Macrosystems EDDIE:
Introduction to Ecological Forecasting
Instructor's Manual

Module Description

Ecological forecasting is an emerging approach which provides an estimate of the future state of an ecological system with uncertainty, allowing society to prepare for changes in important ecosystem services. In this module, students will apply the iterative forecasting cycle to develop an ecological forecast for a National Ecological Observation Network (NEON) site of their choice. This module will introduce students to the basic components of an ecological forecast; how a forecasting model is constructed; how changes to model inputs affect forecast uncertainty; and how productivity forecasts vary across climatic regions.

Pedagogical Connections

Phase	Functions	Examples from this module
Engagement	Introduce topic, gauge students' preconceptions, call up students' schemata	Short introductory lecture; Stepping through each stage of the forecast cycle and answering discussion questions
Exploration	Engage students in inquiry, scientific discourse, evidence-based reasoning	Developing hypotheses of how primary productivity responds to different ecological conditions; Testing these hypotheses by generating an ecosystem forecast with different model parameters
Explanation	Engage students in scientific discourse, evidence-based reasoning	Comparing forecast output with observations; Updating the productivity model to generate a new forecast
Expansion	Broaden students' schemata to account for more observations	Generating and comparing ecological forecasts of primary productivity at different sites in different climatic regions
Evaluation	Evaluate students' understanding, using formative and summative assessments	In-class discussion of forecast output and how ecological forecasting can be used to improve ecosystem understanding and natural resource management

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Learning Objectives

By the end of this module, students will be able to:

- Describe an ecological forecast and the iterative forecasting cycle
- Explore and visualize NEON data
- Construct an ecological model to generate forecasts of ecosystem primary productivity with uncertainty
- Adjust model parameters and inputs to study how they affect forecast performance relative to observations
- Compare productivity forecasts among NEON sites in different ecoclimatic regions

How to Use this Module

This entire module can be completed in one 3-hour lab period or two 75-minute lecture periods for introductory undergraduate students in Ecology, Environmental Science, Ecological Modeling, and Quantitative Ecology classes. We found that teaching this module in two separate periods, in which the first period included the instructor lecture (~20 minutes) before having the students complete Activity A, and the second period was focused on completing Activity B worked well.

Lesson structure, depending on the time available for your class:
- Two classes (75-90 minutes)
  - Class 1 – Introductory lecture – 30 mins, Activity A – 45mins
  - Class 2 – Activities B and C – 45 mins, presentation/discussion of each groups' results as time permits
- One class (3 hours)
  - Introductory lecture – 30mins, Activity A – 45mins, break – 5mins, Activities B and C – 45mins, presentation/discussion of each groups' results as time permits

If time is limited, you can ask students to present their Activity B forecasts to a group that has selected a different site instead of the whole class.

Quick overview of the activities in this module
- Activity A: Students explore data at a NEON site of their choice and create a productivity model.
- Activity B: Students use their model to generate an ecological forecast.
- Activity C: Students update the model and forecast again.

Module Workflow (for either in-person or virtual instruction)

1. Instructor chooses method for accessing the Shiny app:

   1. In any internet browser, go to: **https://macrosystemseddie.shinyapps.io/module5/**

      - This option works well if there are not too many simultaneous users (<20)

      - The app generally does not take a long time to load but requires consistent internet access

- It is important to remind students that they need to save their work as they go, because this webpage will time-out after 15 idle minutes. It is frustrating for students to lose their progress, so a good rule of thumb is to get them to save their progress after completing each objective

2. The most stable option for large classes is downloading the app and running locally, see instructions at: **https://github.com/MacrosystemsEDDIE/module5**

   - Once the app is downloaded and installed (which requires an internet connection), the app can be run offline locally on students' computers

   - This step requires R and RStudio to be downloaded on a student's computer, which may be challenging if a student does not have much R experience (but this could be done prior to instruction by an instructor on a shared computer lab)

   - If you are teaching the module to a large class and/or have unstable internet, this is the best option

3. As a last option, the app is accessible in any internet browser via Binder hosting: **https://mybinder.org/v2/zenodo/10.5281/zenodo.7249986/?urlpath=shiny/app/**

   - Prior to class, the instructor should go to the Binder webpage and make sure that it loads (because Binder is provided as a free platform, it occasionally needs to be loaded more than once the first time)

   - It takes ~5-10 minutes to load, so it's helpful for students to start loading this webpage prior to instruction

   - During instruction, this webpage occasionally times out if there are many users (even if on good internet), so this is a less stable alternative than options 1 or 2

Regardless of which option you pick, all module activities are the same!

2. Give students their module report ahead of time to read over prior to class or distribute reports when they arrive to class. There is also an option to download the report directly from the Shiny app. The report includes pre-class readings, videos, and a short pre-class activity introducing some current examples of ecological forecasts. Students will also answer the questions embedded throughout the Shiny app in the module report, which could be submitted to the instructor for grading if desired.

3. Instructor gives a brief PowerPoint presentation that introduces ecological forecasting, the iterative forecasting cycle, and a basic ecosystem productivity model (~30mins).

4. After the presentation, the students divide into pairs. Each pair selects their own NEON site and visualizes their site's data, which is used to build and calibrate an ecosystem productivity model (Activity A). The two students within a pair each build their own model with unique inputs and

parameters to compare the performance of two different models for the same ecosystem. For virtual instruction, we recommend putting two pairs together (n=4 students) into separate Zoom breakout rooms during this activity so the two pairs can compare results.

5. The instructor then introduces Activities B and C, potentially revisiting some of the slides from the introductory presentation as a reminder to students about the next steps. For virtual instruction, this would entail having the students come back to the main Zoom room for a short check-in.

6. The students work in their pairs to forecast primary productivity at their chosen site using each model, and investigate how the forecast uncertainty changes with different model inputs and parameters (Activity B). At the end of Activity B, students assess their forecasts. They may also compare their forecasts with their partner's. For virtual instruction, we recommend putting the two pairs back into the same Zoom breakout rooms. Optionally, instructors may bring the class back together at the end of Activity B to discuss performance of students' initial forecasts before beginning Activity C.

7. Student pairs then update their forecast models and generate a second forecast, thus completing and recommencing the iterative forecast cycle (Activity C). The students work together in a group to present the results from their site and different models to the rest of the class. The class may discuss why the forecasts are similar or different among the different sites and models.

Important Note to Instructors:
The R Shiny app used in this module is continually being updated, so these module instructions will periodically change to account for changes in the code. If you have any questions or have other feedback about this module, please contact the module developers (see "We'd love your feedback" below).

We highly recommend that instructors familiarize themselves with the Shiny app prior to the lesson. This will enable you to be more prepared to answer questions related to certain areas of the app's functionalities.

