Macrosystems EDDIE:
Cross-Scale Interactions

Carey, C.C. and K.J. Farrell. 13 August 2017.

Macrosystems EDDIE: Cross-Scale Interactions.

Macrosystems EDDIE Module 2, Version 2.

http://module2.macrosystemseddie.org

Macrosystems EDDIE

Environmental Data-Driven Inquiry & Exploration in Macrosystems Ecology

NSF

SERC the Science Education Resource Center at Carleton College

GLEON global lake ecological observatory network

Plan for today:

- Short overview on changing water quality in lakes globally, and how we can use a macrosystems ecology and lake modeling approach to study this problem!

- **Activity A:** Run and explore a lake water quality model in R.

- **Activity B:** Select a climate scenario, generate hypotheses, and model how different lakes respond.

- **Activity C:** Model the effects of climate and land use change scenarios on different lakes, and make predictions about drivers of phytoplankton blooms at large spatial scales.

Nara Souza, Florida Fish and Wildlife Commission

Phytoplankton blooms increasing globally

- Blooms occur when phytoplankton populations rapidly increase
  - Result in turbid water, surface scums

- Pose a major water quality threat to drinking water
  - Many bloom-forming species produce toxins harmful to humans and other animals

- Bacteria decomposing dead phytoplankton consume large quantities of oxygen
  - "Dead zones" of low oxygen & fish kills

NASA Visible Earth

NOAA

What are the drivers of these blooms?

- Land use change
  - Changing forest into agricultural fields or urban areas increases the amount of phosphorus (P) flowing into lakes
  - Phosphorus stimulates phytoplankton growth

- Warming climate
  - Many phytoplankton species thrive in warmer waters
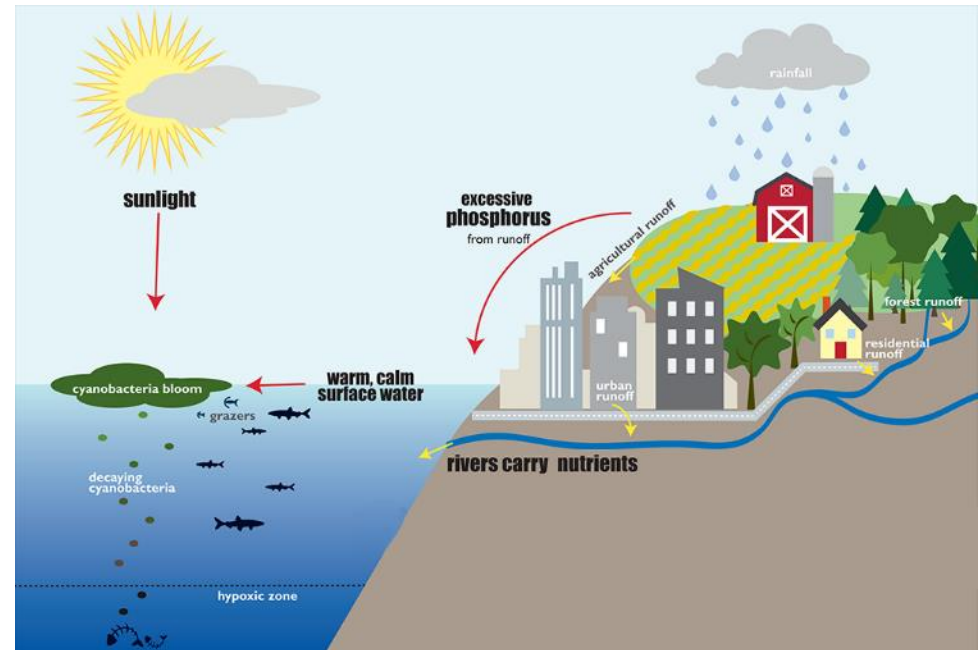
Image modified from: Lake Champlain Basin Program (sol.lcbp.org)

Using a macrosystems ecology approach to study phytoplankton blooms

- Drivers of blooms occur at both local and regional scales
  - Local = e.g., land use
  - Regional = e.g., climate change

- Macrosystems ecologists study ecological dynamics and feedbacks at multiple interacting spatial and temporal scales

- We can study local and regional drivers using high frequency sensor data + simulation models
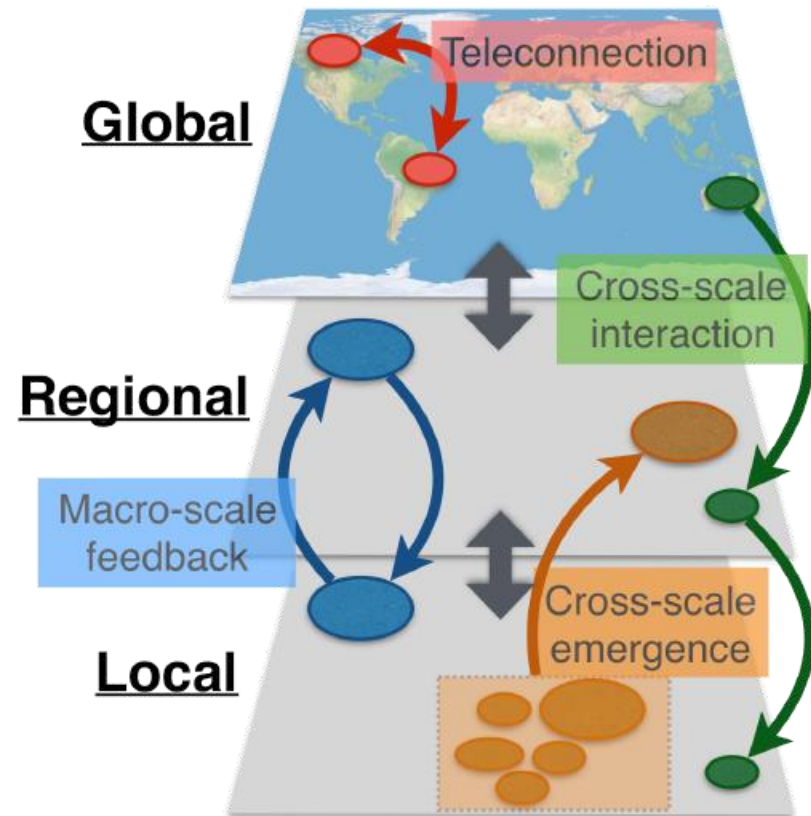
Figure modified from: Heffernan et al. 2014

Cross-scale interactions:
What are non-linear responses?

