

Macrosystems EDDIE: Cross-Scale Interactions

Student Handout

Learning Objectives:

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

- Understand the concepts of macrosystems ecology and cross-scale interactions, and how different ecological processes can interact at local, regional, and continental scales.
- Simulate phytoplankton blooms in multiple lakes using ecosystem models of lake water quality set up with publicly-available high-frequency sensor datasets (Activity A).
- Test the effects of a climate scenario on the different lake models, and examine how the timing and intensity of phytoplankton blooms change with climate warming (Activity B).
- Examine the effects of both local nutrient loading and regional climate forcing to determine how factors acting at different scales interact to affect the intensity and timing of phytoplankton blooms (Activity C).
- Predict how lake phytoplankton blooms may respond globally to changing climate and land use.

Why macrosystems ecology?

Macrosystems ecology is the study of ecological dynamics at multiple interacting spatial and temporal scales (e.g., Heffernan et al. 2014). Macrosystems ecology recently emerged as a new sub-discipline of ecology to study ecosystems and ecological communities around the globe that are changing at an unprecedented rate because of human activities (IPCC 2013). The responses of ecosystems and communities are complex, non-linear, and driven by feedbacks across local, regional, and global scales (Heffernan et al. 2014). These characteristics necessitate novel approaches for making predictions about how systems may change across time and space. Consequently, macrosystems ecologists are increasingly combining large datasets of sensor observations with simulation models of ecological phenomena to predict how changes in climate, land use, and other factors may affect the structure and function of communities and ecosystems (Weathers et al. 2016).

A macrosystems approach to lake ecology

Using a macrosystems approach is necessary for studying environmental challenges that are driven by multiple factors across space and over time. In freshwater lakes and reservoirs worldwide, phytoplankton surface scums (blooms) are increasing in frequency and severity due to local, regional, and continental drivers (Brookes and Carey 2011). Some lakes are experiencing more frequent blooms due to changing land use in their watershed; for example, converting forest into agricultural fields or urban areas increases the amount of phosphorus, an element that stimulates phytoplankton growth,

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entering nearby lakes. Other lakes are experiencing increased blooms due to a warmer climate, because many phytoplankton species can proliferate in warmer waters. Here, changing land use is an example of a local driver, and changing climate is an example of a regional driver. Together, both drivers contribute to an increase in blooms in lakes worldwide, though the dominant driver causing the blooms varies substantially from lake to lake.

The theme of this module is studying **cross-scale interactions**, or processes at one scale that interact with processes at another scale, which can sometimes create non-linear ecosystem responses. In this module, you will work with a partner to study how lakes will respond to regional changes in climate and local changes in land use using an ecosystem simulation model, with the goal of predicting how these local and regional drivers will interact to promote or suppress phytoplankton blooms. We will examine how local, regional, and continental processes interact over time to produce macrosystem-level phenomena (here, focusing on phytoplankton blooms in lakes across the U.S.).

Module overview:

- 1) Introduction to Macrosystems Ecology: pre-readings and PowerPoint in class
- 2) Download and set up R software and module files on your computer
- 3) Activity A: Explore and run a lake water quality model in R
- 4) Activity B: Generate hypotheses about lake responses to climate warming, and model how different lakes respond
- 5) Activity C: Model the effects of climate and land use change scenarios on multiple lakes, and make predictions about continental-scale phytoplankton blooms.

Optional pre-class readings and video:

- Heffernan, J.B., et al. 2014. Macrosystems ecology: understanding ecological patterns and processes at continental scales. *Frontiers in Ecology and the Environment* 12: 5-14.
- Raffa K.F., et al. 2008. Cross-scale drivers of natural disturbances prone to anthropogenic amplification: the dynamics of bark beetle eruptions. *BioScience* 58: 501–17.
 - *Note:* focus on pages 501-507.
- Paerl, H.W. 2017. Controlling cyanobacterial harmful blooms in freshwater ecosystems. *Microbial Biotechnology*. 10: 1106-1110.

