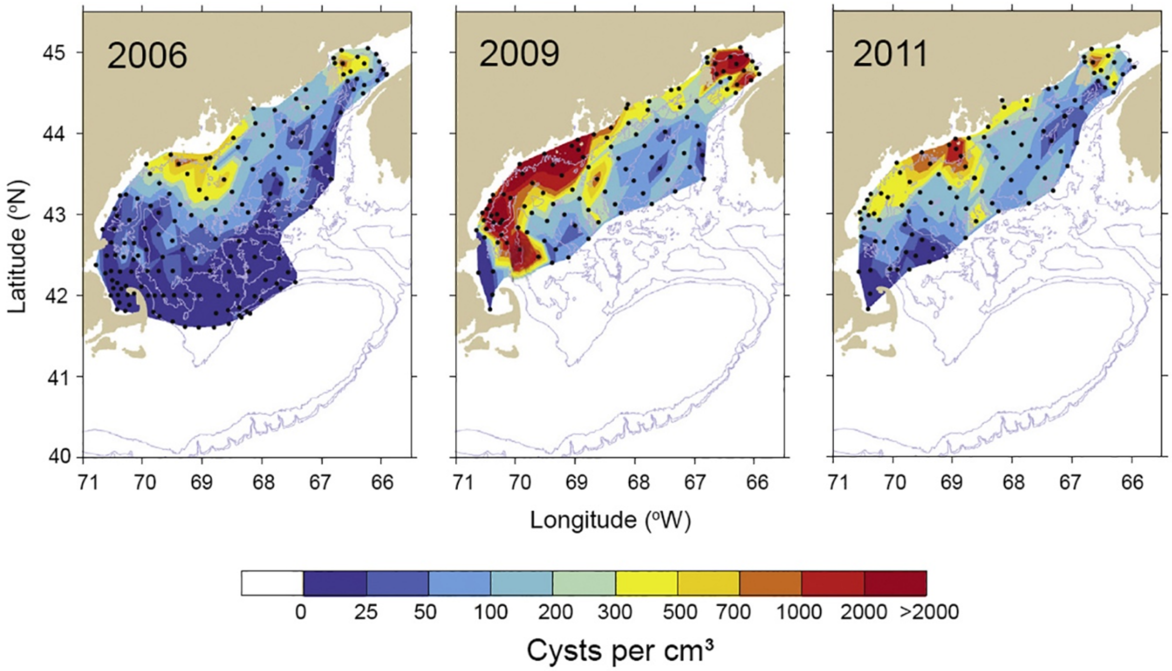


Figure 4A-C. Heat maps of diatom cyst concentrations in the Gulf of Maine from three different years. Figure courtesy of D. Anderson.