- Cross-scale interaction: processes at one scale interact with processes at another scale, which can sometimes create *non-linear responses*

- Non-linear responses occur when the change of an output is not proportional to the change of the input
  - Responses may appear unpredictable or counterintuitive
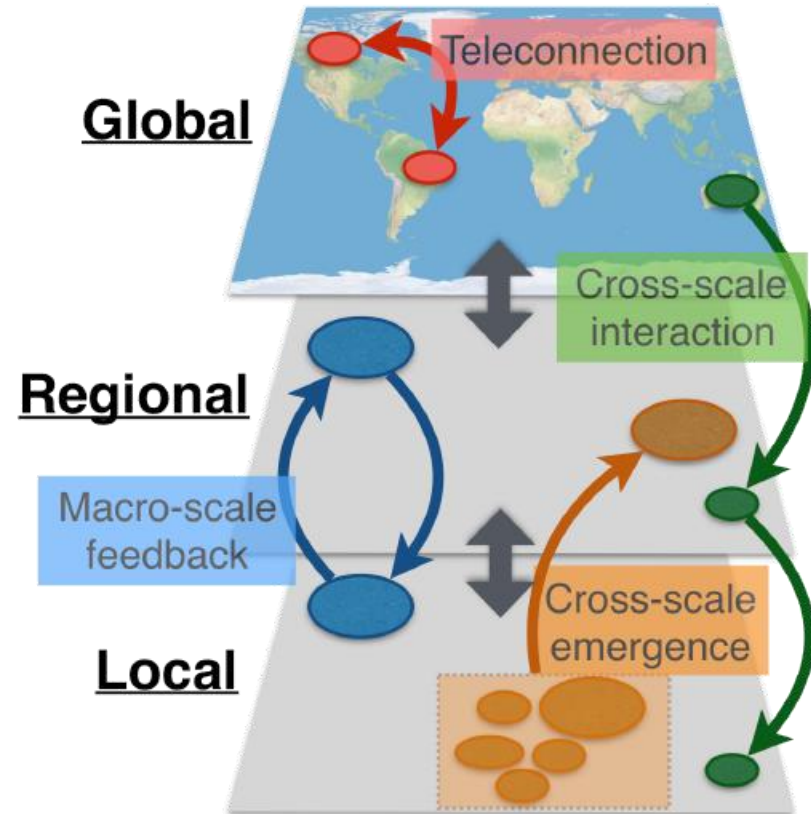
Figure modified from: Heffernan et al. 2014

Cross-scale interactions: Example

- A non-ecological cross-scale interaction could occur when trying to predict a farmer's income for a particular year.
  - *Local* weather affects how well crops will grow
  - *Global* demand for crops affect market prices

- These two factors operate on very different scales, and *interact* to affect a farmer's income

- It would be very difficult to predict the interactive effects of local & global factors on farmer income by looking at them in isolation
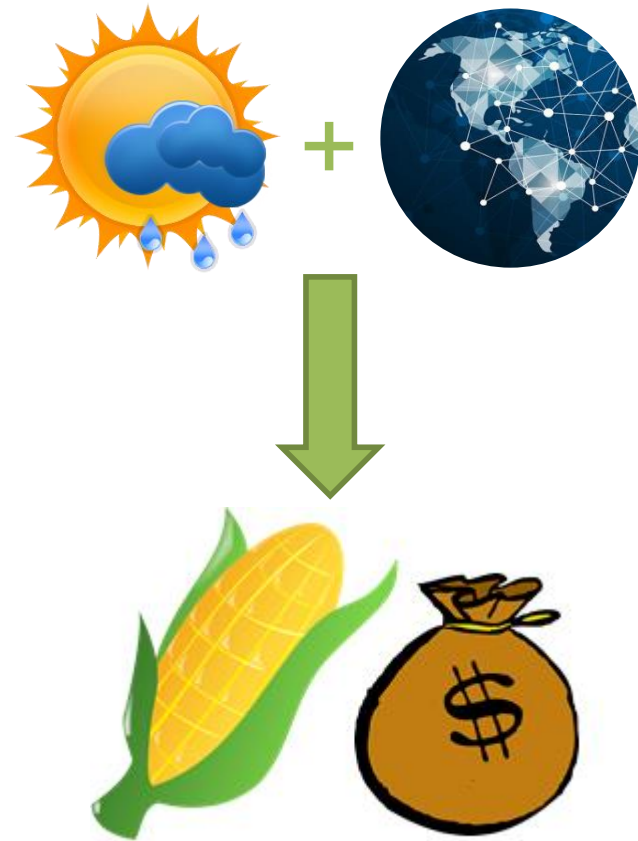
Cross-scale interactions in lakes

- Phytoplankton blooms exhibit cross-scale responses to regional warming climate and locally-increasing lake nutrients due to land use change
    - Bloom severity and timing can be difficult to predict due to cross-scale responses to climate + land use

- Moreover, cross-scale interactions prevent us from predicting whether an algal bloom will occur in a particular lake by looking at climate change or land use change alone

C.C. Carey

C.C. Carey

Our focal question:

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

Models to understand multiple drivers

- How can we test the effects of drivers from different spatial scales on lake phytoplankton blooms?
  - Impossible to experimentally manipulate all possible climate and land use drivers in a real lake!
- Simulation modeling allows us to explore what would happen if we changed one driver, or multiple drivers at once:
  - For example, how would phytoplankton bloom severity change if air temperatures were 2°C warmer than they are now? 4°C? 6°C?
  - What if phosphorus inputs to the lake increased or decreased?