Things to do prior to starting the instructor's presentation
- Have the students read through the module report, especially the 'Why macrosystems ecology and ecological forecasting?' and 'Today's focal question' sections.
- Optionally, have students complete the pre-class activity, where they are asked to access examples of ecological forecasts that are publicly available and answer questions about the variables being forecasted and the usefulness of the forecast for management.

Introductory PowerPoint Presentation
Note: the numbers below match the PowerPoint slide numbers. The text for each slide is also in the "Notes" of the PowerPoint, so can be viewed when projecting in Presenter View.

1. Welcome the students to class.

    a. It is important at this point to emphasize that there will be lots of new material covered during this module, and that going slowly and asking for help is very much encouraged!

    b. If the students are using the Binder option for accessing the module, asking them to start loading the module in an internet browser will save time later (see link above).

2. Quick road map of what will be covered in this lesson

    a. Overview slide for the day (Will require instructor edits if adapting for different class lengths!)

    b. 2 classes (1:15 -1:30 in length), completion of Activity A in class 1 and Activities B and C in class 2; reports collected as homework; optional presentation of each groups results as time permits or in a 3rd class period

    c. 1 class (3:00 in length), Activity A - 45mins, 5min break, Activities B and C – 45 mins followed by presentation/discussion of each group's results as time permits

3. Big picture, framing ecological forecasts in the context of changing climate and land use. Focus on aquatic ecosystems today, management of these resources could be improved my having advance knowledge of how they could potentially change. Why do we want to generate ecological forecasts? Answer: Because there is lots of variability in how climate change is occurring globally and lakes provide critical ecosystem services for humans, so ecological forecasts are critical to help management of these resources in the short-term.

4. Ask the class "What is a Forecast?" – if teaching virtually, prompt them to either type answers into the chat or raise their hand to ask the question. Key aspects of a forecasts are listed in the slide. Actionable implies that the information is given in a time frame that allows for a response. For example, you could forecast air temperature five minutes into the future with relatively low uncertainty, but this is not much use compared to a forecast for air temperature three days into the future.

5. Ask the class 'What do we forecast?'. Encourage them to provide answers by either un-muting or typing into the chat or raising their hand. Add the examples with the animation and detail how forecasting is prevalent across many different sectors of society.

6. There are two main purposes of forecasts. Talk through the examples and stress the difference between a situation when we have no control over the outcome (passive) and when we can influence the outcome (active)

    a. Preparation – the example is Hurricane Sandy in 2012 - passive

    b. Actionable – the example is COVID-19 - active

7. Today, we are going to focus specifically on ecological forecasting. Question to ask the students on this slide: what is an ecological forecast? Highlight the inclusion of "uncertainty"

8. Ecological forecasts are being produced today! These examples are selected from the pre-class "Exploration" activity that students may have completed. You might ask students, "Who do you think might use these forecasts, and why?"

9. Introduce each point in the forecast cycle and that you will break each of them down. Highlight that it is "iterative" which means that it is a repetitive process, hence why it is described as a cycle

10. We will begin with creating a hypothesis, which is a proposed explanation for a phenomenon observed in the real world. For example, we might hypothesize that "More nutrients will

increase the algal biomass in a lake." You might ask students to provide additional examples of ecological hypotheses.

11. Next, we can build our hypothesis into a mathematical model. For example, here we have built our hypotheses about nutrients and phytoplankton into a very simple model, which says that the amount of phytoplankton in a lake today depends on the amount of phytoplankton yesterday, plus the amount of growth due to nutrient uptake, minus death. Growth, in turn, depends on the phytoplankton growth rate (this is a parameter) times the amount of nutrients available yesterday and the amount of phytoplankton yesterday. Emphasize that the amount of growth will depend on the amount of available nutrients, and this is how the hypothesis is built into the model.

12. Before generating a forecast, we should quantify the uncertainty associated with our forecast. Calculating the uncertainty associated with a forecast is critical to help forecast users make decisions based on forecast output. For example, how confident are we in our estimates of the amount of phytoplankton present yesterday or phytoplankton mortality? You will learn more about how to quantify uncertainty as you progress through the module.

13. Finally, we can run our mathematical model, with uncertainty, to create a forecast. The different lines here represent different runs of the model under different conditions. We call these different model runs "ensemble members". The ensemble allows us to quantify our uncertainty.

14. After generating a forecast, we communicate our forecast to end users. Good forecast communication may require us to translate a forecast into a different visualization for an end user. For example, here the original forecast plot is translated into a stoplight graphic to more quickly communicate the risk of an algal bloom occurring tomorrow.

15. The next step is to wait until the future arrives and then assess our forecast. Here, I am showing the example forecast we generated, but layered on top of it is an additional week of observations, which occurred after the forecast was generated. We can use these new observations, plotted in red, to assess the performance of our forecast.

16. After assessing our forecast, we can update our model to try to improve it for the next forecast. Here is the same plot shown on the previous slides, but the model has been updated with new parameter values to try to make it better match recent observations, and a "re-forecast" has been generated with the new parameters. The original forecast is shown in green and the reforecast is shown in red. The hope is that by updating the model, we can improve the performance of the next forecast, continuing the forecast cycle.

17. Today, we are going to generate forecasts of **primary productivity** in lakes using an **ecological model** calibrated to real data from the **National Ecological Observatory Network**.
    a. **Primary productivity** is the rate at which energy is converted into biomass by producers.
    b. Ask the class, what are some of the drivers of primary productivity in a lake?
    c. Answer: light, water temperature, available nutrients, phytoplankton, zooplankton, among others

18. Why forecast **primary productivity?** Excess primary productivity can lead to harmful algal blooms, which compromise water quality through:
    a. Production of toxins,
    b. Production of taste and odor compounds,
    c. Creation of anoxic zones, leading to fish kills

    d.   Pre-emptive notice of a possible harmful algal bloom via an ecological forecast could allow managers to prevent or mitigate these adverse water quality impacts.

19. We will use ecological models to generate our forecasts
    a.   An **ecological model** is a simplified representation of nature, with the goal of understanding and predicting environmental dynamics
    b.   A simple version of a model is a linear model: "y = mx + b", but today we will be using a model to predict chlorophyll-a concentrations in a lake, where chlorophyll is the "y" in the equation but will add in other drivers such as surface water temperature and incoming light.

20. Today, we will use a simple primary productivity model, where phytoplankton are the producers which determine the rate of primary productivity. Phytoplankton grow by taking up nutrients, in this case nitrogen, and also die, releasing nutrients back into the water column. The rate of phytoplankton growth is also affected by the water temperature and the amount of incoming light, which phytoplankton need for photosynthesis.

21. To calibrate our model, we will use data from the U.S. National Science Foundation's National Ecological Observatory Network, or NEON. **NEON** is a continental-scale observatory designed to collect long-term open access ecological data to better understand how U.S. terrestrial and aquatic ecosystems are changing. We will be using data from five different lake sites within NEON.

