A MANAGER'S DILEMMA: DEFENDING SALT MARSHES AGAINST RISING SEAS

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Grade Level
Advanced High School (AP/IB)
Google Based Classrooms Only

Subject Area
Environmental Science

VA SEA is a collaborative project between the Chesapeake Bay National Estuarine Research Reserve, the Virginia Institute of Marine Science's Marine Advisory Program, and Virginia Sea Grant. The VA SEA project is made possible through funding from the National Estuarine Research Reserve System Science Collaborative, which supports collaborative research that addresses coastal management problems important to the reserves. The Science Collaborative is funded by the National Oceanic and Atmospheric Administration and managed by the University of Michigan Water Center.

<u>*This lesson plan is only compatible with Google schools, in which students have Gmail and Google Drive accounts.</u>

Title: A Manager's Dilemma: Defending salt marshes against rising seas

Focus: With a partner, students will investigate certain features of salt marshes and the effectiveness of salt marsh restorations with sea-level rise, using an online model that simulates a salt marsh's development over time. Students will interpret results, defend their stance on the best management strategy for their salt marsh, and develop a conservation plan based on their results interpretation.

Grade Level: 11–12th grade advanced environmental science class

VA Science Standards:

ES.1 The student will demonstrate an understanding of scientific and engineering practices by

a. asking questions and defining problems
b. planning and carrying out investigations
c. interpreting, analyzing, and evaluating data
d. constructing and critiquing conclusions and explanations
e. developing and using models
f. obtaining, evaluating, and communicating information

ES.6 The student will investigate and understand that resource use is complex. Key ideas include

a. global resource use has environmental liabilities and benefits;
b. availability, renewal rates, and economic effects are considerations when using resources;
c. use of Virginia resources has an effect on the environment and the economy

Learning objectives:

- ✓ Students will use outputs from a computer model to make inferences about salt marshes related to marsh elevation compared to sea level.
- ✓ Students will manipulate inputs to a model to match conditions of their chosen salt marsh.
- ✓ Students will compare graphs of model outputs for different marsh simulations and will develop and refine arguments, supported by evidence, that advocate for a certain salt marsh restoration (or no restoration) strategy.

Total length of time required for the lesson: 60–80 minutes total

Advance preparation of materials: 10 to 15 minutes

Setup: 5 minutes

Introduction to ecosystem services of marsh: 10 minutes

Demonstration with class: 10 minutes

Activity: 90 minutes

Discussion: 5 minutes

Breakdown: 2 minutes

Key words, vocabulary, concepts:

- **Salt marsh:** coastal lowlands that experience tidal influx and outflux of water, nutrients, and sediment and that are composed of salt-tolerant vegetation like grasses and rushes
- **Ecosystem**: the living and non-living components and interactions (relationships) within a defined area (examples: forest, salt marsh)
- **Ecosystem services**: goods and services provided by ecosystems to support people
    - **Carbon sequestration**: removal of carbon from the atmosphere into some semi-permanent storage place, like in sediments or long-term plant biomass.
- **Ecosystem restoration**: attempted return of a degraded (low-health) ecosystem to previous, more resilient conditions
    - **Offshore sill**: a structure located close to land that acts as an impediment (barrier) to incoming waves; can reduce erosion of the shoreline; a type of restoration strategy
    - **Thin-layer placement**: a restoration strategy in which sediment is placed on a marsh in a "thin" layer; this supports elevation gain for wetlands that may be at risk for drowning due to sea-level rise
- **Numerical model**: a simplification of a real-world system that uses equations to simulate a response to changing conditions
    - **Model input**: a value that you feed into a model that controls the simulation response or behavior
        - **Sea-level rise rate**: increase in sea level elevation per unit of time; a model input for this activity
        - **Suspended sediment concentration**: the amount of sediment in the water; sediment that incoming tide brings to the salt marsh; a model input for this activity
        - **Erosion rate**: the width of shore being eroded per unit of time; a model input for this activity
    - **Model output**: a value that the model produces after being run
        - **Elevation profile**: the elevation along a straight line over land or water; a model output for this activity
        - **Width of vegetated marsh**: the width of the marsh that can/is supporting salt marsh plants; a model output for this activity

- **Carbon accumulation rate**: how much carbon is stored per unit area (or per ecosystem) per unit time; usually expressed in kg of carbon per m^2 per year, or kg of carbon per year in an entire ecosystem; a model output for this activity
- **Nitrogen uptake rate**: how much nitrogen is taken up by the salt marsh (or per ecosystem) per unit time; nitrogen uptake by the marsh lowers nitrogen levels in the water and thus increases water quality; usually expressed in g of nitrogen per m^2 per year; a model output for this activity

Background Information:

Salt marshes are coastal lowlands that experience temporary flooding, as tides rise and fall. These ecosystems are adapted to thrive between low and high tide levels, relying on sediment from the incoming tide to help build elevation and supply nutrients to plants. Salt marshes are expert ecosystems at surviving the harsh conditions found at the interface (or connection point) between land and sea. Several forms of salt marsh vegetation are highly adapted to low elevations that are regularly flooded, with special features that allow them to survive low-oxygen and high-salt conditions. Although salt marshes over the past several thousand years have faced the threat of drowning by sea-level rise, they have two natural mechanisms for building elevation at a pace nearly equal to sea-level rise. Firstly, dense and tall salt marsh grasses slow incoming water and facilitate (contribute to or make easy) the dropping of sediment carried in with the tide. This sediment built-up leads to gains in elevation. Secondly, photosynthesis and biomass production by plants also contribute to elevation gain through expansion of roots belowground and the build-up of organic matter like roots, rhizomes, and leaves. However, the ability of salt marshes to survive more rapid rates of sea-level rise now and coming in the next few decades is unclear.

The future of stability of salt marshes are not just threatened by sea-level rise. Erosion of the edge of salt marshes also leads to major losses of marsh area, and all the accompanying ecosystem services. How quickly this erosion occurs is variable (wide-ranging), with some salt marshes not experiencing any erosion but rather developing outward, and with others experiencing up to 6 meters (20 feet) per year of retreat (or loss) (Leonardi et al., 2016; Schwimmer, 2001). Factors that influence erosion rates include strength and height of incoming waves, boat wake, storms, and how erodible the sediment is.

Communities increasingly recognize these threats as important problems to solve. Once thought by humans to be useless land with no ability to grow crops, salt marshes are now understood to be highly valuable, based on the ecosystem services they provide to local communities. For example, they are an important habitat for a variety of fish, shellfish, birds, and mammals, offering these creatures good habitat for feeding and raising young. They are also valued due to recreational opportunities for fishermen and women, hunters, and outdoor naturalists. Since the early 2000s, salt marshes have been increasingly recognized for their ability to store large amounts of carbon, offering a balance to the carbon emissions that drive climate change. Finally, they filter excess nutrients and pollutants from water, enhancing local water quality.

Now that coastal communities recognize the importance of protecting salt marshes, they have developed several strategies for restoration. For salt marshes experiencing rapid rates of sea-level rise, marsh managers are increasingly trying a strategy known as thin-layer placement. This involves depositing anywhere from approximately 3 to 25 cm of sediment on top of the marsh to help create a higher elevation relative to sea level. For marshes experiencing rapid rates of erosion, marsh managers typically protect the edge of the marsh by building offshore sills. These sills slow incoming waves that otherwise would batter against the marsh edge.

Finally, marsh managers and scientists who study marshes can use what is known as numerical modeling. Numerical models can help managers and researchers understand marsh processes and support their management decisions. At its foundation, a numerical model links several to hundreds of related equations together, creating a series (or a web) of equations that produce outputs that feed the next equation. These equations are typically based on real-world measurements. By using models, researchers can take observations of important environmental conditions, feed them (or input them) into the model, and then simulate the marsh processes that are controlled by those conditions. For example, (and in this activity), important environmental conditions like the rate of sea-level rise, the suspended sediment concentration, and the rate of edge erosion are the inputs for the model that drive change in elevation, marsh width, and carbon storage.

Materials & Supplies:

- Online Manager'sDilemma_Marsh Model with link here: https://tinyurl.com/yc533cj6
- VASEA.zip zip file (downloadable with this lesson plan on the VASEA website)
    - Teacher should share this with students via Google Drive
    - Students need to save this as part in their main Google Drive (not in a subfolder!)
- At least one computer per group (preferably one per student)

Procedure:

1. Teacher passes out handouts and computers or shares handouts with students (either as a Google document or a Microsoft Office document)
2. Teacher instructs students to open their computers and access their Google Document, walking around to make sure that every student is ready before proceeding. Teacher instructs students that after the class has run through the PPT together, they will be put in groups, but for questions #1-4, they will be answering independently.
3. Teacher displays the second slide of the PowerPoint (provided), which shows a salt marsh habitat

a. Teacher reads the definition of "ecosystem service" which is shown on the top of the slide
b. Teacher explains that he/she will show examples of beautiful ecosystems and some of their services in the next few slides

4. Teacher displays the third slide of the PowerPoint, which shows a forest [can skip if a short class period or students are already familiar with ecosystem services; this step is for students who need a general introduction to ecosystem services]
    a. Teacher explains that the forest provides numerous ecosystem services that benefit society
    b. "I DO": Teacher names one (habitat for plants and animals that are important sources of food and medicine for some communities)
    c. Teacher explains that it might be hard to visualize these services in this image, so teacher clicks to the next slide.
    d. Teacher observes aloud one more ecosystem service that are shown in the image: trees for lumber/construction
    e. "WE DO": Teacher asks for student volunteers to identify other ecosystem services referenced in the photo
    f. Teacher clicks to the next slide to display other possible answers
5. Teacher displays the next slide of the PPT, which shows a salt marsh habitat and tells students that they will watch what happens to a salt marsh during a complete tidal cycle because understanding what the tides bring in and take out from the salt marsh is the first step to understanding their ecosystem services.
    a. Teacher clicks to the next slide with a GIF of a mudflat, salt marsh, forest diagram.
    b. Teacher instructs students to watch the GIF.
    c. Teacher clicks to the next slide in which two questions appear, which are the same #1 and #2 questions on the students' handout.
    d. Students write down their answers to #1 and #2.
    e. Teacher asks for students to volunteer the answers and class reviews answers together.
    f. Teacher clicks to next slide which displays answers.
    g. "YOU DO": Teacher clicks to next slide and instructs students that they have 30 seconds to identify and write down at least two salt marsh ecosystem services based on the diagram.

6. Teacher then walks through possible answers, pausing when an arrow appears on the screen, and asking for a student volunteer to answer why the first action is important
    a. What does absorbing nutrients do? Why is it important? Improves water quality by removing excess nutrients and pollutants.
    b. Why do fish and birds need habitat? What do they do with that habitat? Find food and raise young
    c. Why is carbon storage important? Why do we not want it in our atmosphere but want it in the soil? Because carbon in the atmosphere contributes to climate change and global warming
    d. Why is slowing waves down important? When would people living near the coast want slower or smaller waves? Slowing waves means less wave-power reaches houses. This can protect structures and peoples from storms
    e. Teacher should give students the option to share any other ways that salt marshes support coastal communities.
7. Teacher asks for student volunteer to read sea-level rise slide.
8. Teacher asks for student volunteer to read about the two examples of marsh restorations.
    a. Teacher instructs students to answer question #4 from PPT (slide #35) on their Google Doc as a quick comprehension check
9. Teacher asks for student volunteer to read definition of numerical model
10. Teacher explains model inputs following definitions on the PPT.
    a. Teacher explains the text "Site Conditions" outlined in red is an example of the information students will receive for their marsh. These are the constants for the experiment
    b. Teacher explains that the black box "1) Site Conditions (model inputs)" is what the computer model looks like
    c. Teacher explains that marsh restoration is the independent variable for the students' model experiments –they want to see what effect marsh restorations have on the health of their marsh's ecosystem services. Students can check or uncheck the marsh restoration options in the model to turn the restorations "off" or "on." They can also be used together.
11. Teacher explains model outputs and has a student volunteer read what they are equivalent to in an experiment (the dependent variables)
    a. An example marsh elevation profile (outlining the elevation of the marsh from the marsh edge and water on the left to more inland marsh on the right)
    b. Teacher explains that the blue line outlines the marsh's elevation at the start of the model experiment, and the orange outlines the marsh after 50 years.

c. Teacher explains that students will have to analyze how their marsh has changed over 50 years, so let's do this one together. Teacher asks class what changes they observe and then clicks next slide where answers appear.