GLM: <u>G</u>eneral <u>L</u>ake <u>M</u>odel

- **Authors:** Matt Hipsey, Louise Bruce, and David Hamilton

- The **General Lake Model** (GLM) is an open-access model for simulating lake dynamics. It simulates vertical stratification and mixing and accounts for the effect of inflows/outflows, surface heating and cooling.

- GLM has been designed to be an open-source community model developed in collaboration with members of the **Global Lake Ecological Observatory Network (GLEON)** to integrate with lake sensor data.

- Available from: http://aed.see.uwa.edu.au/research/models/GLM/
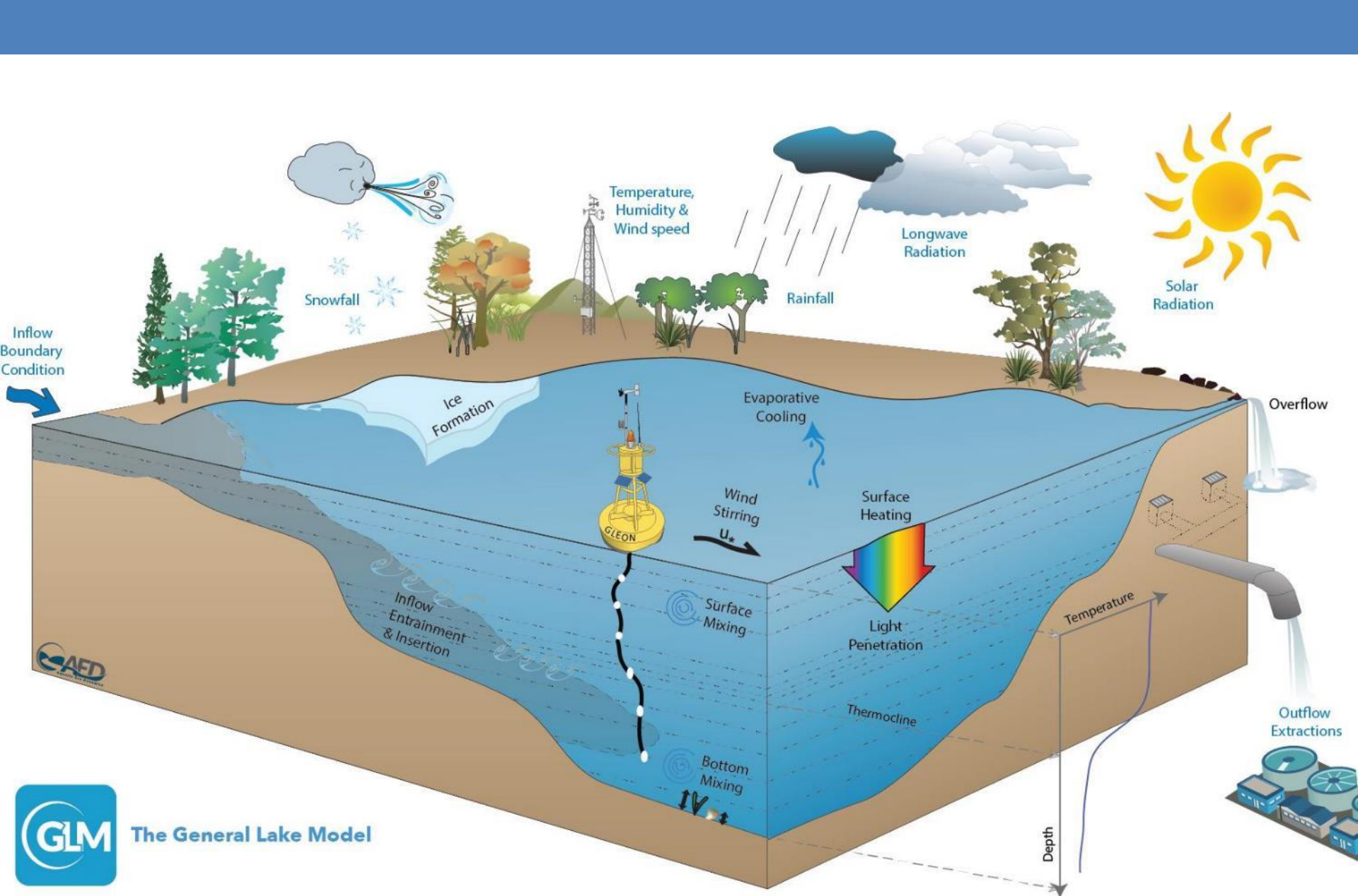
Figure: Hipsey et al. 2014

AED: <u>A</u>quatic <u>Eco</u><u>D</u>ynamics

- The Aquatic EcoDynamics (AED) module couples with GLM to model changes in water chemistry and biology

- Can model nutrient, phytoplankton, and zooplankton dynamics

- Today, we'll focus on phytoplankton (as chlorophyll-a)