22. Learning objectives!
    a.   Talk through these with the students one by one: use the embedded animations to sequentially show each of the six bullet points.
    b.   Most importantly, the goal here is to have students develop their own ecological model for their aquatic ecosystem, and then step through each stage of the forecast cycle.
    c.   At the end of the module, the instructor may request that students make mini-presentations to share their forecast results at the end of Activity C, permitting comparison of primary productivity forecast performance across lakes in different eco-regions.

23. Introduce Activity A, which has five objectives (have students work in pairs).
    a.   Select a NEON site
    b.   Visualize the variables at the site
    c.   Explore variable relationships
    d.   Explore the lake ecosystem model structure
    e.   Within pairs, each student builds their own ecosystem model; students then compare the performance of the two different models in predicting productivity at the same lake

24. Activity B – continue working in pairs and answer the questions individually. Step through each step of the forecast cycle
    a.   Quantify forecast uncertainty
    b.   Generate a forecast of primary productivity for your site
    c.   Communicate forecast
    d.   Assess forecast with data

25. Activity C – continue working in pairs. Each student will update their model and generate a new forecast
    a. Update model to improve forecast
    b. Generate the next forecast
    c. At the end of Activity C, regroup as a class and each of the groups present the results from their forecast and how their forecast got better or worse over time
26. Shiny App:
    a. The module can be accessed as described above via Shiny, GitHub or Binder (see above)
    b. This is an interactive webpage built using R code
    c. It has interactive plots and options embedded which allow you to build your own personal model, visualize and explore the data, and answer questions
27. Generating the student report. At this point, the instructor may choose to navigate to the Shiny app and demonstrate its features while screen sharing the app in a browser. Alternatively, the instructor may cover the material on slides 27-29 in PowerPoint.
28. Saving & resuming progress in the Shiny app.
29. We recommend that you save your progress often!
30. Help students transition over to the Shiny app and get started. Instructors may use the table to record which students are working with which lake sites, if helpful.
31. Thank you for participating! If you would like to learn more, please check out the other Macrosystems EDDIE ecological forecasting modules.

Module Overview
This is the landing page of the Shiny app. It gives an overview of the module - there are no questions students need to complete on this tab.

Presentation
The presentation tab has key slides from the introductory presentation embedded so students may review this material. There are no questions students need to complete on this tab.

Introduction
The introduction outlines the workflow for the module and provides instructions about how to save and resume progress. This is also where they will download the module report into which they should type their answers. Students should answer questions 1-2 (hereafter, denoted as Q1-2).

Activity A: Visualize data from a selected NEON site
Activity A challenges the students to explore the data at a NEON site, explore variable relationships and construct a model to simulate primary productivity (chlorophyll-a concentrations).
Important: Tell the students to read through the detailed text in each section as this will explain what is happening within each objective.

Common stumbling blocks for Activity A include:

- In Objective 3, for Q5, students might not understand clearly what is meant by "Relationship". Explain that if there is a positive relationship, both variables increase. In a negative relationship, an increase in one variable causes a decrease in the other, and if there is no relationship, there would be no discernible pattern in the two variables. Emphasize that variable relationships can also sometimes be more nuanced, e.g. "high concentrations of chlorophyll-a only increase when surface temperatures are above some threshold."
- In Objective 4, students might skim past the "What is a Model?" section. Encourage students to slow down and read through the text and to scroll through the slides to gain a better understanding of how an ecological model is built. This information will be needed to answer the questions in Objective 4.
- In Objective 5, students may be unsure how good is a "good enough" model fit to data.
  - Encourage students to read the "Calibration tips" and examine the example calibration plots at the top of the Objective 5 page.
  - Encourage students not to spend too long on this objective; remind them that this a relatively simple model, so focus on getting the model to simulate concentrations around the average observed values, not perfectly recreate the data's patterns. After 5-10 minutes, encourage them to move on from the model calibration to the next activity.
    - Example model settings that produce an adequate model fit are provided in the table below for each lake. **NOTE: These should not be considered as the "correct" model settings, as similar or better results might be obtained with different model settings. These are just examples for reference to demonstrate what an adequate model fit might look like.**

Lake	Phytoplankton	Mortality	Growth
Crampton	1	0.8	0.2
Barco	0.5	0.6	0.2
Prarie Pothole	0.5	0.6	0.3
Little Rock	10	0.8	0.07
Prarie Lake	8	0.5	0.3

  - Sometimes students move through this exercise quickly and forget to save their model settings, which is required for progressing to Activity B.
- Walk around the pairs/move between breakout rooms and make sure that everyone can follow along the Shiny app successfully. Ensure that students have been able to successfully download and copy-paste the plot for Q11 into their final reports.
- If you are ending class after students complete Activity A, be sure they bookmark their progress by obtaining a link and saving it in their final report.

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Activity B: Generate a forecast and work through the forecast cycle

At this point, students will work through the different steps of the forecast cycle using the model they have built from Objective 5. Through these steps, they will gain further understanding of how the parameters and initial conditions can affect model performance.

If you are continuing from a previous lesson it is good to show the students how to resume progress by copy-pasting their saved link into their internet browser. If students have lost their link, they will need to:

1. re-select their site in Objective 1,
2. input their calibrated model settings in Objective 5, and
3. save the model settings in Objective 5 before proceeding to Activity B.

At the end of Activity B, you could optionally spend some time going around the classroom (in person or virtually) so that each student pair can show their initial forecast and the forecast assessment. This could be done by either sharing their screen and showing within the app or by generating their report and sharing that on the screen and talking through it. Ask probing questions and try to initiate a class discussion in which the other students respond to questions and ask their own. Questions could include:

- Why do you think your forecast did not predict observations well on the first forecast?
- Was it an easy or difficult task to describe the forecast? Why?
- Is the image of the plot or the description in words better for communicating the forecast?
- What are some of the challenges to assessing your forecast?

Alternatively, you may wait to regroup until the end of Activity C, and use these discussion questions as part of that regrouping.