12. Teacher shows map of marsh sites and explains that the directions on the slide
13. Teacher walks through the example handout with the class, following the text in red
14. Teacher walks through one ultimate example with the class, showing them how to read the pie charts, how to fill out their Google Doc tables.
    a. Teacher asks who remembers how we can monitor how much marshes improve water quality? (reference to Slide #28).
    b. Teacher explains the drop-down menus in the Google Doc tables.
    c. Teacher explains the how to select the correct restorations and ecosystem services in the model and how to copy and paste the resulting graphs in the Google Doc table.
    d. Teacher walks through the comparison of the sill marsh vs the no restoration marsh and shows the example "Assessment…" text to insert into the right-most column in the table.
    e. Teacher does the same for the TLP marsh, showing students the green text box that appears with the graph, saying "The nitrogen uptake rate drops following each thin-layer placement because salt marsh plants uptake more nitrogen when elevations are closer to sea level because the marsh is flooded more. However, thin-layer placements increase elevation beyond sea level, resulting in less flooding."
    f. Finally, teachers ask students to decide if this was their marsh, and if they were only managing for water quality ecosystem services, and they could only decide between sill and TLP, which should they choose? Student volunteer should say the sill.
15. Teacher follows the online link to the model.
    a. Teacher demonstrates how to save the provided .zip file containing all the necessary data to Google Drive (not in a subfolder)
    b. Teacher has student volunteers read the five instructions at the top of the model for how to use the model
    c. Teacher gives 1-minute demonstration of selecting inputs and observing graph outputs
16. Teacher instructs students to answer preliminary questions on handout, which gives them background knowledge about how to use the online model outputs and the elevation that salt marshes develop.

a. Teacher switches to next, and last, slide that shows the map of marsh sites that students will have to starting at Question #10
b. Teacher walks around and answers questions and passes out marsh site handouts based on which site students choose to manage (choosing between a salt marsh in Virginia, Louisiana, Massachusetts, or California)
c. Teacher continues to walk around and answer questions and give students time checks.

17. With 5 minutes remaining in class, teacher instructs students to finish their last question. Teacher asks groups to raise their hand if they had Site #1. Teacher asks: a) which ecosystem services they were managing for, b) which metrics they used to track whether those services were maintained, c) which restoration strategy those chose.
    a. Teacher does the same for the remaining Sites #2-4.
18. Teacher instructs students to submit assignments, put computers away, collect the site handouts, and pack up.

References:

Holzwarth, Stefanie & Thonfeld, Frank & Abdullahi, Sahra & Asam, Sarah & Canova, Emmanuel & Gessner, Ursula & Huth, Juliane & Kraus, Tanja & Leutner, Benjamin & Kuenzer, Claudia. (2020). Earth Observation Based Monitoring of Forests in Germany: A Review. Remote Sensing. 12. 10.3390/rs12213570.

Leonardi, N., Defne, Z., Ganju, N. K., and Fagherazzi, S. (2016), Salt marsh erosion rates and boundary features in a shallow Bay, *J. Geophys. Res. Earth Surf*., **121**, 1861-1875, doi: 10.1002./2016JF003975.

Schwimmer, R.A. Rates and processes of marsh shoreline erosion in Rehoboth Bay, Delaware, U.S.A. *Journal of Coastal Research* **17**, 672–683 (2001).

Handouts & Student Worksheets:

1. Student instructions document, which is downloadable with this lesson plan on the VASEA website AND included below
2. Marsh site handouts, which is downloadable with this lesson plan on the VASEA website AND included below
    - Must be printed and cut in half ahead of time
    - Students select which marsh site to "manage," so teacher should print more than enough for multiple groups to choose the same site!
3. Student worksheet, which is available in three versions, according to teacher preference (the first two use drop-down menus for several questions, and hence don't work as a printed document for students to complete by hand)
    - Google document with link here: https://tinyurl.com/8fudznup
    - Microsoft Word document (for students to complete on their computers), downloadable with this lesson plan on the VASEA website
    - Printable Microsoft Word document (for students to complete by hand), downloadable with this lesson plan on the VASEA website AND included below

Student Instructions for "A Manager's Dilemma"

PART I: MARSH ECOSYSTEM SERVICES

Questions 1 through 4:

Already answered during the teacher's presentation

PART II: WHERE DO SALT MARSHES LIKE TO GROW?

Question 5:

1. Follow the link to the model that you will be using: http://tinyurl.com/ydb33d7z
2. Read through the five instructions at the top!
3. Hit the first "play button," and then accept all permissions for this file to connect to your Google Drive. This will allow your data to upload to the model!
4. Choose model inputs for the 3 variables that appear below.
   a. These are like your "constants" that you don't change between experiments.
   b. Only when "constants" stay the same from one experiment to the next, can we actually measure the effect of our independent variables (in your case: the type of restoration that works best to save your marsh!).
5. You can choose any combination* of these 3 to answer Questions #5-9 on your handout.
   a. *The only combination that won't work is SLR: 6, Erosion: 1,4, SSC: 10 because the marsh drowns very early in the model run.
6. Scroll to "B) Sea-level rise (model outputs)" and press the play button.
7. Press the "Graph sea level" button, and wait ***(it will take up to 30 seconds)*** as the model produces your first model output, a sea-level rise curve!
8. Answer question #5.

Questions 6 through 9:

1. Scroll down to "C) Sea-level rise and marsh elevation (model outputs)."
2. Hit the button "Create graphs" to create two graphs that compare average marsh elevation to two different x-axis variables: on the left, mean sea level (or average sea level) and on the right, mean high tide (average sea level at high tide).
3. Looking at the graphs, answer questions 6 through 9.

PART III: YOUR MARSH SITE

Questions 10 through 13:

1. Looking at the map that your teacher displays on the board, discuss with your partner which marsh you want to manage as part of this activity.
2. Raise your hand and your teacher will bring around your marsh site handout.
3. Once you have your handout, read the handout to learn about your marsh.
4. In your handout, record information about the inputs specific to your marsh.

PART IV: SOLVING YOUR DILEMMA THROUGH RESTORATION

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PART V: COMMUNICATING YOUR SOLUTION

Questions 14 through 16:

1. Now, you will start your control/no restoration model runs.
2. Return to the top of the model script and designate (select) the correct site conditions (model inputs) based on the rate of sea-level rise, rate of erosion, and amount of suspended sediment at your marsh site.
3. Once you hit the first play button in the section “D) Marsh Restorations (the experiment),” make sure that both the “Offshore sill” and the “TLP” box are NOT checked.
    a. You will come back to those in a second. This way, you can observe the results with a no-restoration (or control) marsh before you restore it.
    b. In these model runs, marshes that receive thin-layer placements get 5 centimeters of sediment **every 15 years**.
4. By hitting the “Create marsh elevation profile” button, you will create a graph (or profile) of your marsh elevation.
5. As your eyes move toward the right (increasing x-axis values), you are increasing the distance from the water and moving more inland. As your eyes move towards the left, you are moving closer to the body of water (a bay or a creek) that feeds water and nutrients to the marsh.
6. Answer questions 14 through 16.

Questions 17 through 22:

1. Now, you should bounce back and forth between section D) and section E) in the model.
2. In Section “E) Marsh ecosystem services (the results!),” you can select which marsh ecosystem services to graph. Pay most attention to the marsh ecosystem services that your community cares most about, according to the poll results.
3. If you want to compare the "no restoration" marsh to your chosen restoration strategy, select the "show control and restoration outputs together" option. Keep in mind that if you don't have a restoration selected under section "D) Marsh Restorations (the experiment!)", then you won't have anything to compare to the no-restoration outputs.
4. Returning to the section: “D) Marsh restorations (the experiment!),” spend some time playing with the different restoration strategies (by clicking the box for the sill only, for the thin-layer placement only, and both at the same time), with the goal of finding the strategy that maximizes (increases the most) the ecosystem services that you are managing for your site. ***Keep in mind that the no-restoration (control) strategy might be the best option for your marsh, depending on your site conditions (inputs) and which ecosystem services your community cares about.***
5. Answer questions 17 through 22

MARSH SITE #1: Golden Gate National Recreation Area, San Francisco, California

Site conditions:

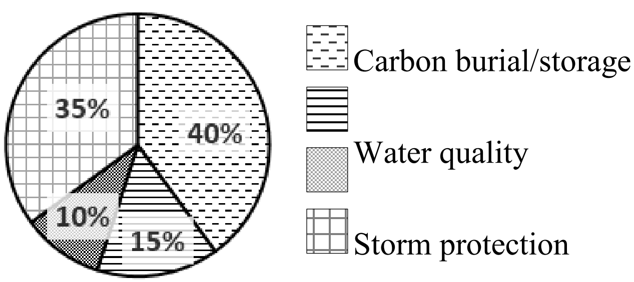
Rate of local sea-level rise: 2 mm yr^{-1} (2 millimeters per year, which is very slow compared to other coastal areas in the U.S.)

Average rate of marsh edge erosion: 4 m yr^{-1} (4 meters of marsh loss per year)

Average suspended sediment concentration in the incoming tidal water: 20 mg L^{-1} (20 mg of sediment per liter of water, which is somewhat low)

Photograph of your management team at your marsh site:

The breakdown of survey responses to the question "Which salt marsh ecosystem service is the most important to you?" is shown below:



These responses make sense to you due to the state's emphasis on climate change and due to its fishing economy and bird migration flyways.

To monitor how well the salt marsh is storing carbon, you should measure carbon accumulation (how much carbon the marsh takes up in a year). To monitor how well the salt marsh provides fish and bird habitat, you should monitor the marsh width.

MARSH SITE #2: Bayou Sauvage National Wildlife Refuge, outside New Orleans, Louisiana

Site conditions:

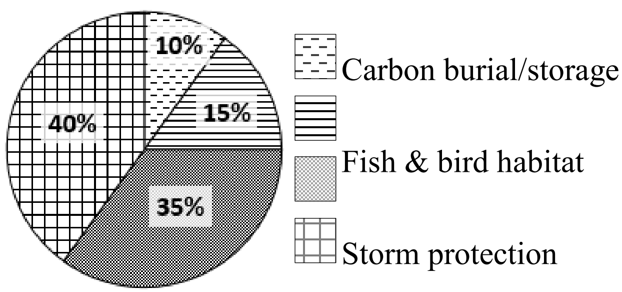
Rate of local sea-level rise: 6 mm yr^{-1} (6 millimeters per year, which is very fast compared to other coastal areas in the U.S.)

Average rate of marsh edge erosion: 4 m yr^{-1} (4 meters of marsh loss per year)

Photograph of your management team at your marsh site:

Average suspended sediment concentration in the incoming tidal water: 30 mg L^{-1} (30 mg of sediment per liter of water, which is somewhat high)

The breakdown of survey responses to the question "Which salt marsh ecosystem service is the most important to you?" is shown below:



These responses make sense to you due to the high number of storms that hit the Louisiana coast as well as farmers' heavy fertilizer use, which lowers nearby water quality.

To monitor how well the salt marsh lowers fertilizer levels, you should measure nitrogen uptake. To monitor how well the salt marsh can lower storm energy, you should measure the width of the salt marsh.

MARSH SITE #3: Norfolk, Virginia

<u>Site conditions:</u>

Rate of local sea-level rise: 6 mm yr^{-1} (6 millimeters per year, which is very fast compared to other coastal areas in the U.S.)

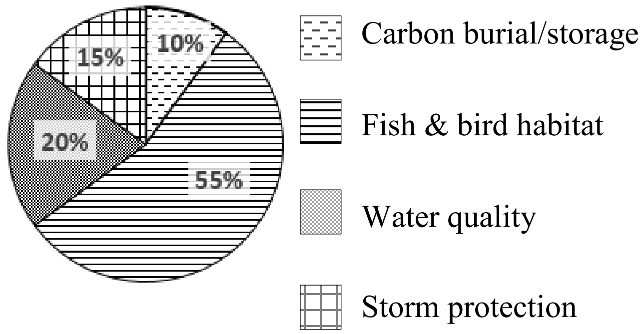
Average rate of marsh edge erosion: 1 m yr^{-1} (1 meter of marsh loss per year)

Average suspended sediment concentration in the incoming tidal water: 20 mg L^{-1} (20 mg of sediment per liter of water, which is relatively low)

Photograph of your management team at your marsh site:

The breakdown of survey responses to the question "Which salt marsh ecosystem service is the most important to you?" is shown below:

These responses make sense to you due to the community of people who like to be explore marshes, observing birds



and other wildlife, and due to water quality issues across the Chesapeake Bay.