Isotope-enabled carbon & nutrient ecosystem model
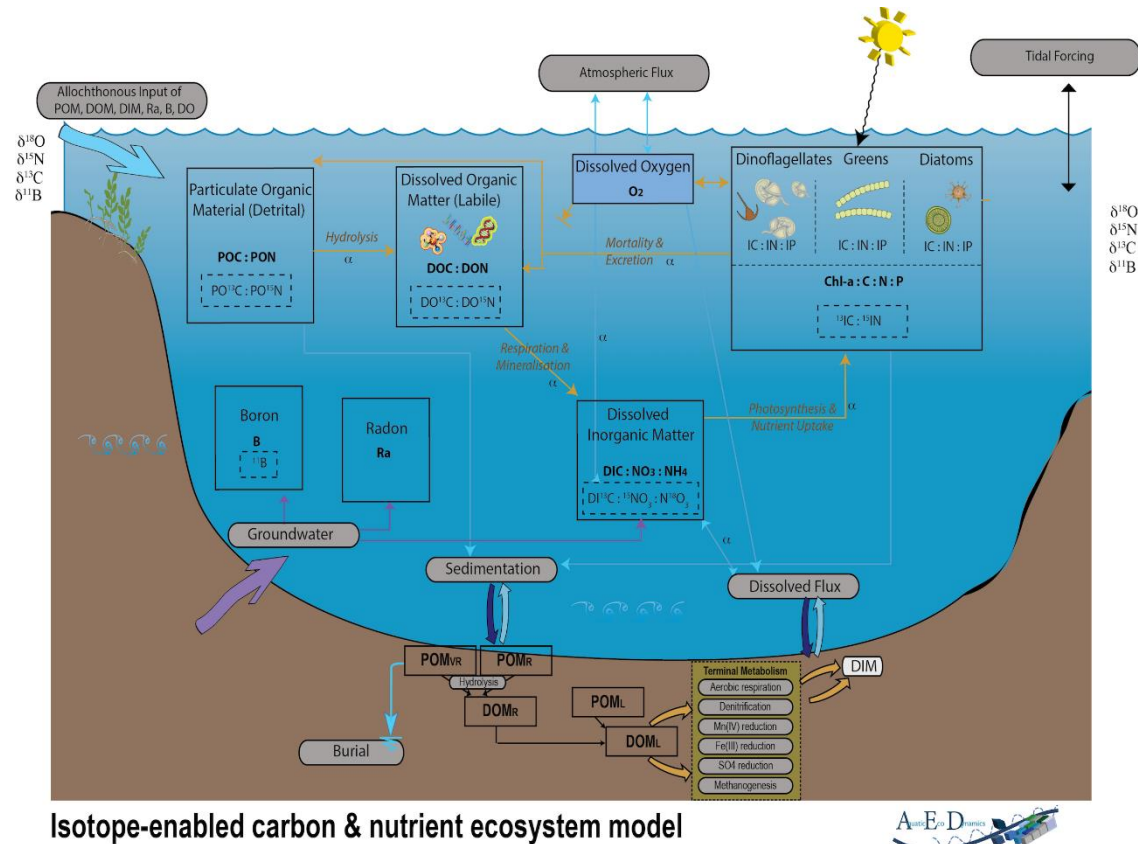
Figure: Hipsey et al. 2013

Basic structure of the model

- You'll create a new folder (directory) on your computer when you unzip the module folder.

- Within this folder, you will have:

  1) A meteorological CSV ('met') file that forces the model (e.g., met_hourly.csv)

  2) 'nml' text files that act as 'master' scripts for the model (e.g., glm2.nml, aed2.nml)

  3) Inflow/outflow CSV files that specify the temperature, flow rate, and concentrations of phosphorus of connected streams entering and leaving the lake

Images: Wikimedia commons
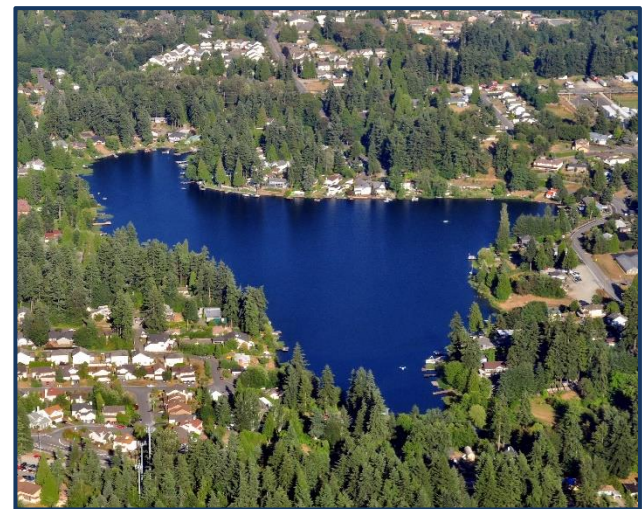
Example met file

Climate scenarios: +2°C, +4°C, or +6°C

	A	B	C	D	E	F	G	H
1	time	ShortWave	LongWave	AirTemp	RelHum	WindSpeed	Rain	Snow
2	2011-09-01 00:00:00	34.33	386.25	30.84	50.04	1.90	0	0
3	2011-09-01 01:00:00	0.00	386.25	28.84	55.67	1.31	0	0
4	2011-09-01 02:00:00	0.00	386.24	26.84	62.03	1.21	0	0
5	2011-09-01 03:00:00	0.00	366.02	24.84	69.22	1.70	0	0
6	2011-09-01 04:00:00	0.00	366.02	24.09	71.30	1.33	0	0
7	2011-09-01 05:00:00	0.00	366.02	23.35	73.40	1.26	0	0
8	2011-09-01 06:00:00	0.00	358.33	22.61	75.56	1.54	0	0
9	2011-09-01 07:00:00	0.00	358.33	21.82	78.48	1.91	0.001	0
10	2011-09-01 08:00:00	0.00	358.33	21.03	81.52	2.47	0	0
11	2011-09-01 09:00:00	0.00	359.96	20.24	84.69	3.13	0	0
12	2011-09-01 10:00:00	0.00	359.96	20.17	86.02	3.02	0	0
13	2011-09-01 11:00:00	0.00	359.96	20.10	87.36	2.93	0	0
14	2011-09-01 12:00:00	84.08	391.87	20.04	88.66	2.89	0	0
15	2011-09-01 13:00:00	229.97	391.87	23.59	75.43	3.37	0	0