Common stumbling blocks for Activity B include:
Important: Tell the students to read through the detailed text within each objective. We have embedded lots of directions, hints, and troubleshooting help within the Shiny app text! We encourage instructors to read and work through the Shiny app before teaching the module so that you are familiar with all of the steps of this activity.
- In Objective 6, the students might skip reading the text on uncertainty. Make sure to remind them that reading the text will help to explain further about the concept of uncertainty.
    - When exploring the weather forecast, encourage students to think about the connection between ensemble weather forecasts and uncertainty quantification.
    - Highlight the relationship between air temperature and water temperature and encourage them to revisit Objective 3. This will help solidify the connection between using this weather forecast to drive our model- if air temperatures go up, likely so will water temperatures, affecting their primary productivity output.
- In Objective 8, they cannot run their forecast unless all the following conditions are met. Students must have:
    - Selected a site in Activity A objective 1

- Saved a "calibrated" parameter set in the Model Settings table in Activity A Objective 5
- Loaded the NOAA weather forecast in Objective 6
- Converted the air temperature and shortwave radiation forecasts to surface water temperature and underwater PAR in Objective 7
- Loaded the driver forecasts in Objective 8
  - Once all these conditions are met, THEN they can run the model. If one of these components is missing, hints will also appear as prompts within the plotting panel.
  - Here they adjust the initial conditions of the phytoplankton to match the concentrations of chlorophyll-a seen in the plot. This allows them to start their forecast from the most up-to-date observations.
- In Objective 9, encourage students to think of how weather forecasts are communicated through words and to be descriptive, while also including uncertainty in their responses.
- In Objective 10, the students assess their forecast by calculating R^2. A point to emphasize here is that this is just one way of assessing your forecasts and there are other ways in which this can be done.
  - Reminding students to download and copy-paste their plots into their final reports as they go is also a good thing to do here!

If a student pair has finished much earlier than the other students, they can then continue with Activity C (and answering the questions in their downloaded report).

Activity C: Update model and generate next forecast

In Activity C, students update their forecast models with new data and generate a second forecast. This Activity is shorter than A and B, with only two objectives.

Common stumbling blocks for Activity C include:

- In Objective 12, students are expected to update the initial conditions of the model for phytoplankton to match the observations in the plot. Again, remind them to download their plots and copy-paste them into the final report as they go. Once they have completed this task, they are finished with Activity C.

We highly recommend having the pairs regroup for a full-class discussion at the end of Activity C, in which each pair gives informal, mini-presentations to describe their NEON sites, the forecasts they produced, and the decisions they made while stepping through the forecast cycle. From our experience, spending 15-20 minutes on the presentations would be recommended for helping ensure that all students can benefit from their classmates' findings.

If you did not have the class regroup at the end of Activity B, see the suggested discussion questions under that activity. Some additional questions specific to Activity C might include:

- When updating your model, did you anticipate how the model would respond?

- Can you think of benefits of updating your model with observations as they become available? Any potential drawbacks?
- How do you think your forecasts might change on a seasonal scale? (e.g. in summer compared to fall)

Resources and References

Optional pre-class readings and videos:
Articles:

- Dietze, M., & Lynch, H. (2019). Forecasting a bright future for ecology. Frontiers in Ecology and the Environment, 17(1), 3. https://doi.org/10.1002/fee.1994
- Dietze, M. C., Fox, A., Beck-Johnson, L. M., Betancourt, J. L., Hooten, M. B., Jarnevich, C. S., Keitt, T. H., Kenney, M. A., Laney, C. M., Larsen, L. G., Loescher, H. W., Lunch, C. K., Pijanowski, B. C., Randerson, J. T., Read, E. K., Tredennick, A. T., Vargas, R., Weathers, K. C., & White, E. P. (2018). Iterative near-term ecological forecasting: Needs, opportunities, and challenges. Proceedings of the National Academy of Sciences, 115(7), 1424–1432. https://doi.org/10.1073/pnas.1710231115
- Jackson, L. J., Trebitz, A. S., & Cottingham, K. L. (2000). An Introduction to the Practice of Ecological Modeling. BioScience, 50(8), 694. https://doi.org/10.1641/0006-3568(2000)050[0694:aittpo]2.0.co;2

Videos:

- NEON's Ecological Forecast: The Science of Predicting Ecosystems
- Fundamentals of Ecological Forecasting Series
  - Why Forecast?

Recent publications about EDDIE modules:
- Carey, C. C., R. D. Gougis, J. L. Klug, C. M. O'Reilly, and D. C. Richardson. 2015. A model for using environmental data-driven inquiry and exploration to teach limnology to undergraduates. Limnology and Oceanography Bulletin 24:32–35.
- Carey, C. C., and R. D. Gougis. 2017. Simulation modeling of lakes in undergraduate and graduate classrooms increases comprehension of climate change concepts and experience with computational tools. Journal of Science Education and Technology 26:1-11.
- Klug, J. L., C. C. Carey, D. C. Richardson, and R. Darner Gougis. 2017. Analysis of high-frequency and long-term data in undergraduate ecology classes improves quantitative literacy. Ecosphere 8:e01733.
- Farrell, K.J., and C.C. Carey. 2018. Power, pitfalls, and potential for integrating computational literacy into undergraduate ecology courses. Ecology and Evolution 8:7744-7751. DOI: 10.1002/ece3.4363

- Carey, C. C., Farrell, K. J., Hounshell, A. G., & O'Connell, K. 2020. Macrosystems EDDIE teaching modules significantly increase ecology students' proficiency and confidence working with ecosystem models and use of systems thinking. Ecology and Evolution. DOI: 10.1002/ece3.6757

We'd love your feedback!

We frequently update this module to reflect improvements to the code, new teaching materials and relevant readings, and student activities. Your feedback is incredibly valuable to us and will guide future module development within the Macrosystems EDDIE project. Please let us know any suggestions for improvement or other comments about the module at http://module5.macrosystemseddie.org or by sending an email to MacrosystemsEDDIE@gmail.com

Answer Key

The following plots are indicative of what student model output should look like (approximately) if the module is run correctly. We note that answers may vary depending on which lake and model the students run in the module. Answers are given below as bullet points beneath each question.

Pre-class activity: Explore ecological forecasts

Choose one of the ecological forecasts above and use the website to answer the questions below.

  a) Which ecological forecast did you select?
  b) What ecological variable(s) are being forecasted?
  c) How can this forecast help the public and/or managers?
  - Help decision makers/stakeholders make decisions in how to preserve the target resource
  d) Describe the way(s) in which the forecast is visualized
  - Is it a time series or spatial map?
  - Is uncertainty included in the visualization?
  - How is uncertainty visualized? Confidence intervals, color, etc.

Introduction

Q1. How have you used forecasts (ecological, political, sports, any kind!) before in your day-to-day life?

- Usually weather forecast is the most widely used forecast, but any reasonable answer is acceptable here.

Q2. How can ecological forecasts improve both natural resource management and ecological understanding?

- If we can predict how ecosystems will change in the future, we can be proactive about avoiding changes that we deem undesirable.
- If we can predict the future responses to management decisions, we can make more informed decisions to optimize natural resource abundance and human benefits.

Activity A:

Objective 1 - Objective 1 - Select a Site

Q3. Fill out information about your selected NEON site:

- Collate information from the description in the Shiny app and also latitude and longitude are available on the Site info page. For some lakes, not all the data is available so they can input NA.