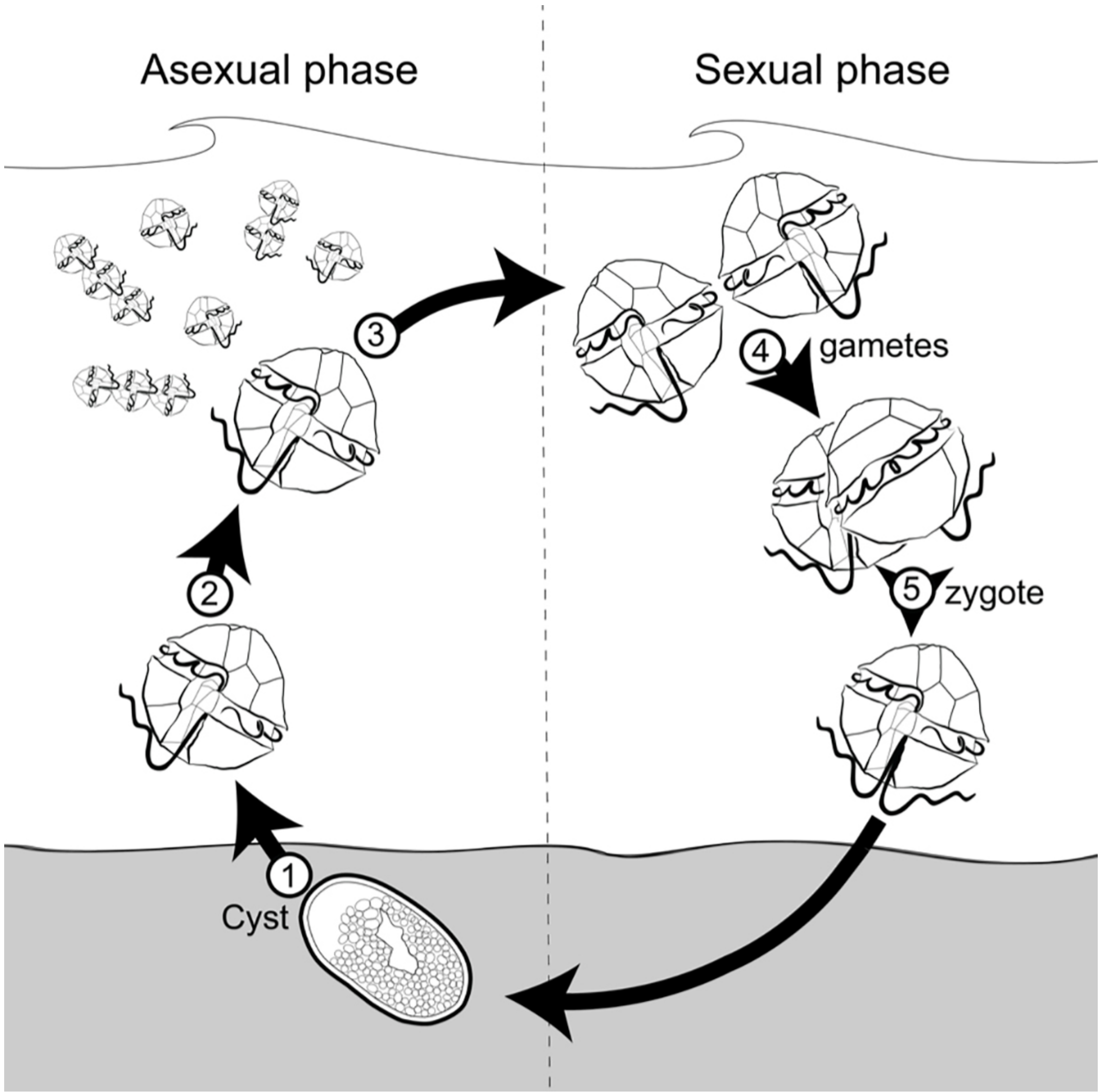


Figure 5. Life cycle of a dinoflagellate that includes a dormant resting phase (1), asexual cell division (2-3) and gamete production (4), and planozygote formation (5). Specifics for each stage are: 1) Cysts of dinoflagellates lay dormant on the ocean floor buried in sediment. Left undisturbed, they can stay in this state for years; 2) When environmental conditions are favorable for growth, cysts germinate and a germling cell called a planomeiocyte emerges. Cyst germination is controlled by a variety of external factors including temperature, light, and oxygen concentrations. Some species have an internal “clock” control; 3) Within a few days of

germination, the swimming cell reproduces by simple division. With abundant nutrients and optimal conditions, cells will reproduce exponentially. A single cell can divide into several hundred cells within weeks. If enough cells "bloom," shellfish can become contaminated with paralytic shellfish poisoning toxins, poisoning humans and the other animals that eat them; 4) Growth stops when conditions are no longer favorable for growth and gametes are formed; and 5) Two gametes fuse, and develop into a planozygote. The planozygote will then thicken its cell wall and condense its cytoplasm to become a cyst. This dormant cyst falls to the ocean floor for germination in subsequent years.