Example .nml file

```
 90   !--------------------------------------------------------------
 91   ! lake details
 92   !--------------------------------------------------------------
 93   !
 94   ! name               [string]
 95   !                      name of the lake
 96   ! latitude           [float, minimum = -90, maximum = 90, unit = deg North]
 97   !                      latitude
 98   ! longitude          [float, minimum = -360, maximum = 360, unit = deg East]
 99   !                      longitude
100   ! base_elev          [float]
101   !                      base elevation (m)
102   ! crest_elev         [float]
103   !                      crest elevation (m)
104   ! bsn_len            [float]
105   !                      basin length at crest (m)
106   ! bsn_wid            [float]
107   !                      basin width at crest (m)
108   ! bsn_vals           [integer]
109   !                      number of depth points on height-area relationship
110   ! H                  [float]
111   !                      elevations (m)   (comma separated list, len=bsn_vals)
112   ! A                  [float]
113   !                      area (m2) (comma separated list, len=bsn_vals)
114   !
115   !--------------------------------------------------------------
116   &morphometry
117      lake_name  = 'Mendota'
118      latitude   = 43
119      longitude  = -89.41
120      bsn_len    = 9500
121      bsn_wid    = 7400
122      bsn_vals   = 15
123      !   H(m)   A(m2 * 1000) V(m3 * 1000)
124      H = 375.00640,376.79166,378.57691,380.36217,382.14743,383.93269, 385.71794,387.50320,389.28846,39
125      A = 0.00000,2827226.39,5654452.79,8481679.18,11308905.58,14136131.97, 16963358.37,19790584.76,226
```

Example inflow file

	A	B	C	D	Nitrogen			Phosphorus
1	time	FLOW	SALT	TEMP	OGM_don	NIT_nit	NIT_amm	PHS_frp
2	2011-09-01 00:00:00	1.50	0	18.8	94.91	949.14	13.33	3.27
3	2011-09-02 00:00:00	2.38	0	17.2	92.60	926.02	14.08	3.34
4	2011-09-03 00:00:00	2.92	0	18.1	65.64	656.42	30.54	4.89
5	2011-09-04 00:00:00	3.08	0	23.3	69.57	695.69	26.78	4.54
6	2011-09-05 00:00:00	2.11	0	23.1	73.16	731.57	23.91	4.25
7	2011-09-06 00:00:00	2.23	0	17.5	77.46	774.56	21.01	3.95
8	2011-09-07 00:00:00	2.03	0	14.7	83.20	832.04	17.88	3.61
9	2011-09-08 00:00:00	1.98	0	13.0	89.70	897.03	15.09	3.29
10	2011-09-09 00:00:00	1.96	0	17.4	96.40	964.01	12.83	3.01
11	2011-09-10 00:00:00	1.98	0	16.8	103.69	1036.87	10.88	2.74
12	2011-09-11 00:00:00	1.92	0	15.5	112.13	1121.33	9.12	2.49
13	2011-09-12 00:00:00	0.90	0	16.4	122.77	1227.68	7.44	2.23
14	2011-09-13 00:00:00	2.78	0	20.3	133.83	1338.32	6.12	2.00
15	2011-09-14 00:00:00	2.02	0	20.1	145.60	1456.03	5.06	1.80

PHS_frp = the type of phosphorus that phytoplankton take up.
High concentrations can promote blooms

We will run GLM-AED using R

- R is a statistical environment that can run on different computer operating systems (PC, Mac, Linux)

- R is reproducible, free(!), and easy to download

- R can run stats, make figures, and do a suite of different analyses in many disciplines

- Many packages for R to merge with other tools (including GLM!)

- We'll walk you through each step of the script, so don't worry if you're new to R!
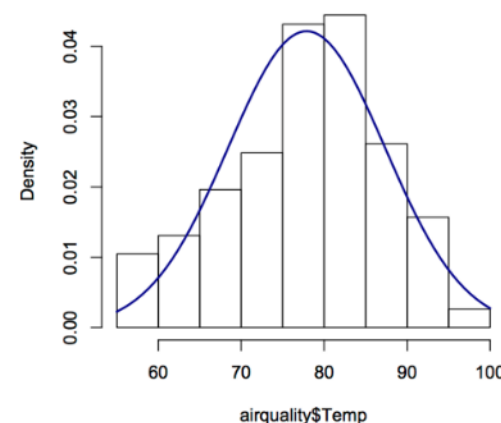
Lakes we're going to model today

Lake Sunapee
(New Hampshire, USA)

- Oligotrophic
  - Low nitrogen
  - Low phosphorus
- Main land uses:
  - 81% Forest
  - 8% Urban
  - 4% Agriculture

GLEON.org

Lake Mendota
(Wisconsin, USA)

- Eutrophic
  - High nitrogen
  - High phosphorus
- Main land uses:
  - 55% Agriculture
  - 20% Urban
  - 1% Forest

engr.wisc.edu
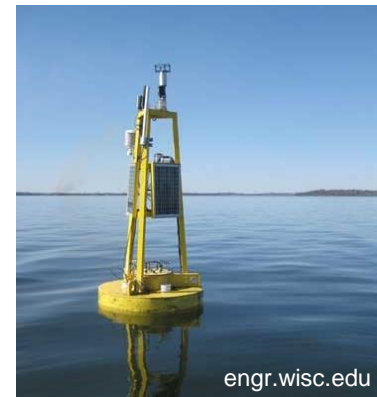
Learning objectives

- 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.