Objective 2 - Inspect the Data

Q4. Fill out the table below with the description of site variables:

- Simple summary statistics which vary by site

Objective 3 - Explore variable relationships

Q5. Describe the effect of each of the following variables on chlorophyll-a. Chlorophyll-a is used as a proxy measurement for phytoplankton concentration and primary productivity in aquatic environments.

- Generally, we are looking for students to describe relationships between variables – e.g., positive relationship, negative relationship. For water temperature and chlorophyll-a, it may be more nuanced, e.g.: "high concentrations of chlorophyll-a occur only when there is high water temperature" but this can vary by site.

Objective 4 – Understand the ecological model

Q6. Describe the relationship between each of these driving variables and productivity according to the ecosystem model we are using today (depicted above). For example, if the driving variable increases, will it cause productivity to increase (positive), decrease (negative), or have no effect (stay the same).

a) Surface water temperature – positive
b) Incoming light – positive

Q7. Classify the following as either a state variable or a parameter by dragging it into the corresponding bin.

State variable	Parameter
Phytoplankton	Maximum growth rate
Nutrients	Mortality rate

Q8. We are using chlorophyll-a as a proxy of aquatic primary productivity. Select how you envision each parameter to affect chlorophyll-a concentrations:

- Maximum growth rate – Positive
- Phytoplankton mortality rate – Negative

Objective 5 – Build model

Q9. Describe the effect of changing phytoplankton initial conditions on your model run. As you increase or decrease initial conditions, how does this affect modeled primary productivity?

- Students should notice a correspondence between the initial conditions value they select and where the model run starts; model runs with very high initial conditions may exhibit a rapid decline in primary productivity, while model runs with very low initial conditions may increase rapidly.

Q10. Describe the effect of changing the phytoplankton mortality parameter on your model run. As you increase or decrease mortality, how does this affect modeled primary productivity?

- Model runs with low mortality should exhibit higher primary productivity than model runs with high mortality (which should exhibit low primary productivity).

Q11. Copy-paste the plot you downloaded that shows your calibrated model run into your final report.

Primary Productivity
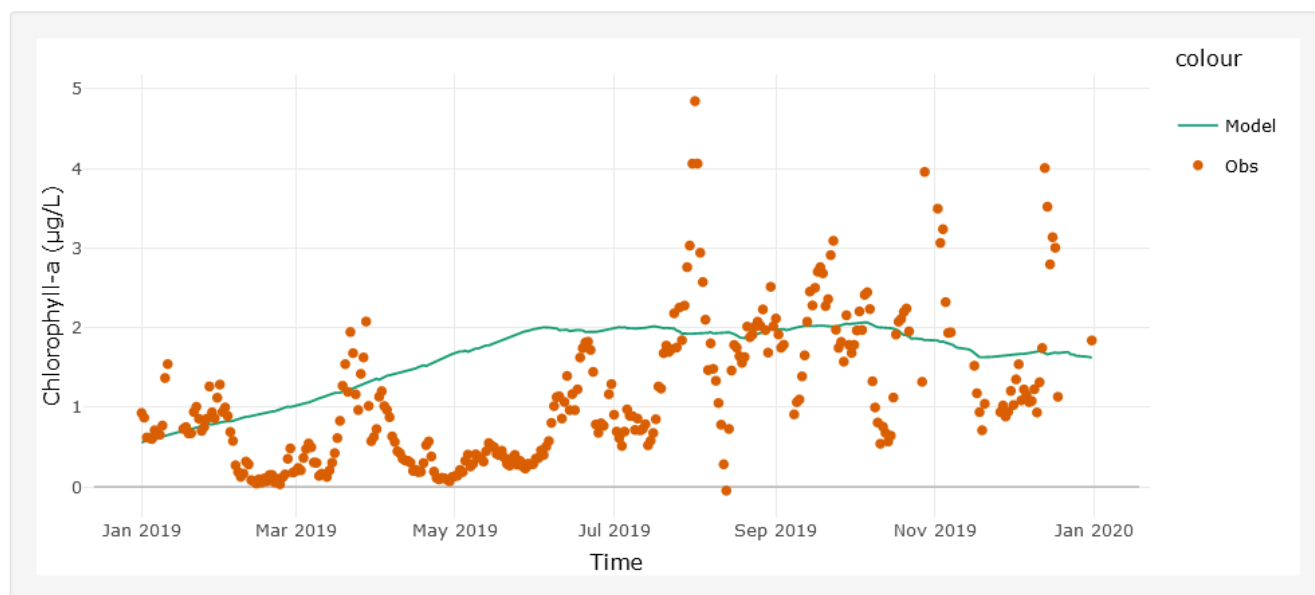
This is an example target plot that students should produce. The aim is to get the model to replicate similar ranges for chlorophyll-a. There will be differences among sites, but we aim to get within ranges.

Q12. Referring to the plot that shows your calibrated model, describe in your own words how well the model fits the data.

- Student answers will vary depending on the site they have selected and the model calibration; the goal is for students to understand that a simple model will not perfectly recreate every chlorophyll-a observation, but will hopefully track the tendency of the observations fairly well.

Q13. Record the model settings of your best-fit calibrated model in the Q14 table.

- Answers will vary depending on the site students have selected

Activity B

Objective 6 - Understand uncertainty and explore a weather forecast

Q14. What is forecast uncertainty? How is forecast uncertainty quantified?

- Forecast uncertainty arises from errors or imperfections in our knowledge and understanding of the ecological system
- Uncertainty can be quantified through ensemble modeling, which involves running a model many times under slightly different conditions

Q15. Inspect the weather forecast data for the site you have chosen:

a. How does increasing the number of ensemble members in the weather forecast affect your impression of the uncertainty in future weather?
   - This is a subjective question, so answers may vary. As you increase the number of ensemble members, the uncertainty increases in the future, but there may be a threshold plateau when adding more members will not substantially affect uncertainty.
b. Using the interactivity of the weather forecast plot, compare the air temperature forecasts for the first week (Sep 25 - Oct 1) to the second week (Oct 2 - 8). How does the forecast uncertainty change between the two periods?
   - The forecast uncertainty is relatively low for the first week, but increases during the second week.
c. Use the 'Save plot' button to save the NOAA forecast plot and copy-paste it into your final report.
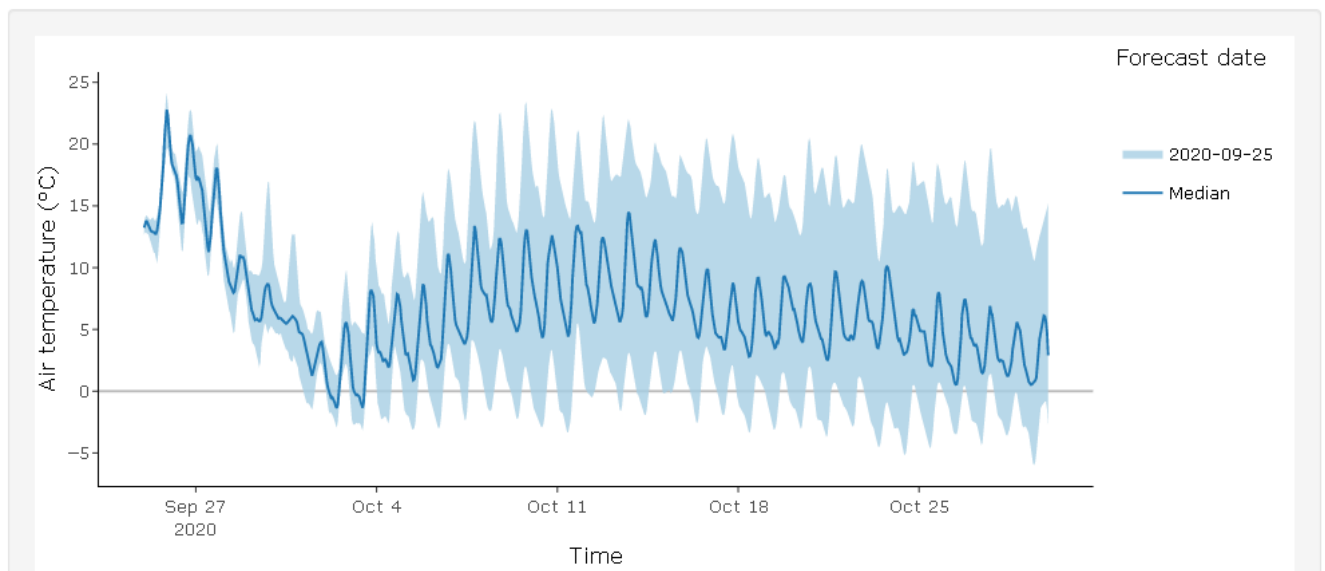
Plot of forecasted air temperature. This will vary by site and by how many members they choose to include.

Objective 7 - Prepare inputs

Q16. Explain, in your own words, why it is necessary to convert the NOAA forecasts of air temperature and shortwave radiation into forecasts of water temperature and underwater PAR as a step towards generating forecasts of primary productivity.

- Our model structure requires water temperature and underwater PAR as driver variables. To run our model into the future, we need forecasts of water temperature and underwater PAR, but NOAA does not provide forecasts of these variables. As a result, we leverage strong positive relationships between air temperature and water temperature and between shortwave radiation and underwater PAR to convert the NOAA forecasts into the driver forecasts we need to run our primary productivity model.

Objective 8 - Generate an Ecological Forecast

Q17. Use the 'Save plot' button to save the plot of your forecast and copy-paste it into your final report.
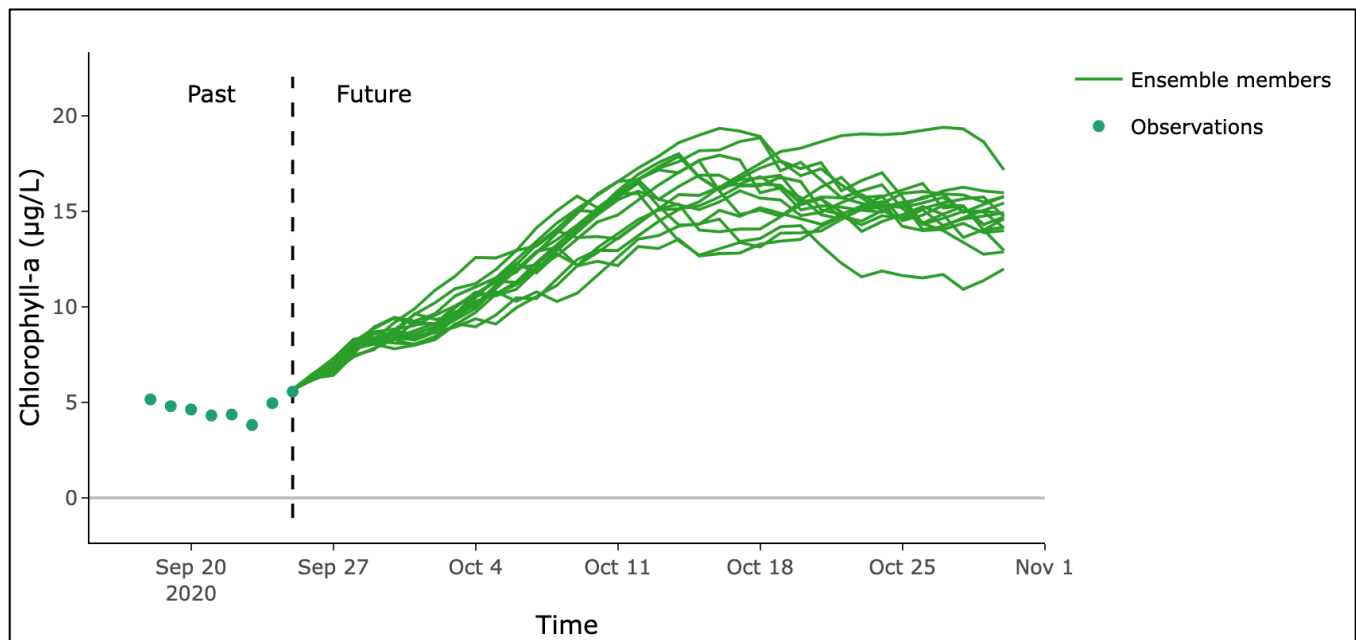
Example forecast. Students are expected to adjust the initial conditions to the observed measurement.

Q18. Examine the plot depicting your forecast.

a) Under 'Load Driver Forecasts', remove the effect of driver uncertainty on your forecast by adjusting the number of ensemble members to 1, and re-run your forecast. Then, adjust the

number of ensemble members to 30 and re-run the forecast. How does including driver uncertainty affect the forecast?

- Without driver uncertainty, only one possible outcome is shown and it is difficult to determine the likelihood of that outcome, while with driver uncertainty, a range of possible outcomes is shown and the forecaster has a better sense of the likelihood of each outcome.

b) How does altering the initial condition of your forecast affect forecast output?

- Changing the initial condition changes the starting point of the forecast, and therefore changes the forecasted values, particularly for the first few days of the forecast

Objective 9 - Communicate an Ecological Forecast

Q19. How would you describe your forecast of primary productivity at your NEON site so it could be understood by a fellow classmate?