To monitor how much fish and bird habitat the marsh provides, you should measure marsh width. To monitor how well the salt marsh lowers nutrient levels, you should measure nitrogen uptake.

MARSH SITE #4: Woods Hole, Cape Cod, Massachusetts

Site conditions:

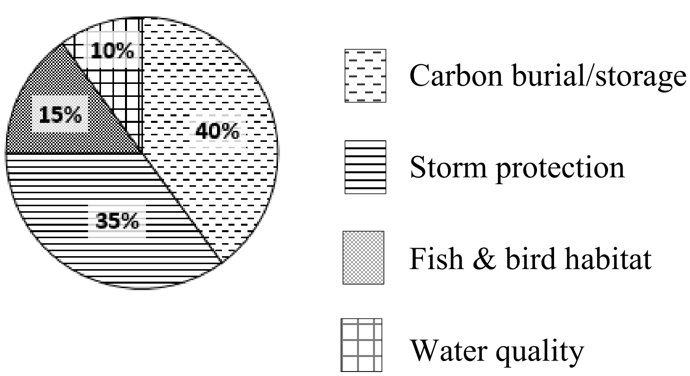
Rate of local sea-level rise: 4 mm yr^{-1} (4 millimeters per year, which is relatively slow compared to other coastal areas in the U.S.)

Average rate of marsh edge erosion: 1 m yr^{-1} (1 meter of marsh loss per year)

Average suspended sediment concentration in the incoming tidal water: 10 mg L^{-1} (10 mg of sediment per liter of water, which is very low)

Photograph of your management team at your marsh site:

The breakdown of survey responses to the question "Which salt marsh ecosystem service is the most important to you?" is shown below:



These responses make sense to you due to the emphasis on climate change in Massachusetts and on the frequent storms that batter the coastline.

To monitor how well the salt marsh is storing carbon, you should measure carbon accumulation (how much carbon the marsh takes up in a year). To monitor how well the salt marsh can reduce storm energy, you should monitor marsh width.

Name: Partner names(s): Date:

PART I: MARSH ECOSYSTEM SERVICES

1. Describe what happens to a marsh during the high tide and during the low tide.

2. Make a hypothesis about what the incoming water (during high tide) delivers to the marsh.

3. Identify at least two ecosystem services you think a salt marsh provides.

4. Imagine the marsh that you are trying to save is being eroded quickly because of high wave energy. Which restoration strategy do you think would be better at protecting your marsh: thin-layer placements every 15 years OR a sill?

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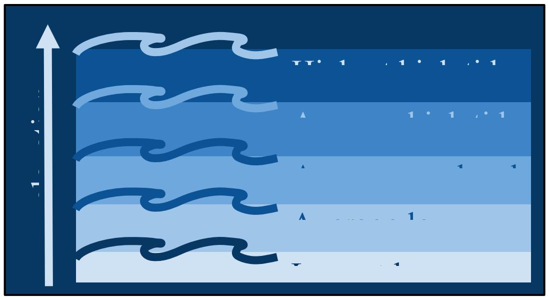
ART II: WHERE DO SALT MARSHES LIKE TO GROW?

5. Which rate of sea-level rise did you choose, and how many meters (plotted on your y-axis) does sea-level increase between year 0 and year 150?

6. Choose a few single "mean sea level" points on the left graph. How does the x-axis value compare to the y-axis value when you pick those points? Is your x-axis value greater, smaller, or the same compared to your y-axis value?

7. Now, choose a few single "mean high tide" points on the right graph. How does the x-axis value compare to the y-axis value when you pick those points? Is your x-axis value greater, smaller, or the same compared to your y-axis value?

8. Draw a circle/dot in the image below that shows at what elevation salt marshes are likely to grow.



9. Using your analysis of the two graphs, circle the correct word in parenthesis or fill in the blanks to complete these statements: Using the model outputs, we can conclude that salt marshes prefer to grow at elevations that are (above, below, **or** equal to) average sea level and (above, below, **or** equal to) mean high tide. We form this conclusion based on model outputs that show a (positive, negative, **or** no) relationship between ______________ (write in your x-axis variable) and ______________ (write in your y-axis variable). This indicates that as (mean sea level **or** average marsh elevation) increases, salt marsh elevation will have to (increase, decrease, stay the same **or** do nothing in particular) in order for marshes to survive.

PART III: YOUR MARSH SITE

10. How quickly is sea level rising at your site? (include units!) ___________
11. What is the marsh erosion rate for your site? (include units!) ___________
12. How much sediment is in the water brought in with the rising tide? (include units!) _____
13. Fill out the table below based on which two marsh ecosystem services the surrounding local community values the most and how will you measure each. (Read your site handout carefully if you're unsure.)

	Marsh ecosystem service	Measurement used to determine how well the marsh is providing the service
First priority		Marsh width, amount of carbon buried every year, **OR** amount of nitrogen used every year
Second priority		Marsh width, amount of carbon buried every year, **OR** amount of nitrogen used every year

PART IV: SOLVING YOUR DILEMMA THROUGH RESTORATION

14. In the plot below, draw the two elevation profiles from year 1 and year 50. Focus on the major trends, not the individual points for each location along the marsh. Spend no more than 2 minutes on this!

15. Describe what happened to your marsh's elevation profile over time. Be specific about elevation and width changes at different locations in the marsh, and be quantitative (using numbers and number comparisons) as much as possible.

16. Based on your answer to #15, do you think that your marsh might benefit from restoration? Why or why not?

17. In the table below, fill in the blank with the first ecosystem service listed in your answer to #13 above.
    a. For each graph, describe how the restoration marsh compares to the no-restoration marsh through time, being quantitative (using numbers and number comparisons) as much as possible. **Make sure to document if the restoration becomes more or less effective as time goes on.**

Restoration	Assessment of how the restoration compares to the no-restoration marsh
Sill	
TLP	
TLP and sill	

18. Follow the same steps as you did for the table above, but for the second ecosystem service from your answer to #13 above.

Restoration	Assessment of how the restoration compares to the no-restoration marsh
Sill	
TLP	

TLP and sill	

19. Comparing the 4 restoration options (including the no restoration option)…
    a. …which restoration strategy maximizes the first ecosystem service you monitored in the table for #17? Think about how much the marsh function improves during the 150 years and by the end. ___________________
    b. …make a hypothesis about why this restoration did the best. (Think about what your no restoration marsh looked like by year 50 according to your graph for #14)

20. Comparing the 4 restoration options (including the no restoration option)…
    a. …which restoration strategy maximizes the first ecosystem service you monitored in the table for #18? Think about how much the marsh function improves during the 150 years and by the end. _________________________
    b. …make a hypothesis about why this restoration did the best. (Think about what your no restoration marsh looked like by year 50 according to your graph for #14)

21. What might happen if you make habitat management decisions based on only one or two ecosystem services and ignore other services that might also be important?

PART V: COMMUNICATING YOUR SOLUTION

22. At this point, you have completed a thorough analysis of the effectiveness of restoration on your marsh's ability to provide certain ecosystem services under sea level rise rates projected for the next 150 years. You have parameterized (set initial input conditions) for your specific marsh site, and now you have the knowledge to make an argument for why you should choose certain restorations over others. Using your responses from previous questions, on a separate sheet of paper, write at least 5 complete sentences to your local and/or state government making the case for why your marsh needs (or does not need) funding for restoration. To make a strong argument, include the following:
    a. why salt marshes are important
    b. what threats salt marshes are facing, leading into your specific marsh
    c. your model outputs showing what may happen to your marsh if not restored
    d. cite at least 3 figures from your model outputs in your argument
    e. reference the preferences of your local community members who responded to the poll
    f. Indicate which restoration strategy is best and WHY

Teacher Answer Key

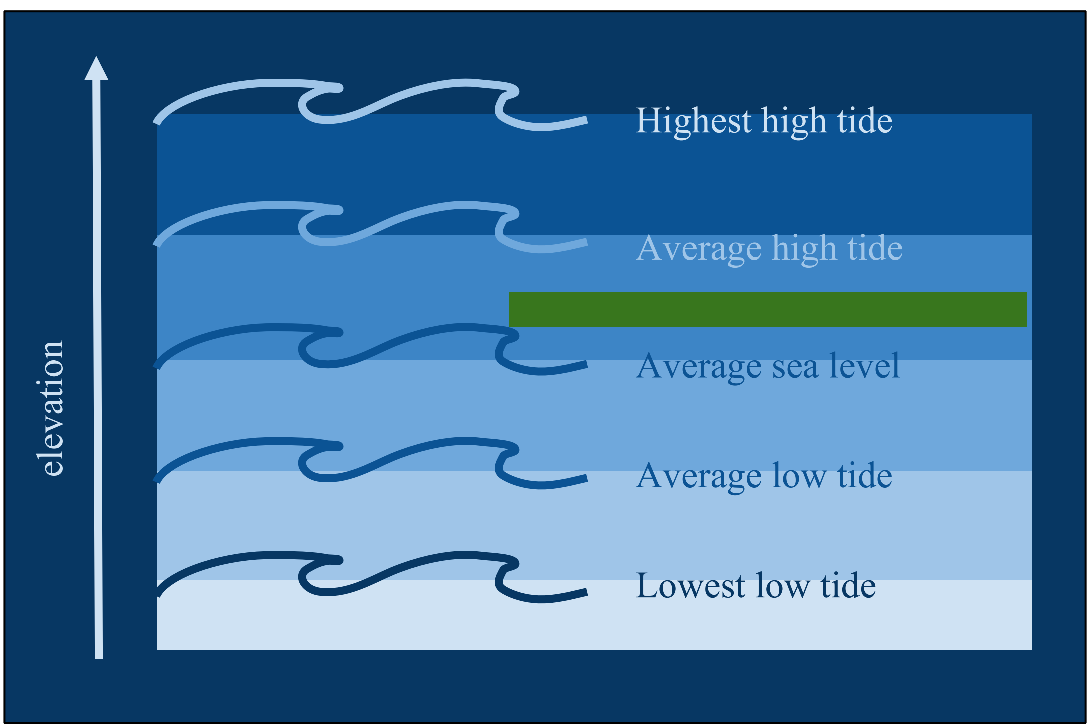
*for Google Doc/Microsoft Office handouts; modify accordingly for printed handouts, which could not incorporate copy and paste features for graphs

PART I: MARSH ECOSYSTEM SERVICES

1. Describe what happens to a marsh during the high tide and during the low tide. The marsh is flooded during high tide and is drained of its water as water level approaches low tide (ebbs).
2. Make a hypothesis about what the incoming water (during high tide) delivers to the marsh. No answer is wrong here, because just want them to make an educated guess, but possibilities include: nutrients, water, oxygen, sediment, animals, predators, waves
3. Identify at least two ecosystem services you think a salt marsh provides. Again, no answers are wrong here, but possibilities include fishing and hunting and recreation opportunities, habitat for animals, protection from storms, improvement in water quality by taking up extra nutrients, storage of carbon, grazing of livestock
4. Imagine the marsh that you are trying to save is being eroded quickly because of high wave energy. Which restoration strategy do you think would be better at protecting your marsh: thin-layer placements every 15 years OR a sill? A sill because it protects against wave-driven erosion of the marsh, while thin-layer placements protect against drowning or low sediment supply

PART II: DEVELOPING A MANAGER'S UNDERSTANDING OF MARSH GROWTH

5. Which rate of sea-level rise did you choose, and how many meters (plotted on your y-axis) does sea-level increase between year 0 and year 100?
    a. If they chose 2 mm/yr: ~0.6 m, or 60 cm
    b. If they chose 4 mm/yr: ~0.8 m, or 80 cm
    c. If they chose 6 mm/yr: ~1 m, or 100 cm
6. Choose a few single "mean sea level" points on the left graph. How does the x-axis value compare to the y-axis value when you pick those points? Is your x-axis value greater, smaller, or the same compared to your y-axis value? The x-axis value is smaller than the y-axis value, meaning that the average marsh elevation is higher than mean sea level.
7. Now, choose a few single "mean high tide" points on the right graph. How does the x-axis value compare to the y-axis value when you pick those points? Is your x-axis value greater, smaller, or the same compared to your y-axis value? The x-axis value is larger than the y-axis value, meaning that the average marsh elevation is lower than mean high tide.
8. Insert a green rectangle (to represent a salt marsh) in the image below that shows at what elevation salt marshes are likely to grow. (Double click on the image to edit it.) Rectangle can be anywhere on that same plane (needs to be in between average high tide and average sea level)



9. Fill out the following statements using your analysis of the two graphs: Using the model outputs, we can conclude that salt marshes prefer to grow at elevations that are above average sea level and below mean high tide. We form this conclusion based on model outputs that show a positive relationship between mean sea level and average marsh elevation indicating that as mean sea level increases, salt marshes elevation will have to increase in order for marshes to survive.