Today's focal question:

*How will changes in land use and climate **interact** at local and regional scales to affect lake water quality metrics, specifically, the timing and intensity of phytoplankton blooms?*

To address this question, we will use an open-source model called GLM-AED (General Lake Model-Aquatic EcoDynamics; Hipsey et al. 2014). The GLM-AED model requires two input files: a meteorological driver file that contains multiple weather variables (including air temperature, solar radiation, wind, and precipitation) as well as an inflow driver file that contains phosphorus loading variables for the streams entering the lake. GLM-AED also has three configuration files, or 'master script' files called nml files (named glm2.nml, aed2.nml, and aed2_phytos_pars.nml) that give basic

information about the lake (e.g., maximum depth, latitude, lake name, etc.) and instructions as to how the model should be run. These instructions include the simulation start and end dates and times, the time step of the model, and the names of the meteorological and inflow data files. From both the input and configuration files, the model will simulate a range of variables, including phytoplankton biomass (as chlorophyll-a concentrations) at many depths over time. For more information about GLM, see: <http://aed.see.uwa.edu.au/research/models/GLM>.

We will be running multiple GLM-AED models configured for different lakes to compare how lakes with high and low baseline water quality (i.e., low and high nutrient concentrations, respectively) respond to climate and land use change. We will be studying lakes that are part of GLEON, the Global Lake Ecological Observatory Network (gleon.org), an organization of scientists who collect and share high-resolution sensor data to study how lakes are changing in response to human activities.

These models were set up using high-frequency datasets from GLEON, NOAA (U.S. National Oceanic and Atmospheric Administration), NASA (U.S. National Aeronautics and Space Administration), and NEON (U.S. National Ecological Observatory Network). We made some changes to the lake models to simplify the surface water hydrology for this module.

Setting up R software and files:

If you have not already downloaded R and RStudio, you will need to complete that step first. You can use the file 'R You Ready for EDDIE' for help. Once you have R and RStudio installed, all the information you need for the modeling activities is embedded into the R scripts within the zipped module project folders for RStudio. First, download the zipped folder, then unzip the folder and open the R script (CSI_R_Script.R). Read through the annotation for each step so that you understand what is happening in each of the lines of code that you are running.

References:

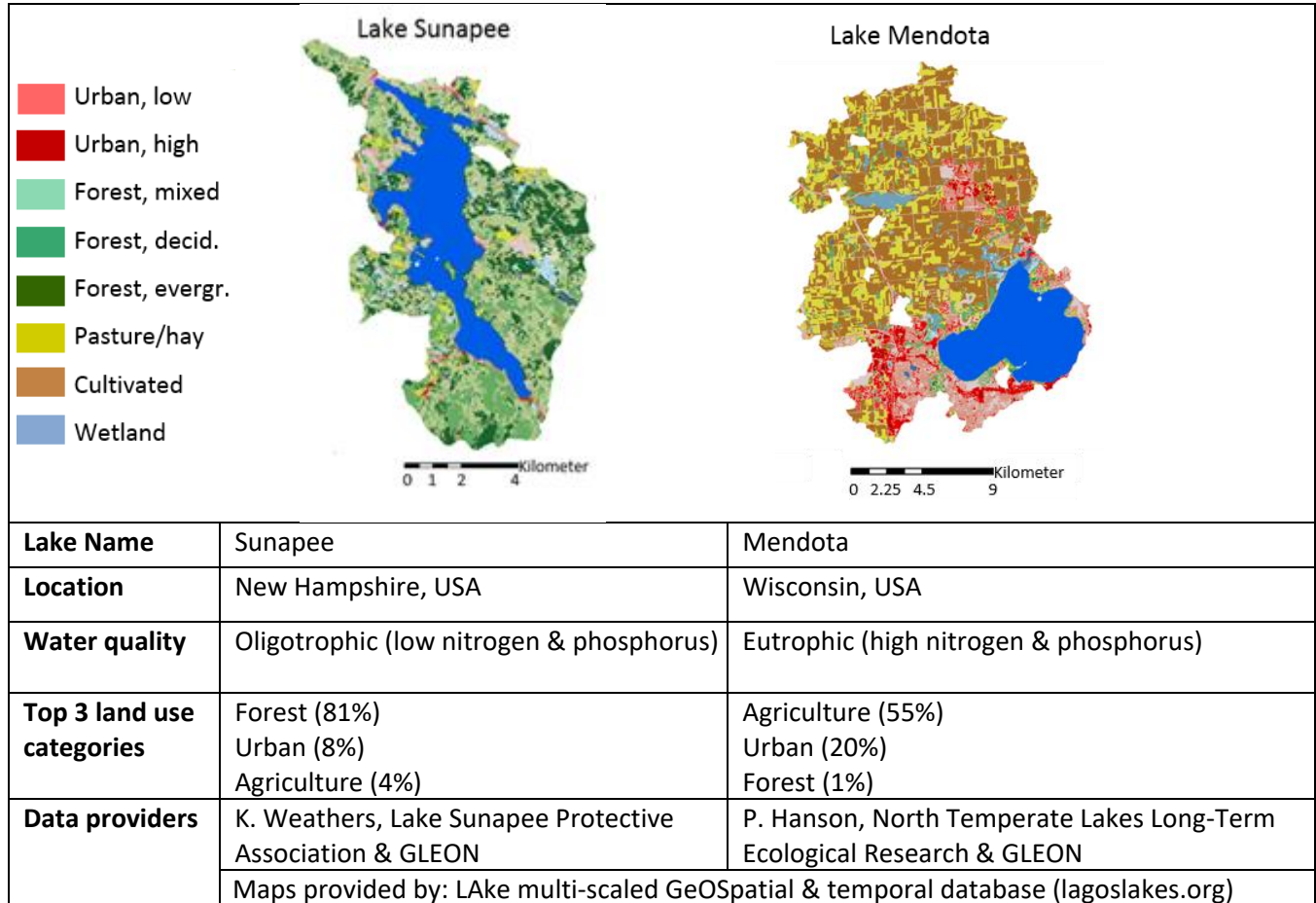
- Brookes, J. D., and C. C. Carey. 2011. Resilience to Blooms. *Science* 334:46–47.
- Hipsey, M. R., L. C. Bruce, and D. P. Hamilton. 2014. GLM - General Lake Model: Model overview and user information. AED Report #26, The University of Western Australia, Perth, Australia. 42 pp.
- IPCC. 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. (T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, Eds.). Cambridge University Press, New York, NY.
- Weathers, K. C., P. M. Groffman, E. Van Dolah, E. Bernhardt, N. B. Grimm, K. McMahon, J. Schimel, M. Paolisso, R. Maranger, S. Baer, K. Brauman, and E. Hinckley. 2016. Frontiers in Ecosystem Ecology from a Community Perspective: The Future is Boundless and Bright. *Ecosystems* 19:753–770.

As you go through the module, you'll answer the questions below and turn in your answers at the end of the activity for credit.

Name:

Think about it!

With a partner, read through the table below, and answer the following questions:



- 1) Which lake most likely *already* exhibits phytoplankton blooms? Why?
- 2) Which lake's water quality is likely to be more sensitive to climate change: i.e., which lake is likely to exhibit a greater increase in phytoplankton blooms with warmer air temperatures? Why?
- 3) Which lake's water quality is likely to be more sensitive to increased phosphorus loading due to land use change? Why?
- 4) If both lakes experience both climate change and land use change simultaneously, which lake is likely to exhibit a greater increase in phytoplankton? Why?

Activity A: Plot water temperature and chlorophyll-a in your model lake

- 5) Objective 1: With a partner, look up the locations of the model lakes using a web mapping tool (e.g., Google Maps in “Satellite” mode). Where are the lakes located? When looking at the satellite version of the map, what do you notice about the different lake watersheds?
- 6) Coordinate with another team of students so that each team is modeling a different lake. With your partner, set up the GLM files and R packages on your computer for your model lake (Objective 1 in the R script). To run your model, you first have to identify your “sim_folder” to set your working directory—read through the R script notes to find out how. Once you have determined your sim_folder location, write it here (and don’t forget to also change it in the R script!):

```
sim_folder <- '/Users/_____/Desktop/cross_scale_interactions/_____'
```

- 7) Run the GLM model and explore the output for temperature and chlorophyll-a (Objective 2).
 - a. Look at the color gradient scale: when is there the highest concentration of chlorophyll-a during the year? What is the value of the maximum concentration?