- We are looking for descriptive answers here which include a description of the uncertainty and a summary of the general trend.
    - Primary productivity is expected to increase substantially in the next day, then plateau at a relatively high level. Chlorophyll-a concentrations will reach around 8 micrograms/L and most likely stay there for the next 7 days.
    - According to my model, the chlorophyll-a concentration spikes up to 30 ug/L and then slowly declines over time.
    - Our forecast predicts that algae will increase over the next month to levels greater than that observed over the last week.

Q20. Examine the example forecast visualizations below.

a) Which of these visualizations do you think most effectively communicates your forecast, and why?

- This is a subjective question and answers may vary. Ideally, students will select a visualization that includes a representation of uncertainty, as this is important for informing decision-making based on forecast output.

b) Download and copy-paste the visualization that you think best communicates your forecast into your final report.
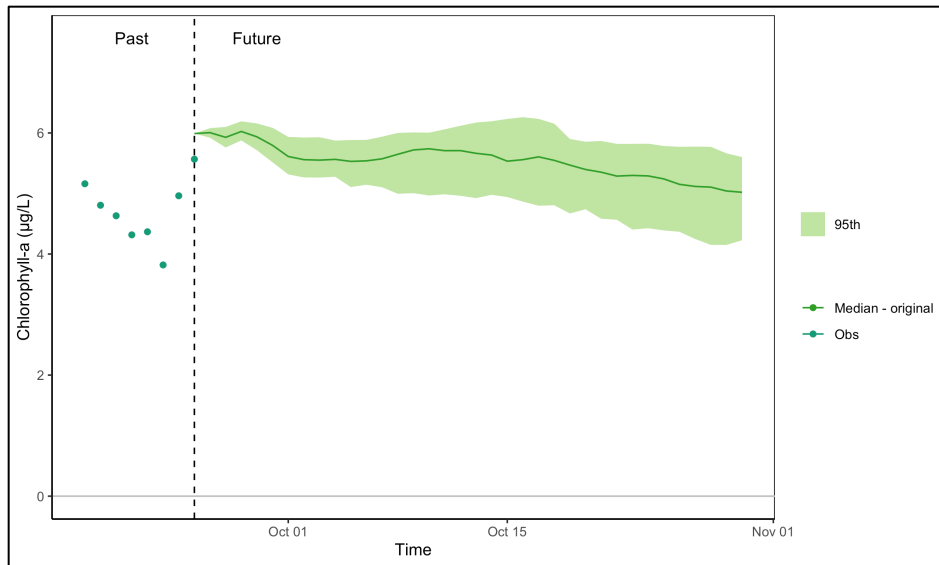
Example visualization chosen by student to communicate forecast.

Objective 10 - Assess an Ecological Forecast

Q21. Examine the predicted vs. observed plot as well as the value of R2.

  a) How well did your forecast do compared to observations?

  • Write and include the R^2 value here and describe the performance.

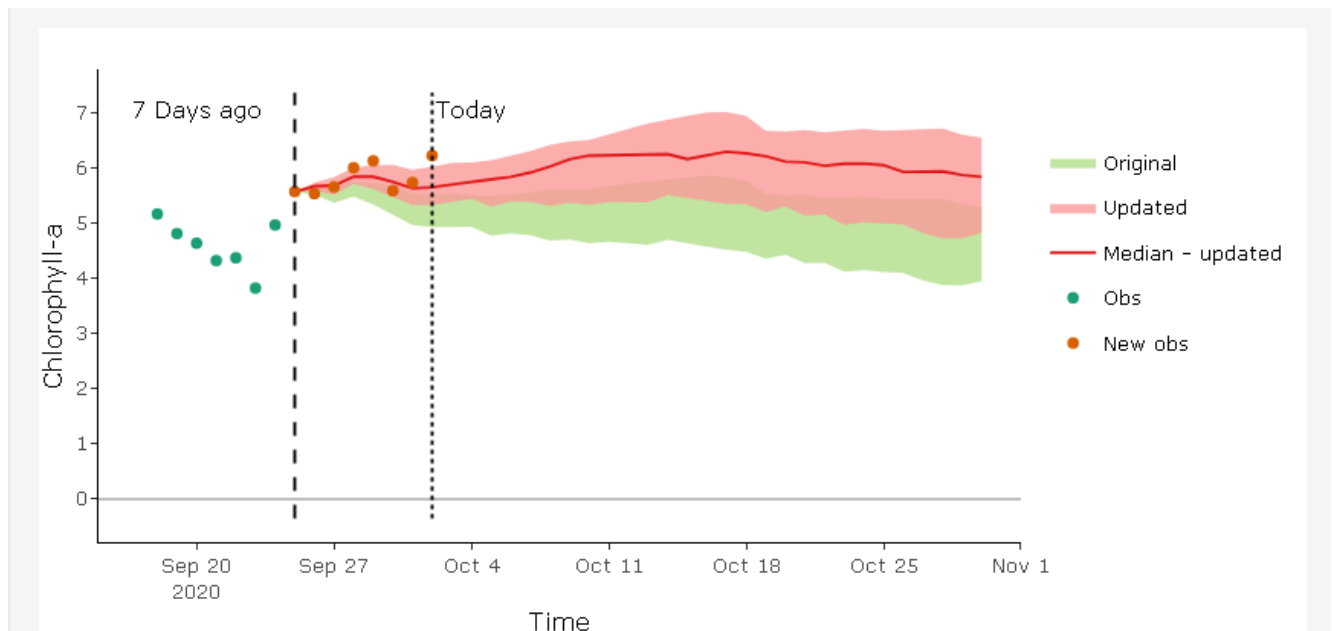 b) Download and copy-paste the forecasted vs. observed plot into your final report.
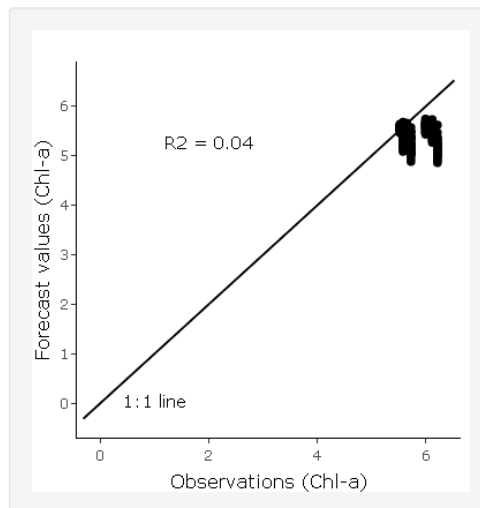
Plot of assessment of ecological forecast.

Activity C
Objective 11 - Update Model

Q22. Complete the following steps to document your forecast updating process.

    a) Record your original and updated model settings in the Q23 table in your final report.

    •   Student answers will vary depending on the selected lake site.

    b) Download and copy-paste your updated forecast plot into your final report.