ANSWERS FOR SITE SITE 1: CALIFORNIA

(scroll down for answers to other sites)

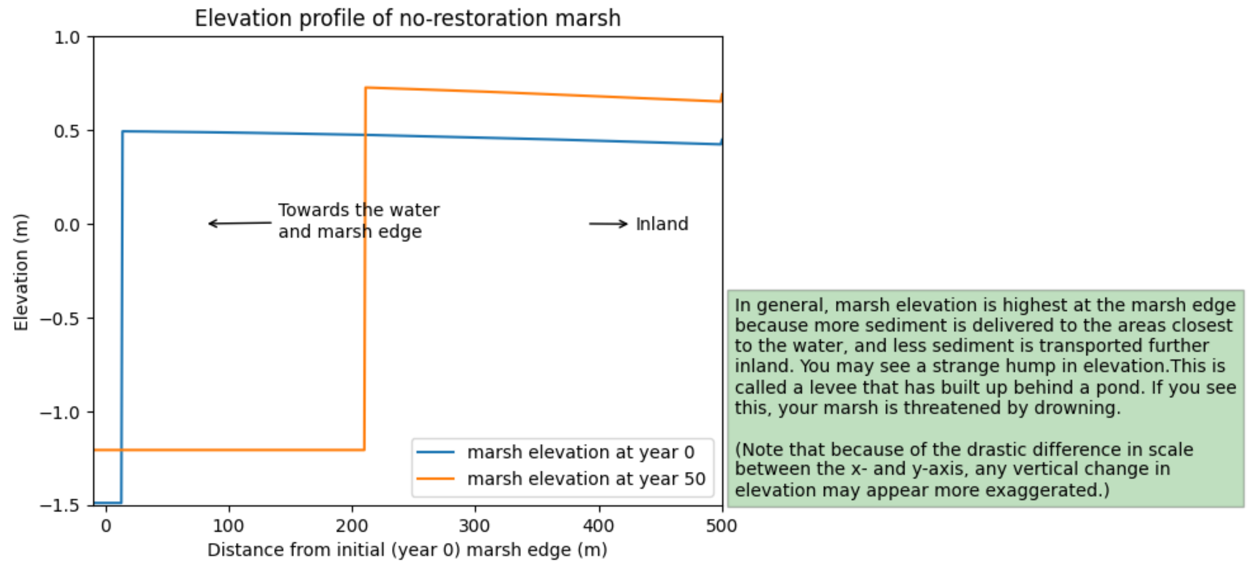
PART III: YOUR MARSH SITE

10. How quickly is sea level rising at your site? 2millimeters per year
11. What is the marsh erosion rate for your site? 4meters per year
12. How much sediment is in the water brought in with the rising tide? 20milligrams per liter
13. Fill out the table below based on which two marsh ecosystem services the surrounding local community values the most and how will you measure each.

	Marsh ecosystem service	What measurement will you use to determine how well the marsh is providing the ecosystem service? (read your site handout carefully if you're unsure.)
First priority	Carbon burial/storage	amount of carbon buried every year
Second priority	Fish and bird habitat	marsh width (in meters)

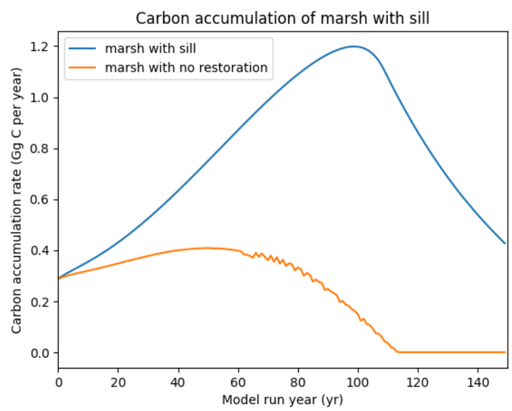
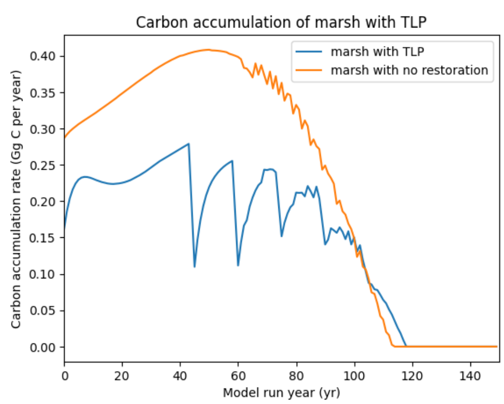
PART IV: SOLVING YOUR DILEMMA THROUGH RESTORATION

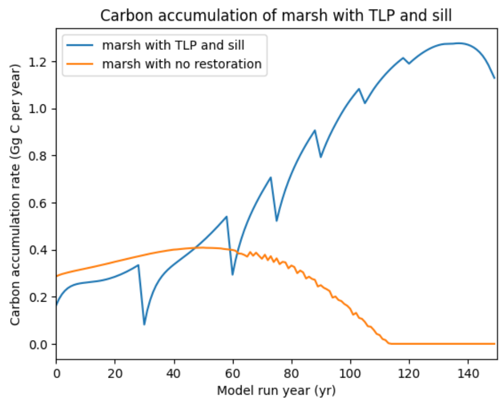
14. Copy and paste the elevation profiles from Year 1 and Year 50 in the space below.



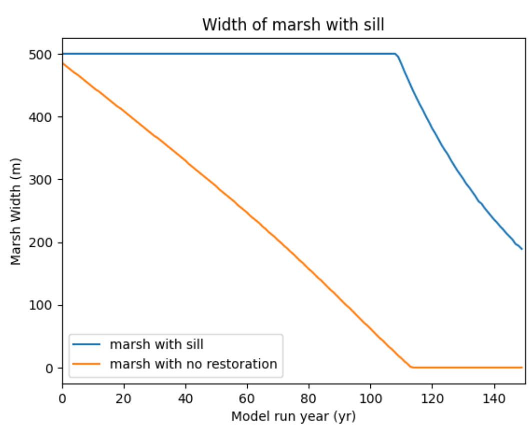
15. Describe what happened to your marsh's elevation profile over time. Be specific about elevation and width changes at different locations in the marsh, and be quantitative (using numbers and number comparisons) as much as possible. The marsh edge moved inland due to erosion, by about 215 meters. The marsh grew higher in elevation, with the marsh edge increasing by about 0.2 m (20 cm). The slope of the marsh platform is about the same.
16. Based on your answer to #15, do you think that your marsh might benefit from restoration? Why or why not? Yes because it is eroding at the edge, which suggests a sill might help it. Because thin-layer placements help prevent excessive flooding (rather than prevent erosion), whether or not thin-layer placements would help is currently unclear, as there is not much evidence of drowning in the elevation profile at year 50 (no very low lying interior areas or sudden changes in elevation).
17. In the table below, select in the dropdown menu (currently a blank line) the first ecosystem service from your answer to #13 above.
    a. Paste the graphs of your first ecosystem service (your first answer to #13 above) from the different restoration model runs (in the correct row, according to which restoration option you have turned "on"). For the marshes that receive TLP, you can crop out the green box that appears to the right of the graphs if you want the graph to appear larger in the table.
    b. For each graph, describe how the restoration marsh compares to the no-restoration marsh through time, being quantitative (using numbers and number comparisons)

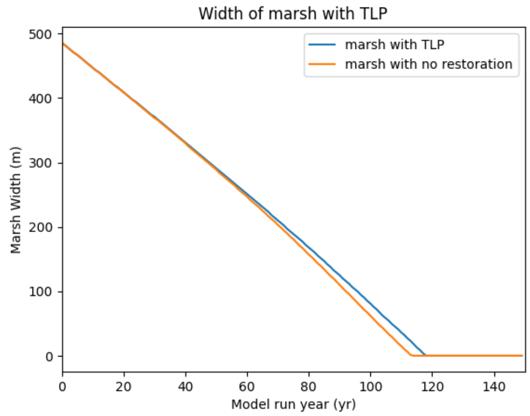
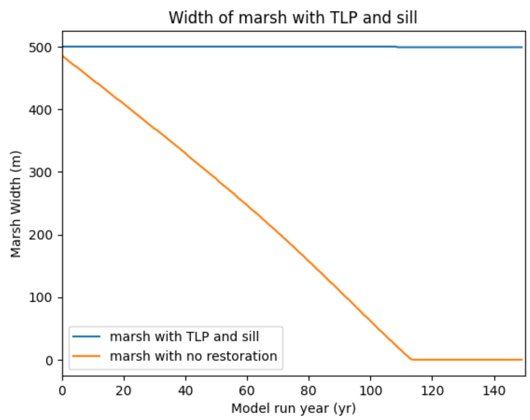
as much as possible. **Make sure to document if the restoration becomes more or less effective as time goes on.**

Restoration	**Graphs of carbon accumulation (showing the restoration and control together)**	**Assessment of how the restoration compares to the no-restoration marsh**
Sill		The sill marsh continuously buries more carbon than the no-restoration marsh, with a maximum difference of ~1 Gg C per year at ~year 100. The carbon accumulation rate in the no-restoration marsh drops to 0 ~year 110, signifying the marsh has completely collapsed, while the sill marsh continues to accumulate carbon for all 150 years.
TLP		Until ~year 115 of the model run, the carbon accumulation rate of the TLP marsh is lower than that of the no-restoration marsh. The carbon accumulation rate of the TLP marsh significant declines every 15 years starting at year 45 (which is a year that receives thin-layer placement), due to the elevation suddenly increasing above that of maximum productivity for marshes (students should be able to infer this from the green boxes that appear next to this graph). However, from year ~115 to 120, the carbon accumulation rate of the TLP marsh is greater than that of the no-restoration marsh.

TLP and sill		The carbon accumulation rate of the combined TLP and sill restoration is lower than that of the no-restoration marsh until ~year 50. The carbon accumulation rate continues to grow, despite drops every 15 years due to the marsh elevation being above that at which marsh plants experience maximum productivity (students should be able to infer this from the green text box.) The restored marsh reaches a maximum carbon accumulation rate ~year 135 that is ~1.3 Gg of carbon accumulation more than the no-restoration marsh, which has collapsed by year 115.

18. Follow the same steps as you did for the table above, but for the second ecosystem service from your answer to #13 above.

Restoration	**Graphs of marsh width (showing the restoration and control together)**	**Assessment of how the restoration compares to the no-restoration marsh**
Sill		The sill marsh is constantly wider than the no-restoration marsh. The no-restoration marsh narrows steadily throughout the model run, collapsing ~year 110. The maximum difference between the two marshes is ~500 meters at year 110, after which the marsh with the sill starts to narrow (not due to erosion but due to interior drowning from sea-level rise).

TLP		The width of the TLP marsh matches that of the no-restoration marsh until ~year 60, where it starts to decrease less quickly. By year ~115, the TLP marsh is ~20 m wider than the no-restoration marsh which has completely collapsed. The TLP marsh only survives ~5 years more until it collapses as well.
TLP and sill		The combined TLP and sill restoration is always wider than the no-restoration marsh, maintaining a width of 500 meters throughout the model run, while the no-restoration marsh collapses by ~year 115.