Activity B: Select a climate scenario, generate hypotheses, and model how the lakes respond

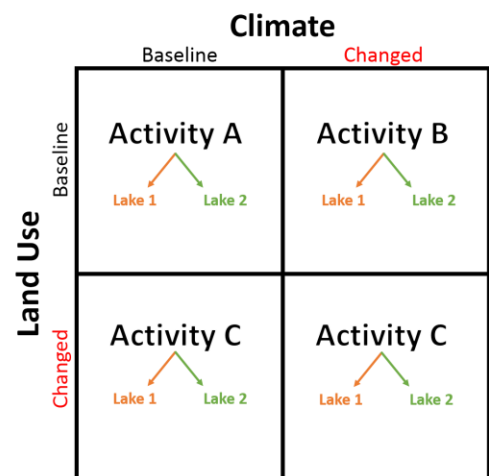
- 8) Working with the other team of students, select a climate change scenario for air temperature.
 - a. Which climate scenario are you modeling for your lakes?
 - b. Develop hypotheses about how changing air temperatures may affect chlorophyll-a in your model lakes: which lake will be most sensitive to your scenario’s air temperatures and why?
- 9) Following the directions in the R script, modify your glm2.nml file for your climate scenario, then run both lake models with the same scenario and analyze the output to determine how this scenario alters chlorophyll-a (Objective 3).
- 10) To analyze the model output, create some figures with your partner and the other team (Objective 4) to help answer these questions:
 - a. How does the chlorophyll-a concentration in the two lakes respond to your climate scenario?

- b. Does the model output support or contradict the hypotheses you listed in 7b?
- c. How does the output from the two lakes compare?
- d. Which lake's chlorophyll-a is more sensitive to the climate scenario?
- e. What are the implications of your climate scenario for future water quality and phytoplankton blooms?

Activity C: Select climate and land use scenarios to test how local and regional drivers interact to affect water quality

11) Working with the other team, select a land use scenario based on changing phosphorus inputs to your lakes (Objective 5).

- a. Which land use scenario are you modeling for your lakes?



- b. Develop hypotheses about how land use change may affect chlorophyll-a in your model lakes: which lake will be most sensitive to your scenario's phosphorus concentrations and why?

12) Update your glm2.nml file to use the baseline meteorology and the land use scenario inflow file, then run both lake models with the same scenario and analyze the output to determine how this scenario alters chlorophyll-a.

- a. How does the chlorophyll-a concentration in the two lakes respond to your land use scenario?
- b. What are the implications of your land use scenario for future water quality and phytoplankton blooms?

- 13) Now, you will use your modified inflow and meteorological files to create a scenario that simultaneously includes climate change (temperature) AND land use (phosphorus). You will have four total scenarios (baseline, land use change only, climate change only, and land use + climate change) for each lake model (Objective 5, see figure above).
- Develop hypotheses about how the combination of climate and land use change may affect chlorophyll-a in your model lakes: do you expect the combined scenario to have a greater effect on chlorophyll-a in your model lakes than climate or land use alone? Why or why not?
- 14) Run the combined climate + land use change scenario for both lakes. Think about how land use and climate change interacted to affect phytoplankton blooms in each lake.
- How do the newest plots that show the combined land use and climate change together compare to the figures you made from climate change or land use change scenarios alone?
- 15) After you have analyzed the model output, organize the figures you created with your partner and the other team to present the output from your four model simulations per lake to the rest of the class (Objective 6). Make sure your brief presentation answers the following questions:
- Does the model output support or contradict your original hypotheses of how climate, land use, and their combined effects will interact to affect the two lakes' chlorophyll-a concentrations?
 - Is the chlorophyll-a in your lake model more sensitive to climate change, land use change, or both? How does this compare with the other lake? (if comparing your heatmaps, be sure to check for differences in the color scales of chlorophyll-a concentration among plots!)
 - Do your lakes show evidence of cross-scale interactions (hint: look at your line plot of all four scenarios)? Why or why not? If yes, are these cross-scale interactions linear or non-linear?
 - The cross-scale interactions of climate and land use in driving phytoplankton blooms can make predicting bloom timing and severity difficult. How would your understanding of phytoplankton blooms be different if you had looked at just climate or land use changes in isolation?