Workflow of module

- We'll be using pre-made climate and land use scenarios based on real predictions for these lakes
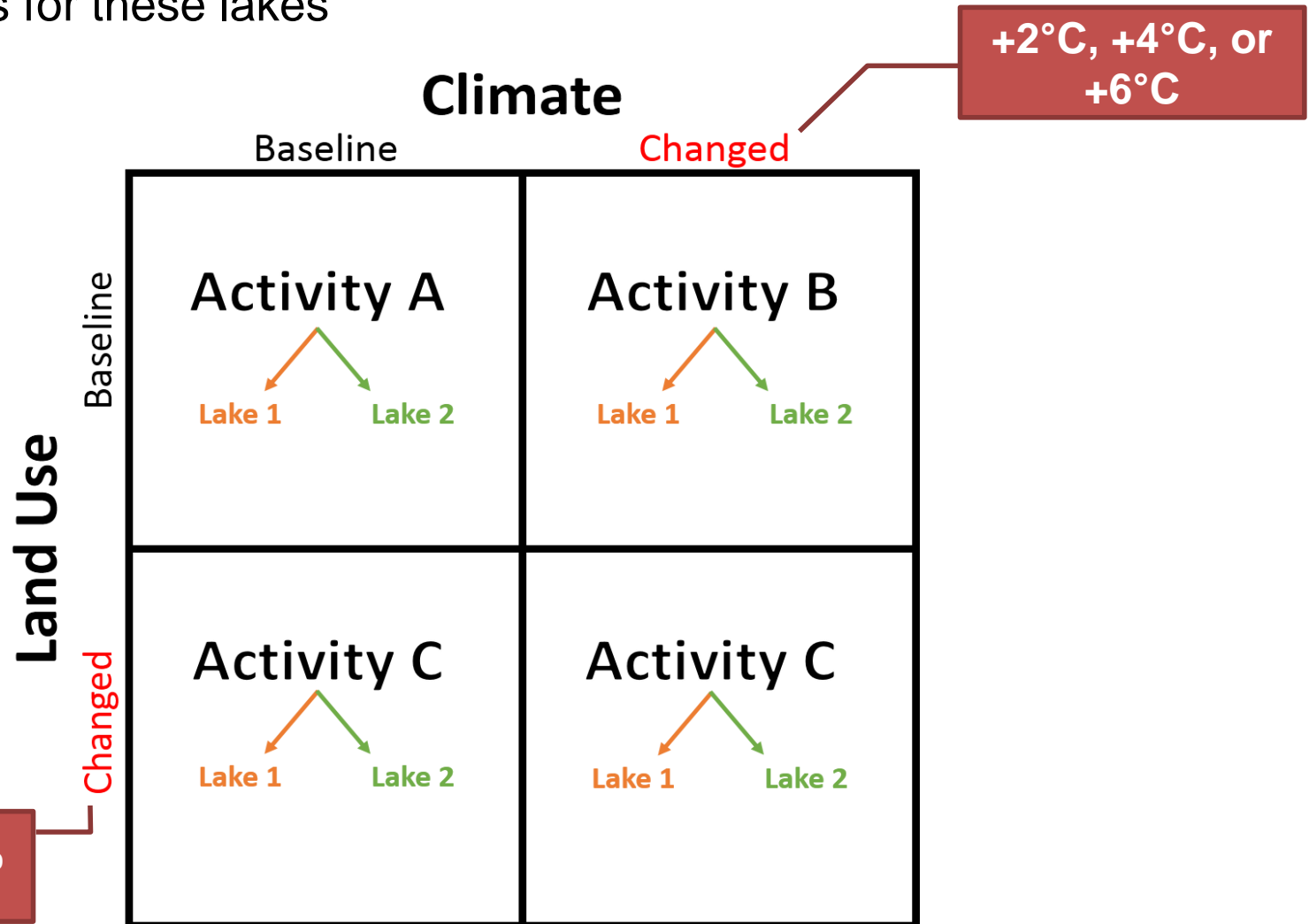
Discussion questions embedded in your handout

- Everyone will need to turn in the completed handout with question answers written out at the end of the module today.
- We encourage you to work with your partner to complete the questions!
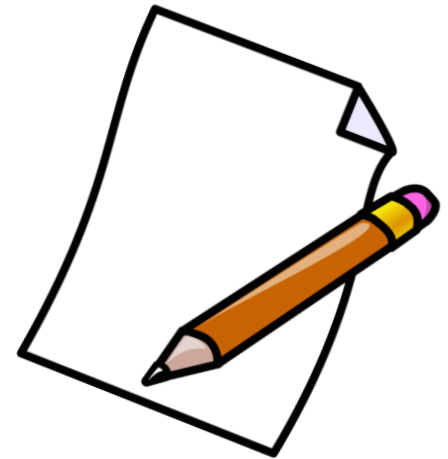
Image: newsfrom4j.wikispaces.com

A few important notes about R

- Lines of code that start with **#** are not read by R
  - These lines include important notes about how and why the R script is running, so be sure you're reading them!

- Lines with **##!!** indicate lines of code where you need to modify something for it to run

- In the glm2.nml file, **!** indicates lines that are not read by the GLM model (tricky!)
  - When you need to modify your glm2.nml file in Activity B, make sure you're not changing the value in a line that starts with a **!** or your changes won't be read by GLM

Activity A: Run a lake model!