19. Comparing the 4 restoration options (including the no restoration option)…
    a. …which restoration strategy maximizes the first ecosystem service you monitored in the table for #17? Think about how much the marsh function improves during the 100 years and by the end. The sill maximizes the carbon accumulation rate during the early years of the model run, but the combined TLP and sill restoration maximized the carbon accumulation rate during the later years.
    b. …make a hypothesis about why this restoration did the best. (Think about what your no restoration marsh looked like by year 50 according to your graph for #14) The sill restoration likely did the best because we know based on our elevation profile shown in the answer to #14 that this marsh was threatened by edge erosion. Therefore a restoration that addresses the edge erosion (like a sill) would help the marsh stay wide so it can continue to accumulate carbon. Any restoration that included TLP was, surrounding years when the marsh received a TLP treatment, more harmful to the carbon accumulation than beneficial, leading to the sill being the most effective.
20. Comparing the 4 restoration options (including the no restoration option)…

a. …which restoration strategy maximizes the first ecosystem service you monitored in the table for #18? Think about how much the marsh function improves during the 100 years and by the end. The combined TLP and sill restoration maximized the marsh width, with the marsh maintaining its 500-meter width throughout the simulation.

b. …make a hypothesis about why this restoration did the best. (Think about what your no restoration marsh looked like by year 50 according to your graph for #14.) The sill was important during the early years for the same reason as listed in 19b. However, the TLP became important for the later years, when the sea-level rise rate was faster and the marsh needed vertical support against rising water levels. We can tell that without the TLP, the marsh that received the sill began to narrow around year 110 due to interior drowning!

21. What might happen if you make habitat management decisions based on only one or two ecosystem services and ignore other services that might also be important? You might make big decisions about the marsh that aren't in the best interest of the other ecosystem services that the marsh provides. For example, in a different scenario, maybe the marsh width is maximized by the sill and TLP combined restorations, but the carbon accumulation rate is maximized by just the sill. If all you cared about was the carbon burial/storage services of the marsh, then you may choose the sill restoration strategy, at the expense of the marsh width, which may decline. Eventually the marsh may completely drown, even while the marsh shows a high carbon accumulation rate to the end.

PART V: COMMUNICATING YOUR SOLUTION

22. At this point, you have completed a thorough analysis of the effectiveness of restoration on your marsh's ability to provide certain ecosystem services under sea level rise rates projected for the next century. You have parameterized (set initial input conditions) for your specific marsh site, and now you have the knowledge to make an argument for why you should choose certain restorations over others. Using your responses from previous questions, write at least 5 complete sentences to your local and/or state government making the case for why your marsh needs (or does not need) funding for restoration. Follow the steps below to make a strong argument, by including the following:
    a. why salt marshes are important
    b. what threats salt marshes are facing, leading into your specific marsh
    c. your model outputs showing what may happen to your marsh if not restored
    d. cite at least 3 figures from your model outputs in your argument
    e. reference the preferences of your local community members who responded to the poll
    f. Indicate which restoration strategy is best and WHY

Their answer should a) list at least two marsh ecosystem services, b) discuss sea-level rise and edge erosion, c) mention the no-restoration elevation profiles from question #14 d) cite at least 3 figure outputs d) reference what their community cares about and e) indicate that the combined **TLP and sill** restoration maximizes the ecosystem services that the community cares about, especially during later years of the model run.

ANSWERS FOR SITE SITE 2: LOUISIANA

(scroll down for other sites)

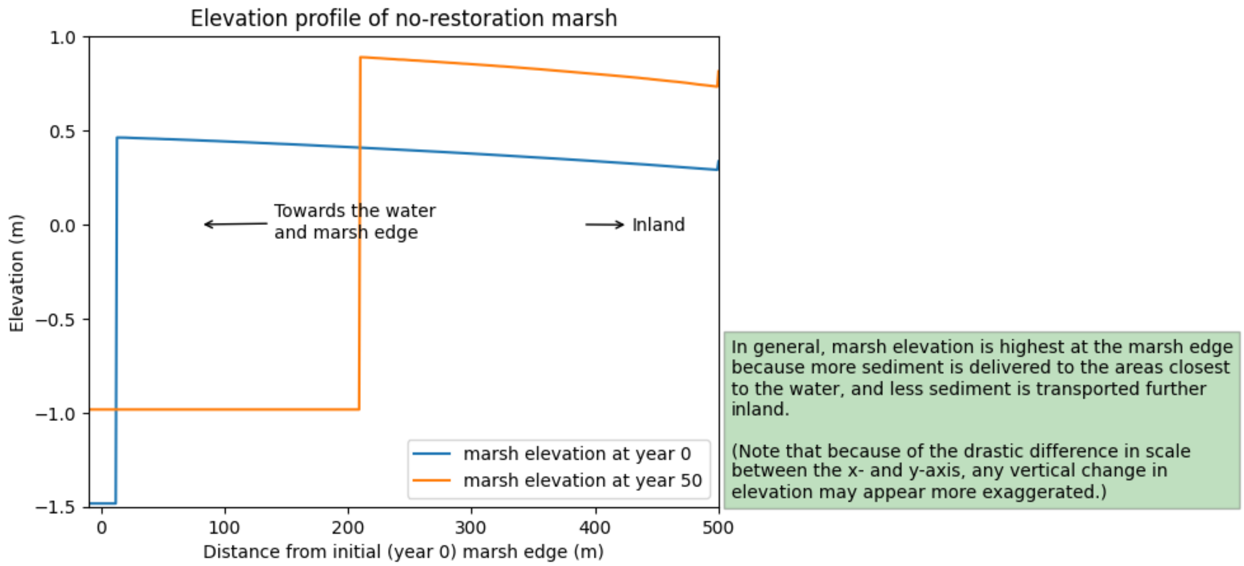
PART III: YOUR MARSH SITE

10. How quickly is sea level rising at your site? 6millimeters per year
11. What is the marsh erosion rate for your site? 4meters per year
12. How much sediment is in the water brought in with the rising tide? 30milligrams per liter
13. Fill out the table below based on which two marsh ecosystem services the surrounding local community values the most and how will you measure each.

	Marsh ecosystem service	What measurement will you use to determine how well the marsh is providing the ecosystem service? (read your site handout carefully if you're unsure.)
First priority	Water quality	amount of nitrogen used every year
Second priority	Storm protection	marsh width (in meters)

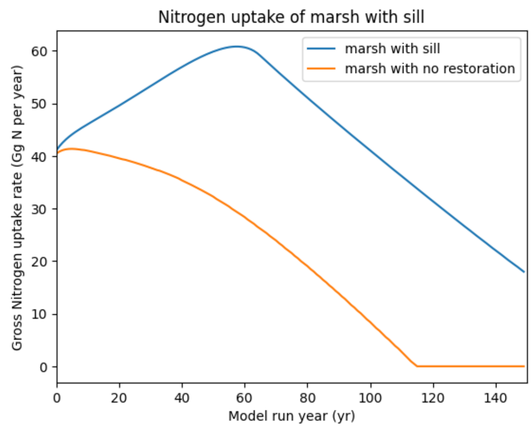
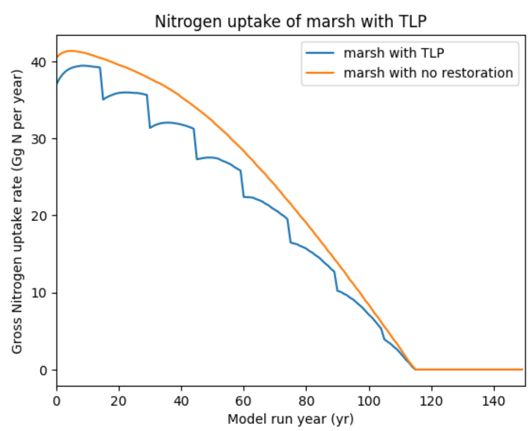
PART IV: SOLVING YOUR DILEMMA THROUGH RESTORATION

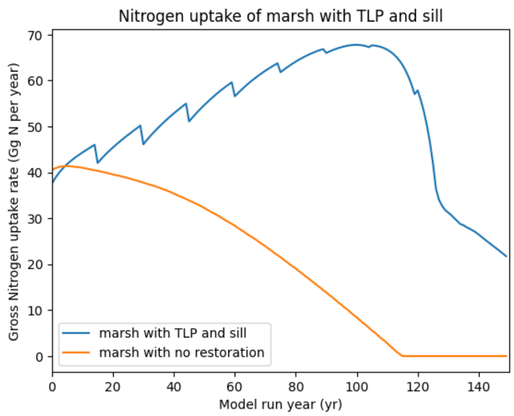
14. Copy and paste the elevation profiles from Year 1 and Year 50 in the space below.



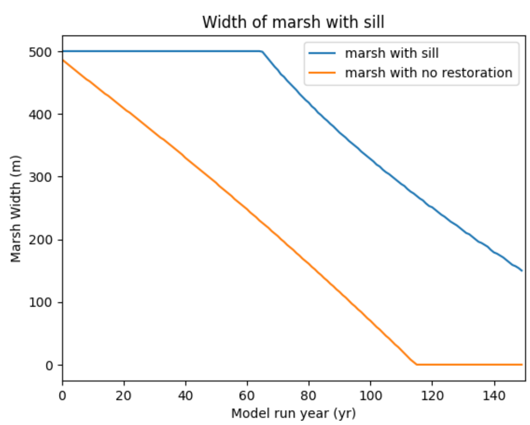
15. Describe what happened to your marsh's elevation profile over time. Be specific about elevation and width changes at different locations in the marsh, and be quantitative (using numbers and number comparisons) as much as possible. The marsh has eroded substantially (almost 215 meters of erosion over 50 years). It has grown in height (by almost 0.5 m, or 50 centimeters). Also the elevation has remained roughly the same slope.
16. Based on your answer to #15, do you think that your marsh might benefit from restoration? Why or why not? Yes because it is eroding at the edge, which suggests a sill might help it. Because thin-layer placements help prevent excessive flooding (rather than prevent erosion), whether or not thin-layer placements would help is currently unclear, as there is not much evidence of drowning in the elevation profile at year 50 (no very low lying interior areas or sudden changes in elevation).
17. In the table below, select in the dropdown menu (currently a blank line) the first ecosystem service from your answer to #13 above.
    a. Paste the graphs of your first ecosystem service (your first answer to #13 above) from the different restoration model runs (in the correct row, according to which restoration option you have turned "on"). For the marshes that receive TLP, you can crop out the green box that appears to the right of the graphs if you want the graph to appear larger in the table.
    b. For each graph, describe how the restoration marsh compares to the no-restoration marsh through time, being quantitative (using numbers and number comparisons)

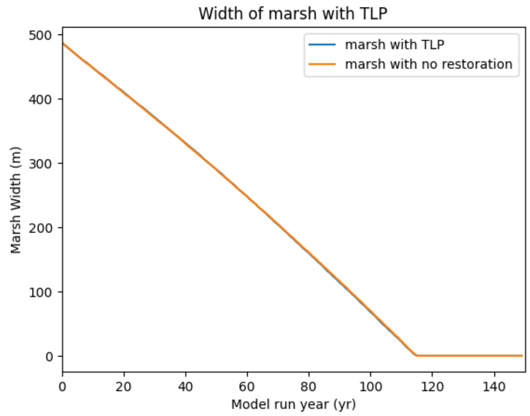
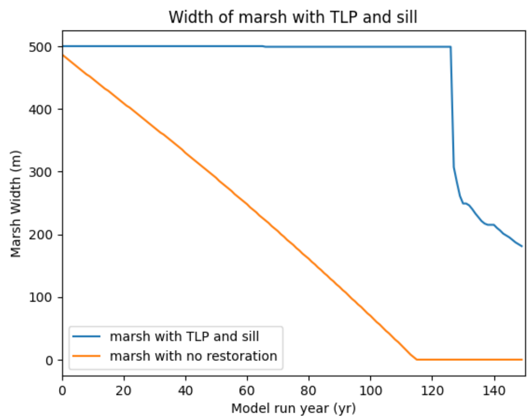
as much as possible. **Make sure to document if the restoration becomes more or less effective as time goes on.**

Restoration	Graphs of nitrogen uptake (showing the restoration and control together)	Assessment of how the restoration compares to the no-restoration marsh
Sill		The sill marsh continuously uptakes more nitrogen than the no-restoration marsh, with a maximum difference of ~35 Gg N per year at ~year 115. The nitrogen uptake rate in the no-restoration marsh drops to 0 ~year 115, signifying the marsh has completely collapsed, while the sill marsh continues to take up nitrogen for all 150 years.
TLP		The TLP marsh leads to a nitrogen uptake rate that is continuously worse than the no-restoration marsh. The TLP marsh nitrogen uptake rate decreases after every TLP treatment due to the elevation suddenly increasing above that of maximum productivity for marshes (students should be able to infer this from the green boxes that appear next to this graph), leading to a ~5 Gg difference between the nitrogen uptake rate of the different strategies.