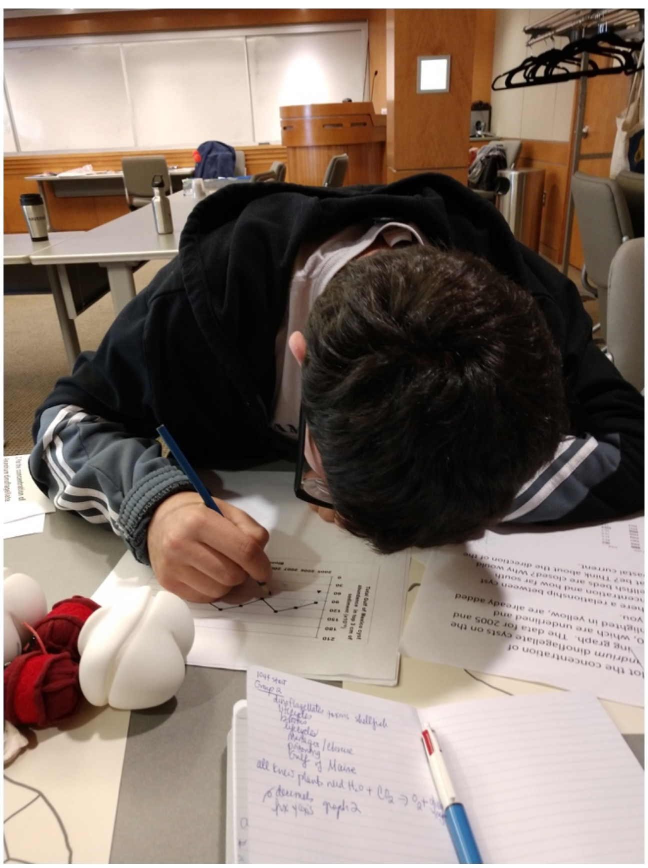


Figure 6. Visually impaired student works on graphing exercise. The 3D dinoflagellate model and plush toy are on the left.