With a partner (work in pairs):

1) Find the two lakes on a satellite map, and examine land use in their watershed

2) Coordinate with another pair of students so that each pair is modeling a different lake

3) Download the zipped folder of R scripts and other files to run this module. Extract to your desktop

4) Download GLM-AED files and R packages onto your computer

5) Run the model and look at the output for temperature and chlorophyll-a for your lake (make sure you save your plots as you go!)
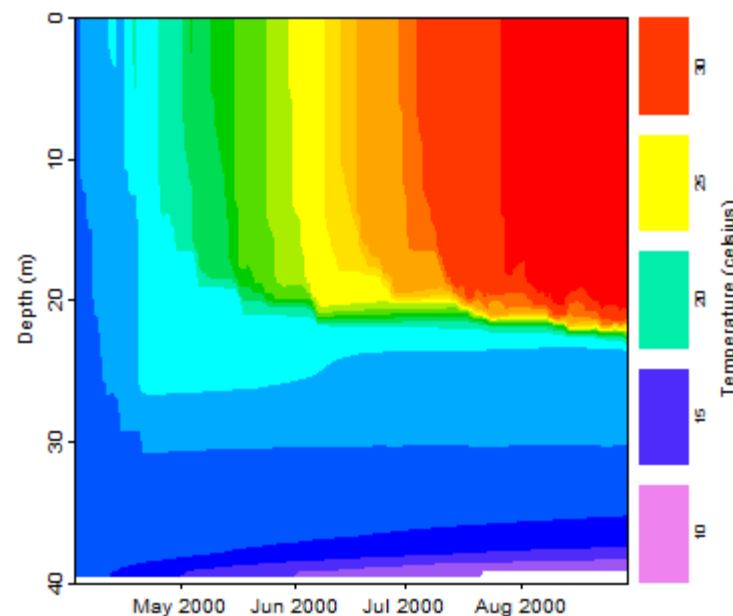
Activity B: Climate change scenario

1) Working with the other pair of students, **select one** of the pre-made climate change scenarios for air temperature. **Develop hypotheses** about how changing air temperatures may affect water temperatures and chlorophyll-a in your model lakes

2) Modify your glm2.nml file to test your hypothesis
   - Run both model lakes with the same scenario
   - Analyze the model output to determine how the scenario changed water temperature and chlorophyll-a

3) **Create a few figures** (save them as you go!) to examine your climate scenario:
   - Does the model output support or contradict your hypothesis?
   - How does the output from the two lakes compare?
   - Which lake's phytoplankton are more sensitive to the climate scenario? How can you tell?

Activity C: Climate and land use change

1) Working with the other pair of students, **select one** land use scenario for phosphorus inputs. Make hypotheses about how land use change will affect phytoplankton blooms. Modify the glm2.nml file, then run the model.

2) Now modify your glm2.nml file to change temperature and phosphorus simultaneously. Run the additional scenario for both lakes. You will now have 4 scenarios (no change, climate change only, land use only, and land use + climate change) for each lake.

3) **Create a few figures** (save them as you go!) to highlight your 4 scenarios & share with the class!

   - Does the model output support or contradict your hypotheses?
   - How does the output from the two lakes compare?
   - Are the phytoplankton in your lake more sensitive to climate change, land use change, or both? How does this compare among different lakes?
   - Do your lakes show evidence of cross-scale interactions? Why or why not?

4) Predict how lake phytoplankton blooms may respond to changing climate globally, given different land uses.

Evidence for Cross-Scale Interactions?

- Phytoplankton blooms are driven by processes occurring at different scales:
  - Increasing lake nutrients (local)
  - Warming climate (regional)

- In your lake, did you observe cross-scale interactions in phytoplankton bloom timing and/or intensity?
  - Climate had an effect
  - Land use had an effect

NOAA

Do we see individual effects of climate and/or land use?

Mendota · Sunapee

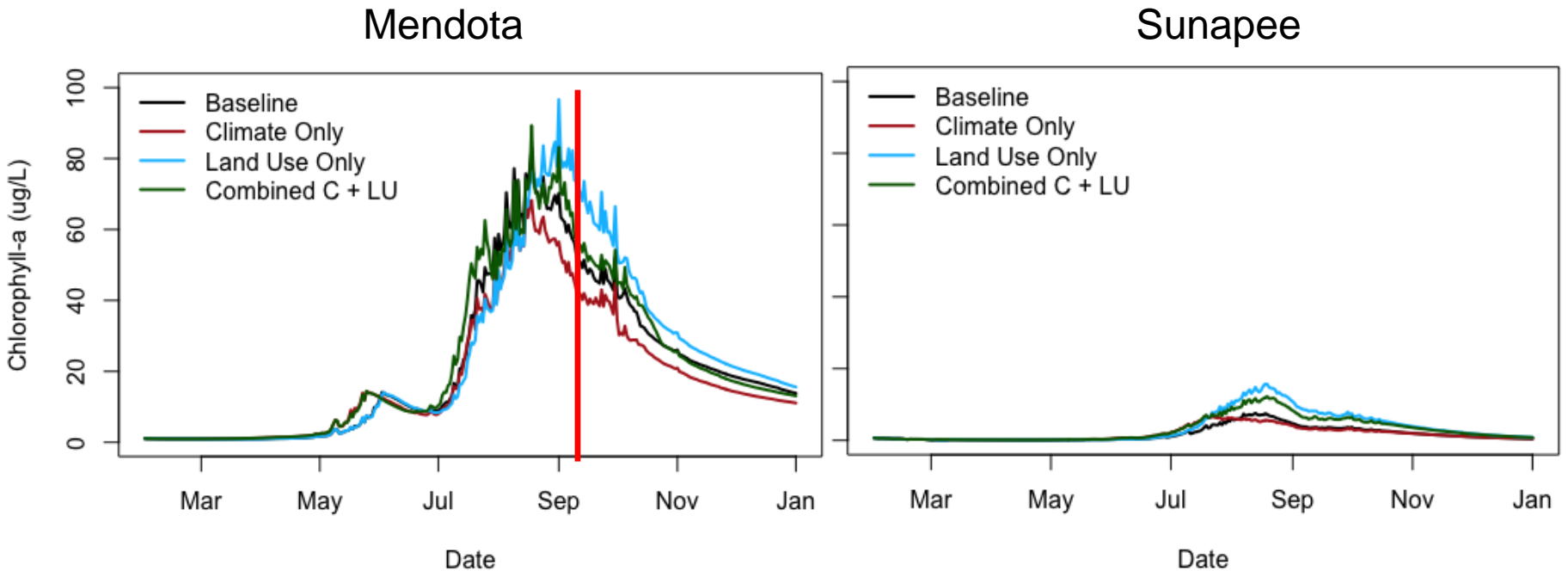| Scenario	Chlorophyll-a (ug/L)	Difference from baseline
Baseline	50	--
Climate only	41	- 9
Land use only	70	+ 20

Evidence for Cross-Scale Interactions?