TLP and sill		The TLP and sill marsh initially uses less nitrogen than the no-restoration marsh, but by ~year 5, the nitrogen uptake surpasses that of the no-restoration marsh, and by years 100-120, it is ~60 Gg of N per year greater than the no-restoration marsh.

18. Follow the same steps as you did for the table above, but for the second ecosystem service from your answer to #13 above.

Restoration	**Graphs of marsh width (showing the restoration and control together)**	**Assessment of how the restoration compares to the no-restoration marsh**
Sill		The width of the sill marsh is always greater than the width of the no-restoration marsh, with ~250 meters difference at its greatest point (by year 115 when the no-restoration marsh has completely collapsed). The sill marsh maintains its 500-meter width until ~year 65 when it starts to narrow (not due to erosion but due to interior drowning from rising sea level).

TLP		The width of the TLP has almost exactly the same width as the no-restoration marsh, indicating that erosion, and not sea-level rise, is the primary reason for marsh loss during those first 100 years.
TLP and sill		The width of the TLP and sill marsh is always greater than the width of the no-restoration marsh. The restored marsh maintains its 500-m width until ~year 120, when it dramatically narrows. At its maximum difference (year 115 to 120), the restored marsh is 500 meters wider than the no-restoration marsh which has collapsed.

19. Comparing the 4 restoration options (including the no restoration option)…
    a. …which restoration strategy maximizes the first ecosystem service you monitored in the table for #17? Think about how much the marsh function improves during the 100 years and by the end. The combined TLP and sill restoration maximized nitrogen uptake rate (students may say sill and as long as their reasoning is strong in their next answer, that's okay.)
    b. …make a hypothesis about why this restoration did the best. (Think about what your no restoration marsh looked like by year 50 according to your graph for #14 and think about the total width of the marsh) Because the sill protects the marsh from narrowing, and the TLP is important in later years for preventing marsh drowning, the combined strategy is best for maintaining a wide marsh throughout the simulation. This wide marsh is then able to maintain a high nitrogen uptake rate that reaches a maximum rate of almost 70 Gg per year around year 110. With

just the sill as a restoration, the marsh width starts to decline rapidly beyond year 60, as the marsh faces a faster rate of sea-level rise that the TLP is crucial for preventing. (this answer may be a little advanced for high school students, but as long as they're thinking critically about this…)

20. Comparing the 4 restoration options (including the no restoration option)…
    a. …which restoration strategy maximizes the first ecosystem service you monitored in the table for #18? Think about how much the marsh function improves during the 100 years and by the end. The combined TLP and sill restoration maximized the marsh width.
    b. …make a hypothesis about why this restoration did the best. (Think about what your no restoration marsh looked like by year 50 according to your graph for #14) Same answer as 19b but focused on marsh width rather than nitrogen accumulation rate
21. What might happen if you make habitat management decisions based on only one or two ecosystem services and ignore other services that might also be important? You might make big decisions about the marsh that aren't in the best interest of the other ecosystem services that the marsh provides. For example, in a different scenario, maybe the marsh width is maximized by the sill and TLP combined restorations, but the nitrogen uptake rate is maximized by just the sill. If all you cared about was the water quality services of the marsh, then you may choose the sill restoration strategy, at the expense of the marsh width, which may decline. Eventually the marsh may completely drown, even while the marsh shows a high nitrogen uptake rate to the end.

PART V: COMMUNICATING YOUR SOLUTION

22. At this point, you have completed a thorough analysis of the effectiveness of restoration on your marsh's ability to provide certain ecosystem services under sea level rise rates projected for the next century. You have parameterized (set initial input conditions) for your specific marsh site, and now you have the knowledge to make an argument for why you should choose certain restorations over others. Using your responses from previous questions, write at least 5 complete sentences to your local and/or state government making the case for why your marsh needs (or does not need) funding for restoration. Follow the steps below to make a strong argument, by including the following:
    a. why salt marshes are important
    b. what threats salt marshes are facing, leading into your specific marsh
    c. your model outputs showing what may happen to your marsh if not restored
    d. cite at least 3 figures from your model outputs in your argument
    e. reference the preferences of your local community members who responded to the poll
    f. Indicate which restoration strategy is best and WHY

Their answer should a) list at least two marsh ecosystem services, b) discuss sea-level rise and edge erosion, c) mention the no-restoration elevation profiles from question #14 d) cite at least 3 figure outputs d) reference what their community cares about and e) indicate that the **thin-layer placement and sill restoration combination** maximizes the ecosystem services that the community cares about.

ANSWERS FOR SITE SITE 3: VIRGINIA

(scroll down for last site)

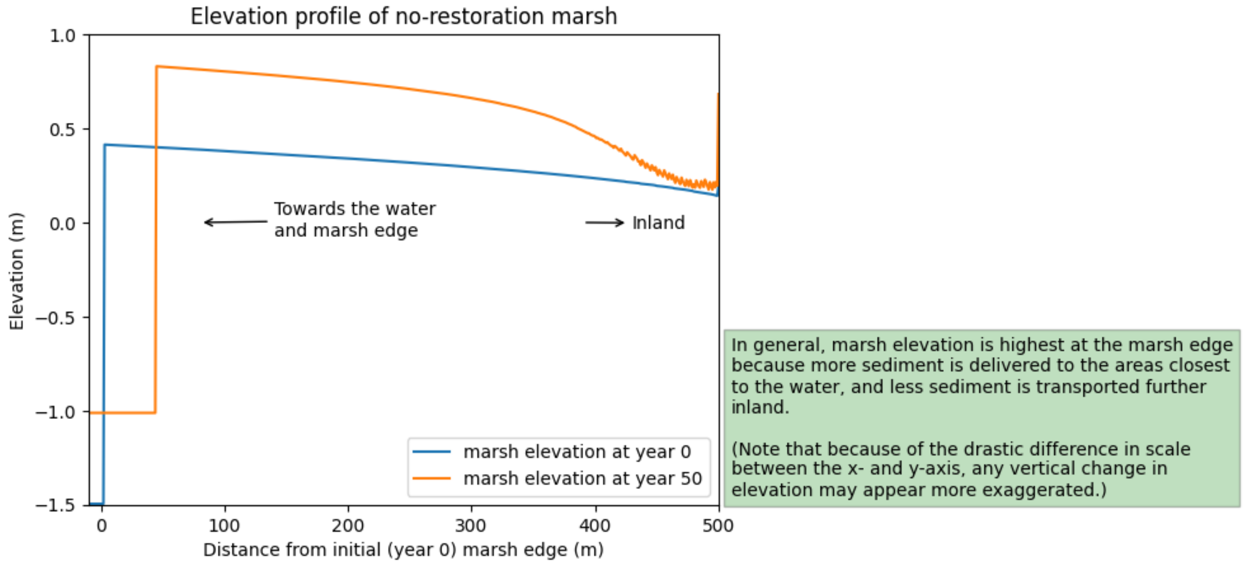
PART III: YOUR MARSH SITE

10. How quickly is sea level rising at your site? 6millimeters per year
11. What is the marsh erosion rate for your site? 1meters per year
12. How much sediment is in the water brought in with the rising tide? 20milligrams per liter
13. Fill out the table below based on which two marsh ecosystem services the surrounding local community values the most and how will you measure each.

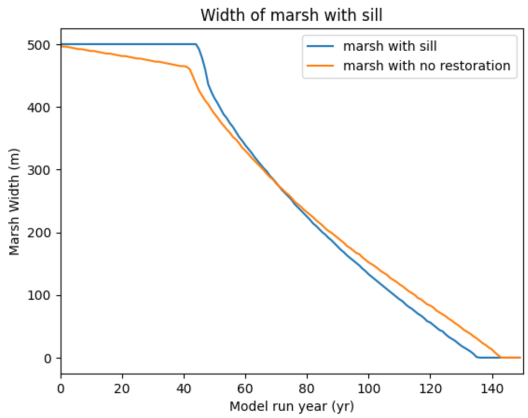
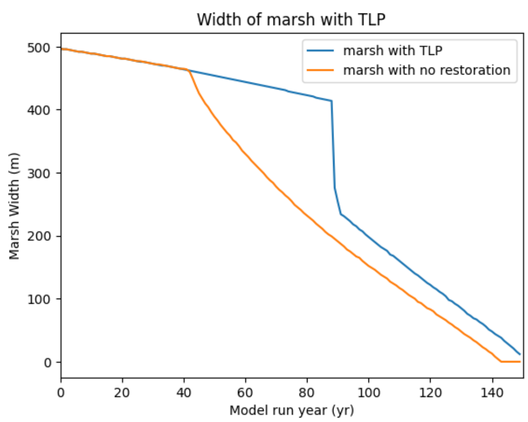
	Marsh ecosystem service	What measurement will you use to determine how well the marsh is providing the ecosystem service? (read your site handout carefully if you're unsure.)
First priority	Fish and bird habitat	marsh width (in meters)
Second priority	Water quality	amount of nitrogen used every year

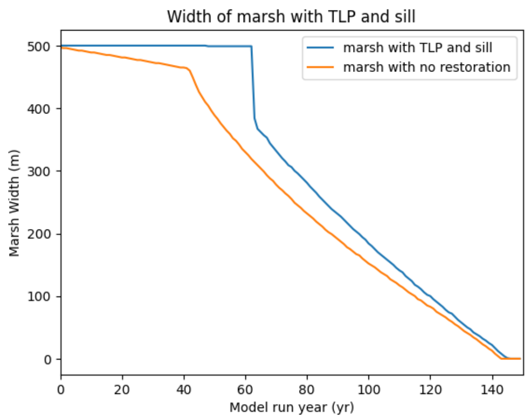
PART IV: SOLVING YOUR DILEMMA THROUGH RESTORATION

14. Copy and paste the elevation profiles from Year 1 and Year 50 in the space below.

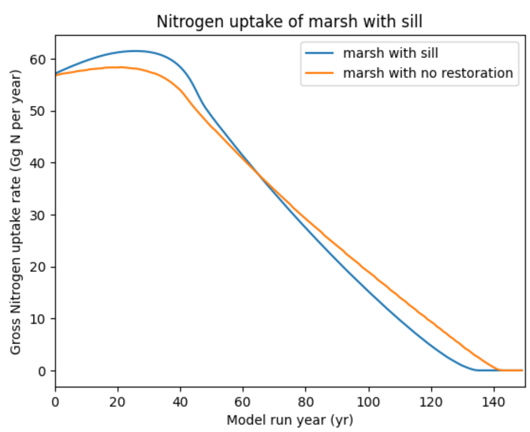


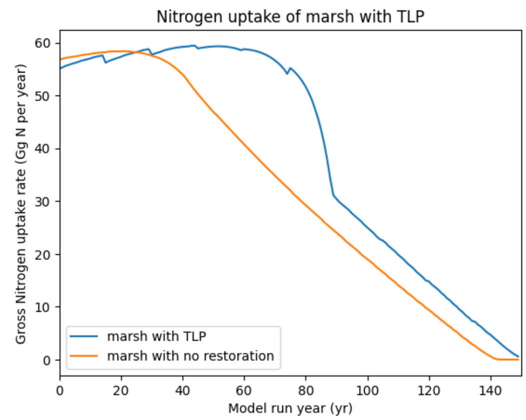
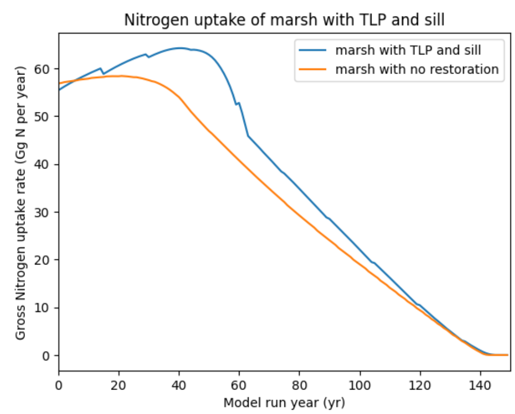
15. Describe what happened to your marsh's elevation profile over time. Be specific about elevation and width changes at different locations in the marsh, and be quantitative (using numbers and number comparisons) as much as possible. The marsh edge moved inland due to erosion, by about 50 meters. The marsh grew higher in elevation, by about 0.4 m, or 40 centimeters at the marsh edge. The more inland part of the marsh dropped in elevation (forming a large pond in the inside of the marsh).
16. Based on your answer to #15, do you think that your marsh might benefit from restoration? Why or why not? Yes because it is eroding at the edge, which suggests a sill might help it. Because thin-layer placements help prevent excessive flooding (rather than prevent erosion), TLP could also help prevent the interior drowning that is occurring around 400 meters in the "inland" portion of the marsh.
17. In the table below, select in the dropdown menu (currently a blank line) the first ecosystem service from your answer to #13 above.
    a. Paste the graphs of your first ecosystem service (your first answer to #13 above) from the different restoration model runs (in the correct row, according to which restoration option you have turned "on"). For the marshes that receive TLP, you can crop out the green box that appears to the right of the graphs if you want the graph to appear larger in the table.
    b. For each graph, describe how the restoration marsh compares to the no-restoration marsh through time, being quantitative (using numbers and number comparisons) as much as possible. **Make sure to document if the restoration becomes more or less effective as time goes on.**