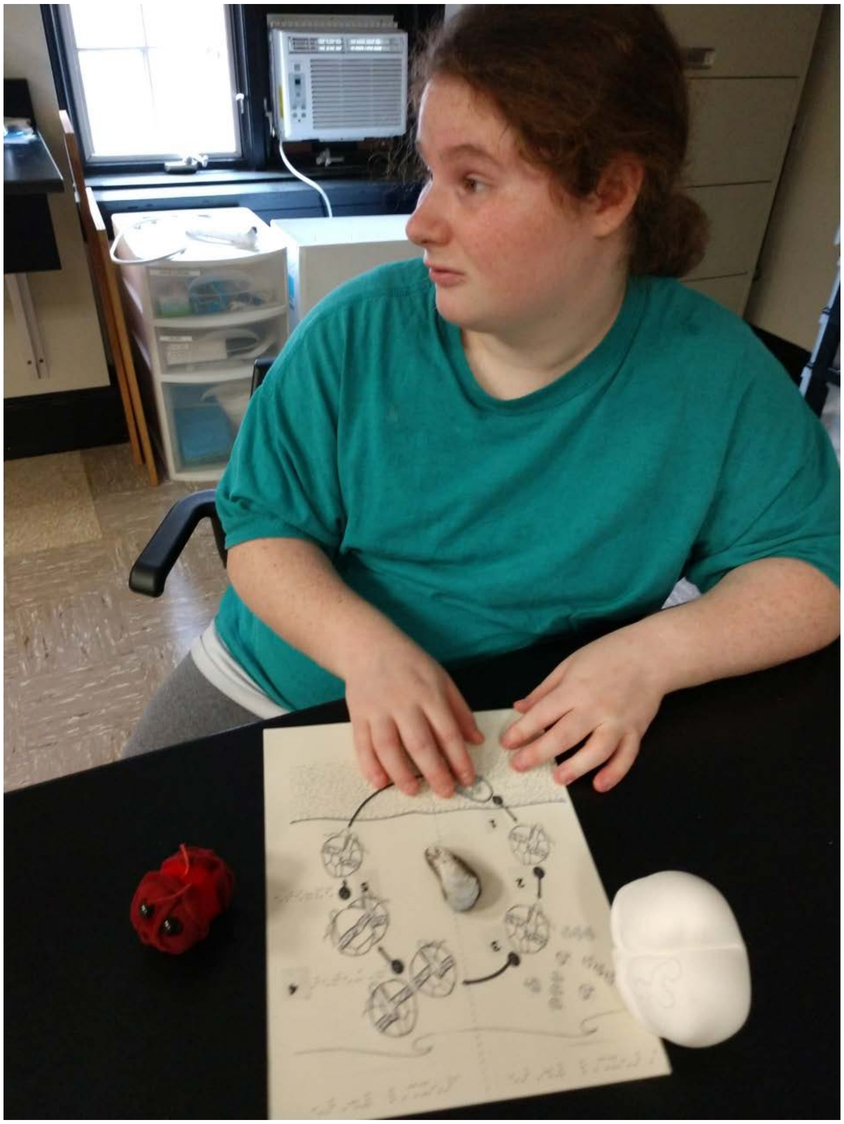


Figure 7. Visually impaired student feels a raised example of the dinoflagellate life cycle. The raised print is made with a Picture in a Flash (PIAF) machine. The dinoflagellate plush toy is on the left and the model dinoflagellate made with a 3D printer is on the right. A mussel, a consumer of dinoflagellates, was placed in the center of the page.