Plot showing the updated model.

    c)   Download and copy-paste the plot assessing your updated forecast into your final report.
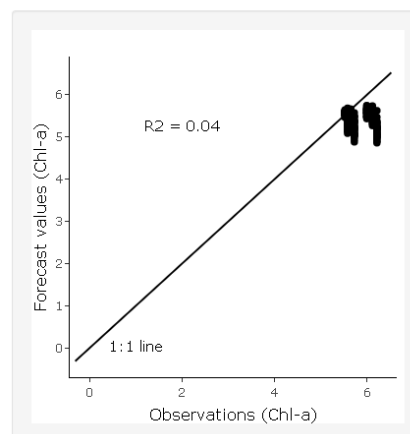
Plot showing assessment of the updated model.

d) Were you able to successfully improve your forecast by updating your model parameters? Explain what you did and how you know whether your forecast has improved.

- From the example figures shown above, a reasonable answer could include:
- Yes, I was able to make the forecast more closely match the observations, OR, The forecast did not improve much, if at all.
- Students should also include a description of how they altered the model parameters and how they assessed whether the forecast improved (e.g., visually inspecting the plots, looking at R^2 value, etc.).

Objective 12 - Next Forecast

Q23. Describe the new forecast of primary productivity.

a) Record all your model settings in the Q24 table in your final report.

- Student answers will vary depending on the selected lake site.

b) Download and copy-paste the plot of your second forecast into your final report.

New Forecast plot
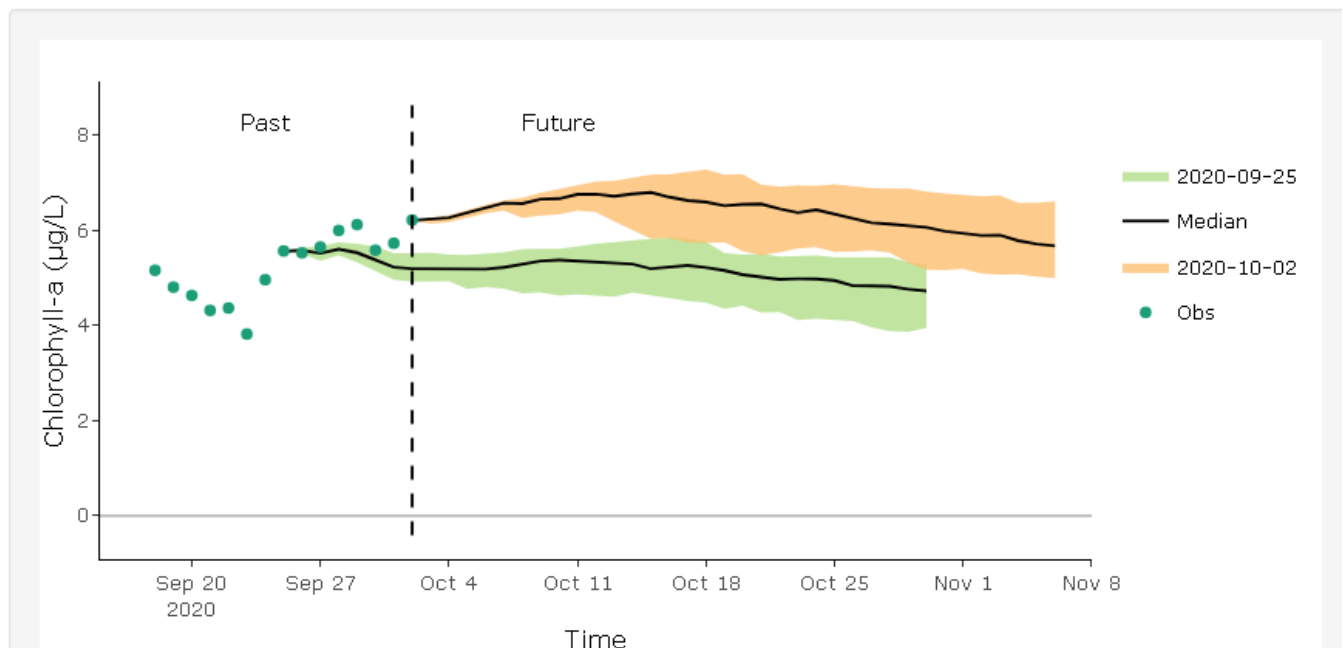
Plot showing the next forecast for CRAM.

c) Describe the new forecast of primary productivity.

- Examples of potential answers include:
  - The new forecast now predicts the primary productivity will increase initially, but not as high as previously forecasted. Then, the primary productivity decreases gradually over the next 7 days.
  - Chlorophyll-a concentrations are forecasted to decline over the course of the forecast period.

Q24. Why is the forecast cycle described as 'iterative' (i.e. repetition of a process)?

- The forecast cycle is iterative because the model is being updated with each new round of data collection before a new forecast is generated.
- With each iteration, the forecast is continually improving over time.

Discussion topics:
Following completion of Activity C, bring the students back into the same room and remind them to complete all the questions and download any plots that are needed for their final report.

- A good exercise to start with would be to ask students present their results to the class. This can be done by either screen-sharing and showing Shiny app and navigating through the relevant tabs or instead using the generated and downloaded Word report:
  - Introduce their site
  - Calibrated model from Obj 5
  - Their first forecast from Obj 8
  - How did they communicate their forecast from Obj 9
  - Their forecast assessment from Obj 10
  - And then their updated forecast from Obj 11
- Throughout this, encourage other students to ask questions and you can also ask questions related to their results e.g.
  - What do you think are some of the shortcomings with this model?
  - Why do the forecasts look the way they do?
  - How did changing/updating the model parameters affect the forecast? E.g. what is the connection between mortality rate and growth rate on phytoplankton concentrations?
  - Do you think this will vary between sites?
  - Why do you think the forecast performed better/worse after updating the model?
  - What do you think would be the most important thing to change to improve the accuracy of the forecast?
  - Describe the uncertainty you saw in your forecasts. Where do you think that comes from?

- Try and ask each of the groups to present (as time permits)
- After discussion, it would be good to summarize some of the key points:
    - Simple ecological models can work well at capturing seasonal variability but not as responsive to sudden short-term events so even though your model captures the seasonal cycle in Obj 5, it might not predict short-term (35 day) events accurately
    - Ecological forecasts follow an iterative cycle
    - Meteorological forecasts use ensembles (multiple realizations of future conditions) to quantify uncertainty
    - This uncertainty transfers into our ecological model
    - Uncertainty generally increases into the future
    - Communicating a forecast is just as important as generating a forecast. If a forecast is not communicated effectively it reduces the potential usefulness of a forecast
    - As more data becomes available it allows the accuracy of the forecast to be assessed and this informs us if the model we are using is accurately predicting future conditions or if we need to make updates to our model