Restoration	Graphs of marsh width (showing the restoration and control together)	Assessment of how the restoration compares to the no-restoration marsh
Sill		The sill maintains a slightly wider marsh (~50 meters wider at year 50) compared to the no restoration marsh for the first 60 years, until the sill marsh starts to narrow more quickly and collapses ~5-10 years earlier than the no restoration.
TLP		The TLP marsh width matches that of the no-restoration marsh for the first ~40 years until the no-restoration marsh declines rapidly, while the TLP marsh continues narrowing at the original rate. This sudden rapid narrowing seen in the no-restoration marsh is due to the combined impact of erosion and interior drowning due to sea-level rise. The TLP prevents interior drowning due to SLR (until ~year 90 when it starts to decline dramatically), but continues to narrow due to erosion. By year 150, the TLP marsh is ~5 meters wide. The maximum difference between the two widths is ~225 meters, around year 90.

TLP and sill		The TLP and sill restoration maintains a 500-meter wide marsh until ~year 60, when it starts to narrow dramatically in a single year and then narrows more rapidly than the no-restoration marsh, almost reaching the same width by year 145, when the no-restoration marsh collapses. Around a year or two later, the restored marsh collapses. The maximum difference between the two widths is ~200 meters, around year 65.

18. Follow the same steps as you did for the table above, but for the second ecosystem service from your answer to #13 above.

Restoration	**Graphs of nitrogen uptake(showing the restoration and control together)**	**Assessment of how the restoration compares to the no-restoration marsh**
Sill		During the first ~60 years, the sill marsh takes up more nitrogen than the no-restoration marsh, with a maximum of ~5 Gg of nitrogen per year difference between the two around year 40. However, beyond year 60, the no-restoration marsh uses more nitrogen than the sill marsh.

TLP		During the first ~25 years, the nitrogen uptake rate of the TLP marsh is lower than that of the no-restoration marsh, with sudden decreases in nitrogen uptake following the TLP treatment which occurs every 15 years. However, after year 25, the TLP marsh uses more nitrogen than the no-restoration marsh and reaches a maximum difference ~25 more Gg of nitrogen taken up compared to the no-restoration marsh around year 70.
TLP and sill		The TLP and sill restoration increases nitrogen uptake compared to the no-restoration marsh between years 5 and 125, with a maximum difference of ~10 Gg of nitrogen more per year taken up by the restored marsh during year 50. This increase shrinks continually and after year 125, the nitrogen uptake rate of the two marshes is equal.

19. Comparing the 4 restoration options (including the no restoration option)…
    a. …which restoration strategy maximizes the first ecosystem service you monitored in the table for #17? Think about how much the marsh function improves during the 100 years and by the end. Students could choose either TLP or TLP+sill options as the correct answer, as long as their reasoning below is logical. **[If TLP-only strategy was students' answer:]** The TLP restoration maximizes marsh width compared to the no restoration marsh and survives longer than the other restoration options. **[If TLP+sill combined strategy was students' answer:]** The combined TLP and sill strategy prolongs the widest marsh for the longest, although it doesn't prolong the life of the marsh beyond 1-2 years. (This answer may be a little advanced for high school students, but as long as they're thinking critically about this…)
    b. …make a hypothesis about why this restoration did the best. (Think about what your no restoration marsh looked like by year 50 according to your graph for #14) **[If TLP-only strategy was students' answer:]** According to our elevation profile

shown in the answer to #14, this marsh was threatened mostly by interior drowning (losing ~100 meters due to ponding) compared to erosion (losing ~50 meters at the seaward edge). Accelerating sea-level rise (shown in the model results in Part B in the model) means that interior drowning also likely accelerated throughout the simulation. Therefore a restoration that addresses the interior drowning (like TLP) would help the marsh stay wide during the majority of the model run. The sill has some negative impact on marsh width that results in TLP-only option being the optimal strategy. (Students won't know this and not enough time to review this, but the sill also diminishes the amount of sediment making it to the marsh surface, and therefore would prevent marsh elevation gain and marsh productivity. This is why the TLP+sill option doesn't do as well). **[If TLP+sill combined strategy was students' answer:]** This one likely did the best because we know based on our elevation profile shown in the answer to #14 that this marsh was threatened by both edge erosion and drowning (or rapid sea-level rise). Therefore a restoration that addresses the edge erosion (like a sill) would help the marsh stay wide so it can continue to accumulate carbon. And a restoration that addresses the drowning (like thin-layer placement) would help the marsh stay above mean sea level and continue to be productive and store carbon as well, especially in the later years as the sea level rise rate increased.

20. Comparing the 4 restoration options (including the no restoration option)…
    a. …which restoration strategy maximizes the first ecosystem service you monitored in the table for #18? Think about how much the marsh function improves during the 100 years and by the end. Students could choose either TLP or TLP+sill options as the correct answer, as long as their reasoning below is logical. The TLP option leads to greater cumulative nitrogen uptake compared to the no-restoration, maintaining greater increases over the no-restoration option throughout the model run. The TLP+sill option shows the highest peak of all four restoration options around year 50.
    b. …make a hypothesis about why this restoration did the best. (Think about what your no restoration marsh looked like by year 50 according to your graph for #14) **[If TLP-only strategy was students' answer:]**The TLP marsh does best because it produces the greatest cumulative increase in marsh width over the no-restoration option compared to the other restoration strategies, and therefore is able to uptake more nitrogen compared to the others. **[If TLP+sill combined strategy was students' answer:]**The TLP+sill combined option has the highest peak in nitrogen uptake rate because it maintains its 500-meter width for the longest compared to the other marshes.
21. What might happen if you make habitat management decisions based on only one or two ecosystem services and ignore other services that might also be important? You might make big decisions about the marsh that aren't in the best interest of the other ecosystem

services that the marsh provides. For example, in a different scenario, maybe the marsh width is maximized by the sill and TLP combined restorations, but the nitrogen uptake rate is maximized by just the sill. If all you cared about was the water quality services of the marsh, then you may choose the sill restoration strategy, at the expense of the marsh width, which may decline. Eventually the marsh may completely drown, even while the marsh shows a high nitrogen uptake rate to the end.

PART V: COMMUNICATING YOUR SOLUTION

22. At this point, you have completed a thorough analysis of the effectiveness of restoration on your marsh's ability to provide certain ecosystem services under sea level rise rates projected for the next century. You have parameterized (set initial input conditions) for your specific marsh site, and now you have the knowledge to make an argument for why you should choose certain restorations over others. Using your responses from previous questions, write at least 5 complete sentences to your local and/or state government making the case for why your marsh needs (or does not need) funding for restoration. Follow the steps below to make a strong argument, by including the following:
    a. why salt marshes are important
    b. what threats salt marshes are facing, leading into your specific marsh
    c. your model outputs showing what may happen to your marsh if not restored
    d. cite at least 3 figures from your model outputs in your argument
    e. reference the preferences of your local community members who responded to the poll
    f. Indicate which restoration strategy is best and WHY

Their answer should a) list at least two marsh ecosystem services, b) discuss sea-level rise and edge erosion, c) mention the no-restoration elevation profiles from question #14 d) cite at least 3 figure outputs d) reference what their community cares about and e) indicate that the **thin-layer placement restoration** (**or** they could make a compelling case for the **combined TLP and sill option**) maximizes marsh width and nitrogen uptake.

ANSWERS FOR SITE SITE 4: MASSACHUSETTS

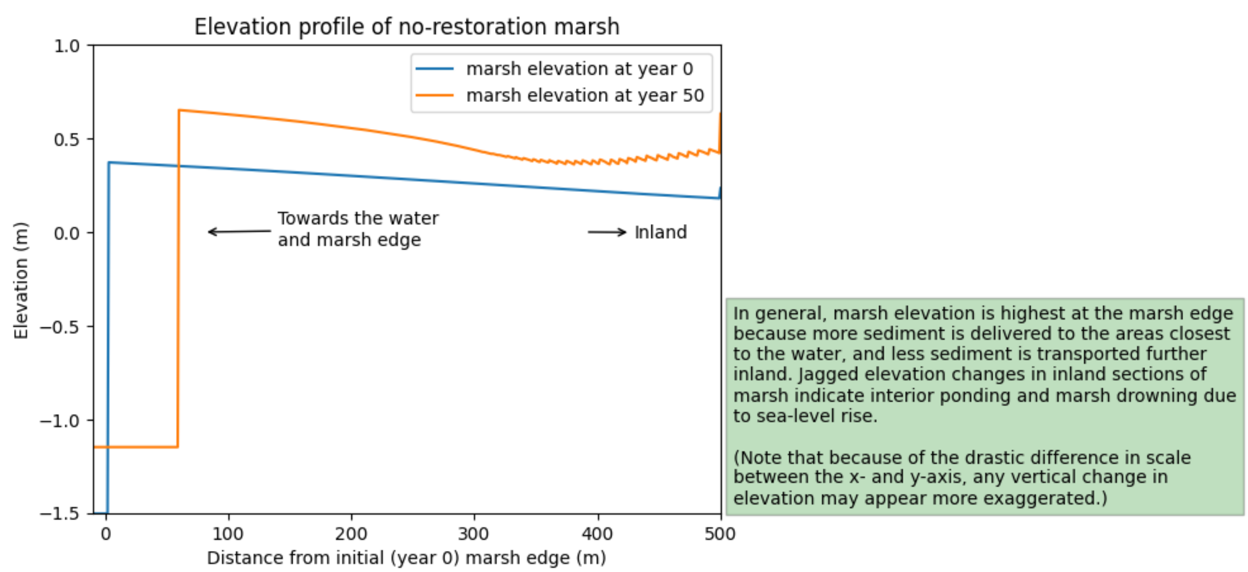
PART III: YOUR MARSH SITE

10. How quickly is sea level rising at your site? 4millimeters per year
11. What is the marsh erosion rate for your site? 1meters per year
12. How much sediment is in the water brought in with the rising tide? 10milligrams per liter
13. Fill out the table below based on which two marsh ecosystem services the surrounding local community values the most and how will you measure each.