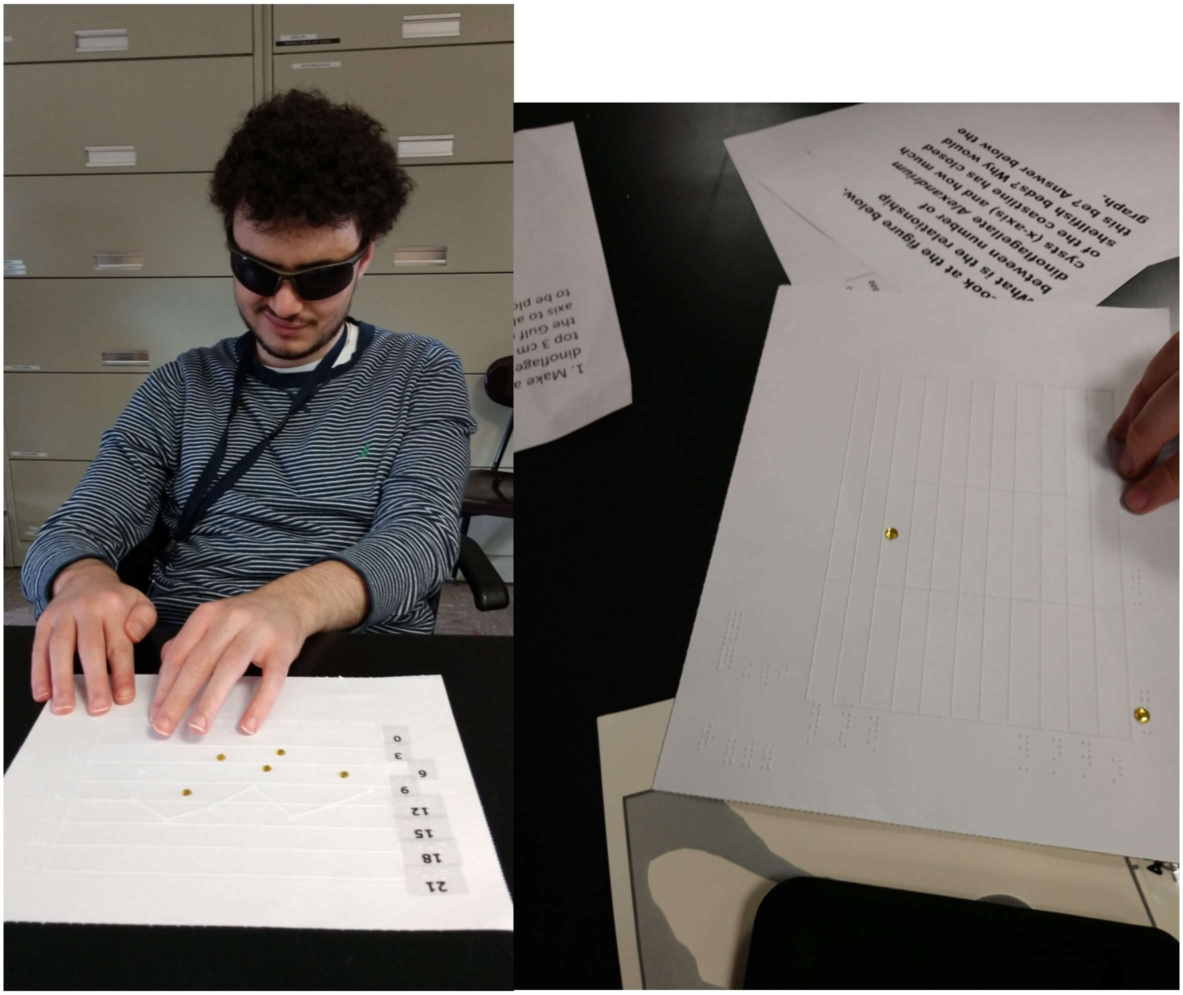


Figure 8. Visually impaired students place stick-on gem data points onto an earlier version in graph provided in braille.

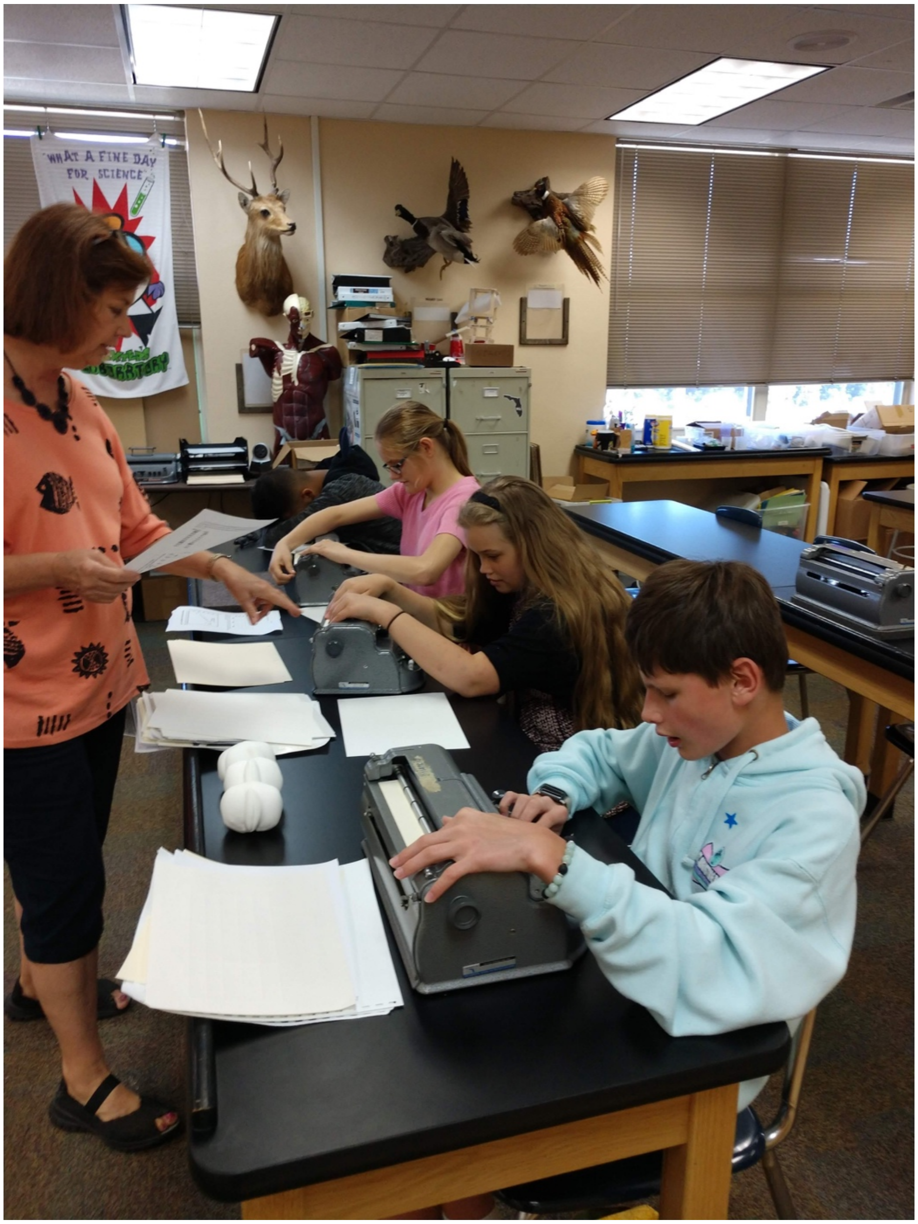


Figure 9. Students at the Florida School for the Deaf and Blind create their own graphs using a braille writer.