	Marsh ecosystem service	What measurement will you use to determine how well the marsh is providing the ecosystem service? (read your site handout carefully if you're unsure.)
First priority	Carbon burial/storage	amount of carbon buried every year
Second priority	Storm protection	marsh width (in meters)

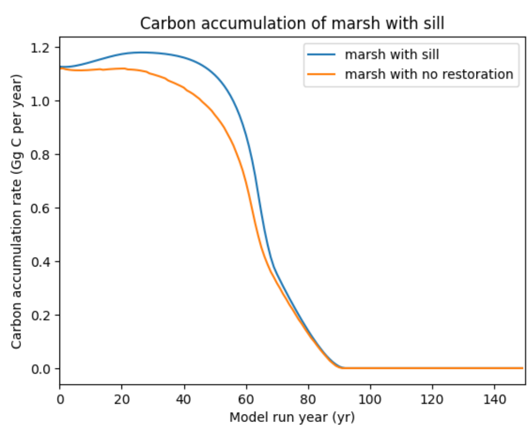
PART IV: SOLVING YOUR DILEMMA THROUGH RESTORATION

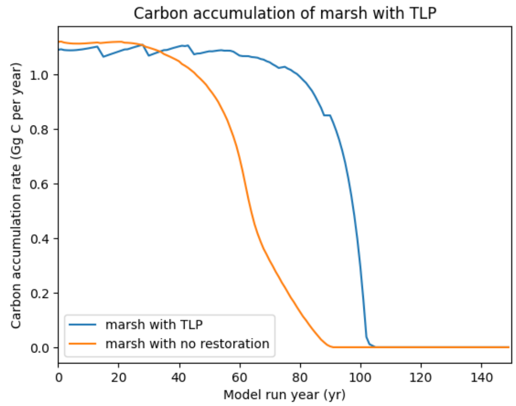
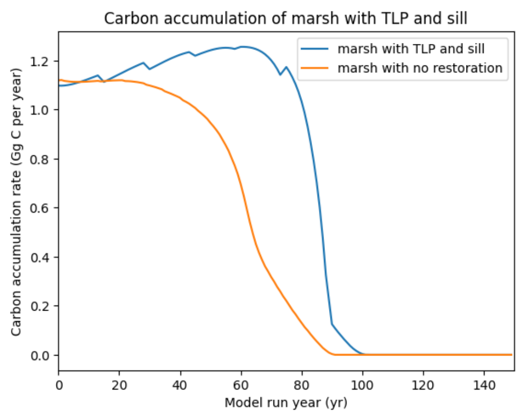
14. Copy and paste the elevation profiles from Year 1 and Year 50 in the space below.



15. Describe what happened to your marsh's elevation profile over time. Be specific about elevation and width changes at different locations in the marsh, and be quantitative (using numbers and number comparisons) as much as possible. The marsh edge moved inland due to erosion, by about 50 meters. The marsh grew higher in elevation by about 0.4 m (or 40 centimeters). The inland section of the marsh (from ~350 to 500 meters) developed some weird squiggles and dropped in elevation (forming a large pond in the inside of the marsh).

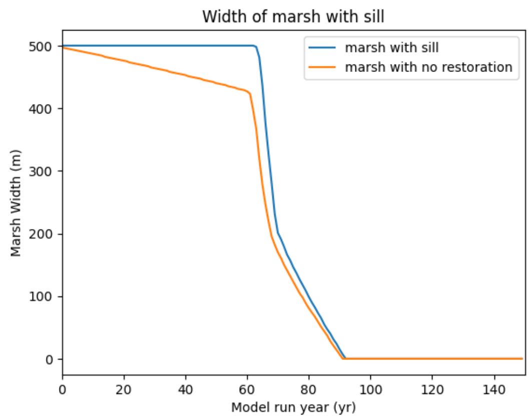
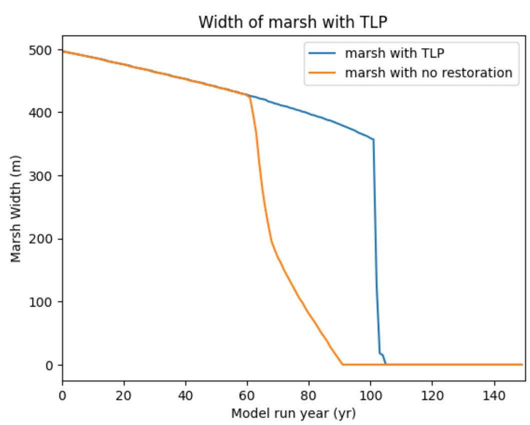
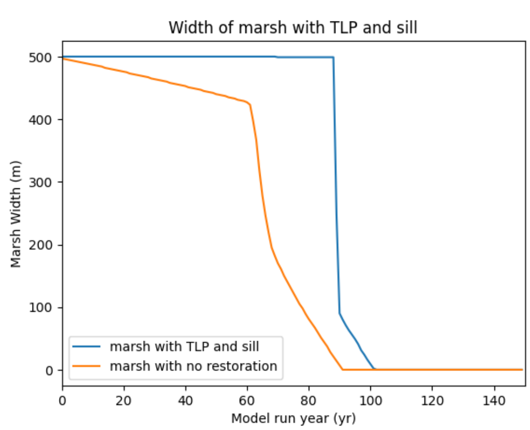
16. Based on your answer to #15, do you think that your marsh might benefit from restoration? Why or why not? Yes because it is eroding at the edge, which suggests a sill might help it. In addition, its elevation is very low in the interior and a pond has formed, suggesting that thin layer placement sediment additions might help prevent drowning.
17. In the table below, select in the dropdown menu (currently a blank line) the first ecosystem service from your answer to #13 above.
    a. Paste the graphs of your first ecosystem service (your first answer to #13 above) from the different restoration model runs (in the correct row, according to which restoration option you have turned "on"). For the marshes that receive TLP, you can crop out the green box that appears to the right of the graphs if you want the graph to appear larger in the table.
    b. For each graph, describe how the restoration marsh compares to the no-restoration marsh through time, being quantitative (using numbers and number comparisons) as much as possible. **Make sure to document if the restoration becomes more or less effective as time goes on.**

Restoration	**Graphs of carbon accumulation (showing the restoration and control together)**	**Assessment of how the restoration compares to the no-restoration marsh**
Sill		The sill increases carbon accumulation by around 0.1 Gg C per year at the point of its biggest difference from the no-restoration marsh. By year 70, the carbon accumulation rate of the sill marsh has fallen to nearly that of the no restoration marsh, meaning that the sill is less effective at later years.

<table>
<tr>
<td>TLP</td>
<td>
</td>
<td>During the first ~40 years, TLP leads to a decrease in carbon accumulation rate, but an increase compared to the no-restoration marsh later in the model run, around year 80, suggesting TLP becomes more effective in later years. At the point of its biggest difference from the no-restoration marsh, the TLP marsh buries 1.0 Gg C per year more than the no-restoration marsh.</td>
</tr>
<tr>
<td>TLP and sill</td>
<td>
</td>
<td>At first, the no-restoration marsh accumulates more carbon compared to the restored marsh, but this only lasts for ~5 years. After, the carbon accumulation rate of the TLP & sill marsh continues to increase away from the no restoration marsh until ~year 80, where it starts to fall. At its peak, it is ~1.0 Gg C more per year than the no-restoration marsh.</td>
</tr>
</table>

18. Follow the same steps as you did for the table above, but for the second ecosystem service from your answer to #13 above.

Restoration	**Graphs of marsh width (showing the restoration and control together)**	**Assessment of how the restoration compares to the no-restoration marsh**

<table>
<tr>
<td>Sill</td>
<td>
</td>
<td>The sill keeps the marsh width at 500 meters until ~year 60, while the no restoration marsh width narrows to ~410 m by year 60. However, both marshes start collapsing rapidly afterward, with the sill marsh more rapidly narrowing and catching up by year 90 to the no-restoration marsh, when both collapse completely.</td>
</tr>
<tr>
<td>TLP</td>
<td>
</td>
<td>The TLP marsh width matches that of the no-restoration marsh for the first ~60 years until the no-restoration marsh declines rapidly, while the TLP marsh continues narrowing at the original rate. This sudden rapid narrowing seen in the no-restoration marsh is due to the combined impact of erosion and interior drowning due to sea-level rise. The TLP prevents interior drowning due to SLR (until ~year 105 when it starts to decline dramatically), but continues to narrow due to erosion. The TLP helps the marsh survive ~20 years longer than the no-restoration marsh.</td>
</tr>
<tr>
<td>TLP and sill</td>
<td>
</td>
<td>The TLP and sill restoration maintains a 500-meter wide marsh until ~year 90, when it starts to narrow dramatically in a single year and then narrows rapidly. The maximum difference between the two widths is ~450 meters, around year 85. The combined TLP and sill strategy prolongs the life of the marsh by ~15 years.</td>
</tr>
</table>

19. Comparing the 4 restoration options (including the no restoration option)…
    a. …which restoration strategy maximizes the first ecosystem service you monitored in the table for #17? Think about how much the marsh function improves during the 100 years and by the end. Students could choose TLP-only strategy or the sill & TLP restoration strategy (as long as they make a strong argument for their choice below). The TLP-only strategy maximizes the carbon accumulation rate for the longest duration, with a peak lasting until ~year 100. The TLP+sill combined strategy leads to the largest peak, reaching a carbon accumulation rate above 1.2 Gg C per year at one point.
    b. …make a hypothesis about why this restoration did the best. (Think about what your no restoration marsh looked like by year 50 according to your graph for #14) **[If TLP+sill combined strategy was students' answer:]** This one likely did the best because we know based on our elevation profile shown in the answer to #14 that this marsh was threatened by both edge erosion and drowning (or rapid sea-level rise). Therefore a restoration that addresses the edge erosion (like a sill) would help the marsh stay wide so it can continue to accumulate carbon. And a restoration that addresses the drowning (like thin-layer placement) would help the marsh stay above mean sea level and continue to be productive and store carbon as well, especially in the later years as the sea level rise rate increased. **[If TLP-only strategy was students' answer:]** According to our elevation profile shown in the answer to #14, this marsh was threatened mostly by interior drowning (losing ~150 meters due to ponding) compared to erosion (losing ~50 meters at the seaward edge). Accelerating sea-level rise (shown in the model results in Part B in the model) means that interior drowning also likely accelerated throughout the simulation. Therefore a restoration that addresses the interior drowning (like TLP) would help the marsh stay wide during the majority of the model run. The sill has some negative impact on marsh width that results in TLP-only option being the optimal strategy. (Students won't know this and not enough time to review this, but the sill also diminishes the amount of sediment making it to the marsh surface, and therefore would prevent marsh elevation gain and marsh productivity. This is why the TLP+sill option doesn't do as well).

20. Comparing the 4 restoration options (including the no restoration option)…
    a. …which restoration strategy maximizes the first ecosystem service you monitored in the table for #18? Think about how much the marsh function improves during the 100 years and by the end. Students could choose either TLP or TLP+sill options as the correct answer, as long as their reasoning below is logical. The TLP option leads to greater cumulative nitrogen uptake compared to the no-restoration, maintaining greater increases over the no-restoration option throughout the model

run. The TLP+sill option shows the highest peak of all four restoration options around year 50.

b. …make a hypothesis about why this restoration did the best. (Think about what your no restoration marsh looked like by year 50 according to your graph for #14) **[If TLP-only strategy was students' answer:]**The TLP marsh does best because it produces the greatest cumulative increase in marsh width over the no-restoration option compared to the other restoration strategies, and therefore is able to uptake more nitrogen compared to the others. **[If TLP+sill combined strategy was students' answer:]**The TLP+sill combined option has the highest peak in nitrogen uptake rate because it maintains its 500-meter width for the longest compared to the other marshes.

21. What might happen if you make habitat management decisions based on only one or two ecosystem services and ignore other services that might also be important? You might make big decisions about the marsh that aren't in the best interest of the other ecosystem services that the marsh provides. For example, in a different scenario, maybe the marsh width is maximized by the sill and TLP combined restorations, but the nitrogen uptake rate is maximized by just the sill. If all you cared about was the water quality services of the marsh, then you may choose the sill restoration strategy, at the expense of the marsh width, which may decline. Eventually the marsh may completely drown, even while the marsh shows a high nitrogen uptake rate to the end.

PART V: COMMUNICATING YOUR SOLUTION

22. At this point, you have completed a thorough analysis of the effectiveness of restoration on your marsh's ability to provide certain ecosystem services under sea level rise rates projected for the next century. You have parameterized (set initial input conditions) for your specific marsh site, and now you have the knowledge to make an argument for why you should choose certain restorations over others. Using your responses from previous questions, write at least 5 complete sentences to your local and/or state government making the case for why your marsh needs (or does not need) funding for restoration. Follow the steps below to make a strong argument, by including the following:
    a. why salt marshes are important
    b. what threats salt marshes are facing, leading into your specific marsh
    c. your model outputs showing what may happen to your marsh if not restored
    d. cite at least 3 figures from your model outputs in your argument
    e. reference the preferences of your local community members who responded to the poll
    f. Indicate which restoration strategy is best and WHY

Their answer should a) list at least two marsh ecosystem services, b) discuss sea-level rise and edge erosion, c) mention the no-restoration elevation profiles from question #14

d) cite at least 3 figure outputs d) reference what their community cares about and e) indicate that the **thin-layer placement restoration** (**or** they could make a compelling case for the **combined TLP and sill option**) maximizes marsh width and nitrogen uptake.