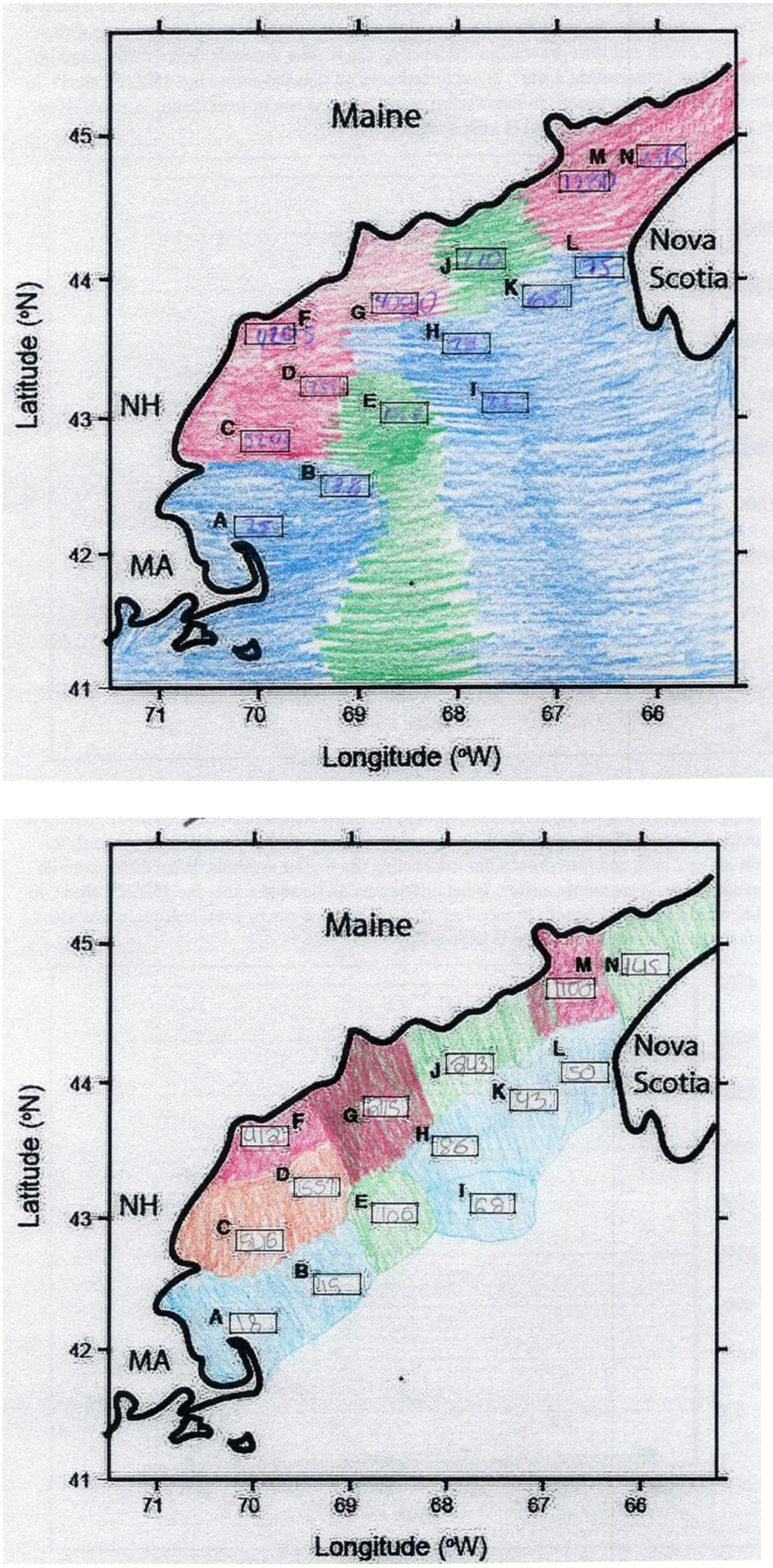


Figure 10. Two examples of heat maps generated by students. A) 2009 and B) 2011.

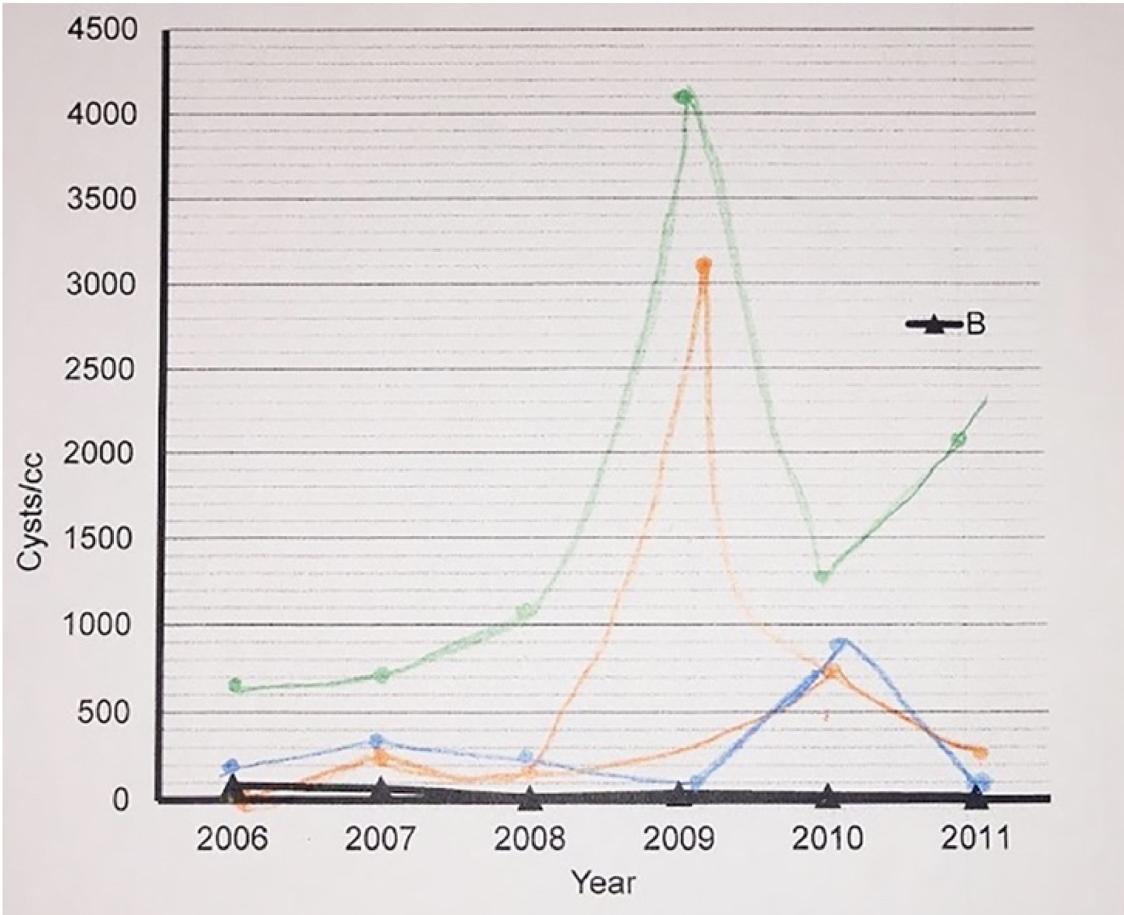


Figure 11. Example of student-generated line graph.