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  - Climate had an effect ✔
  - Land use had an effect ✔
  - Climate + land use had interacting effects

NOAA

Do we see interacting effects of climate + land use?

Mendota

Sunapee

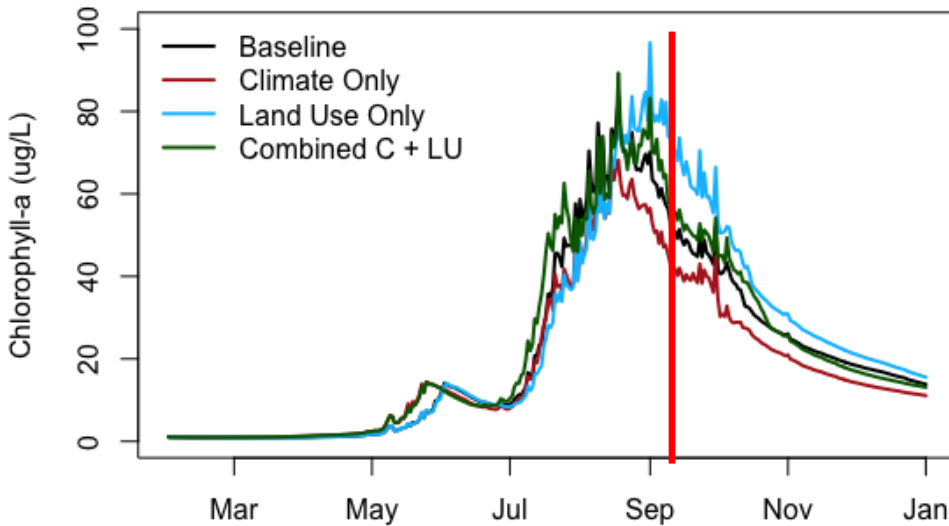| Scenario	Chlorophyll-a (ug/L)	Difference from baseline
Baseline	50	--
Climate only	41	- 9
Land use only	70	+ 20
Climate + Land use	55	+ 5

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  - Climate had an effect ✔
  - Land use had an effect ✔
  - Climate + land use had interacting effects ✔
    - Were these effects linear or non-linear?

NOAA

Are interacting effects of climate + land use linear or non-linear?

Mendota

Sunapee

Scenario	Chlorophyll-a (ug/L)	Difference from baseline	
Baseline	50	--	
Climate only	41	- 9	**+ 11**
Land use only	70	+ 20	
Climate + Land use	55	**+ 5**	

Evidence for Cross-Scale Interactions?

- Phytoplankton blooms are driven by processes occurring at different scales:
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  - Warming climate (regional)

NOAA

- In your lake, did you observe cross-scale interactions in phytoplankton bloom timing and/or intensity?
  - Climate had an effect ✔
  - Land use had an effect ✔
  - Climate + land use had interacting effects ✔
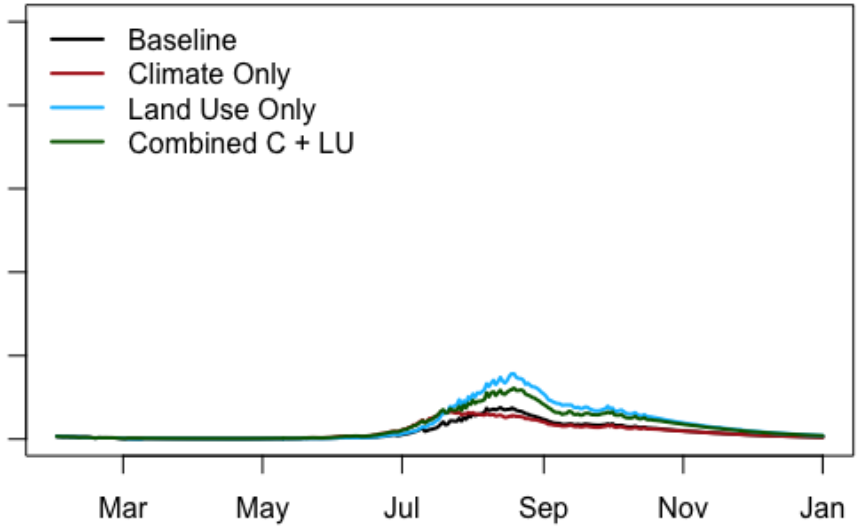   - Were these effects linear or **non-linear**?

- How would your understanding of phytoplankton blooms be different if you had looked at just climate *or* land use changes in isolation?
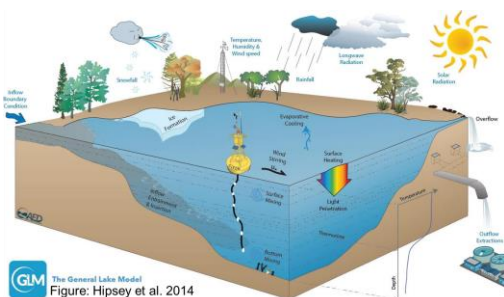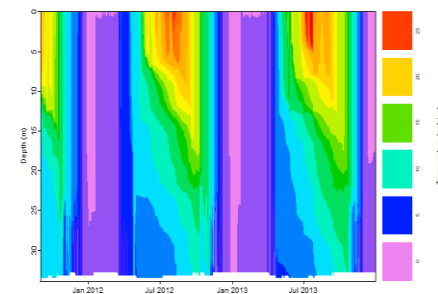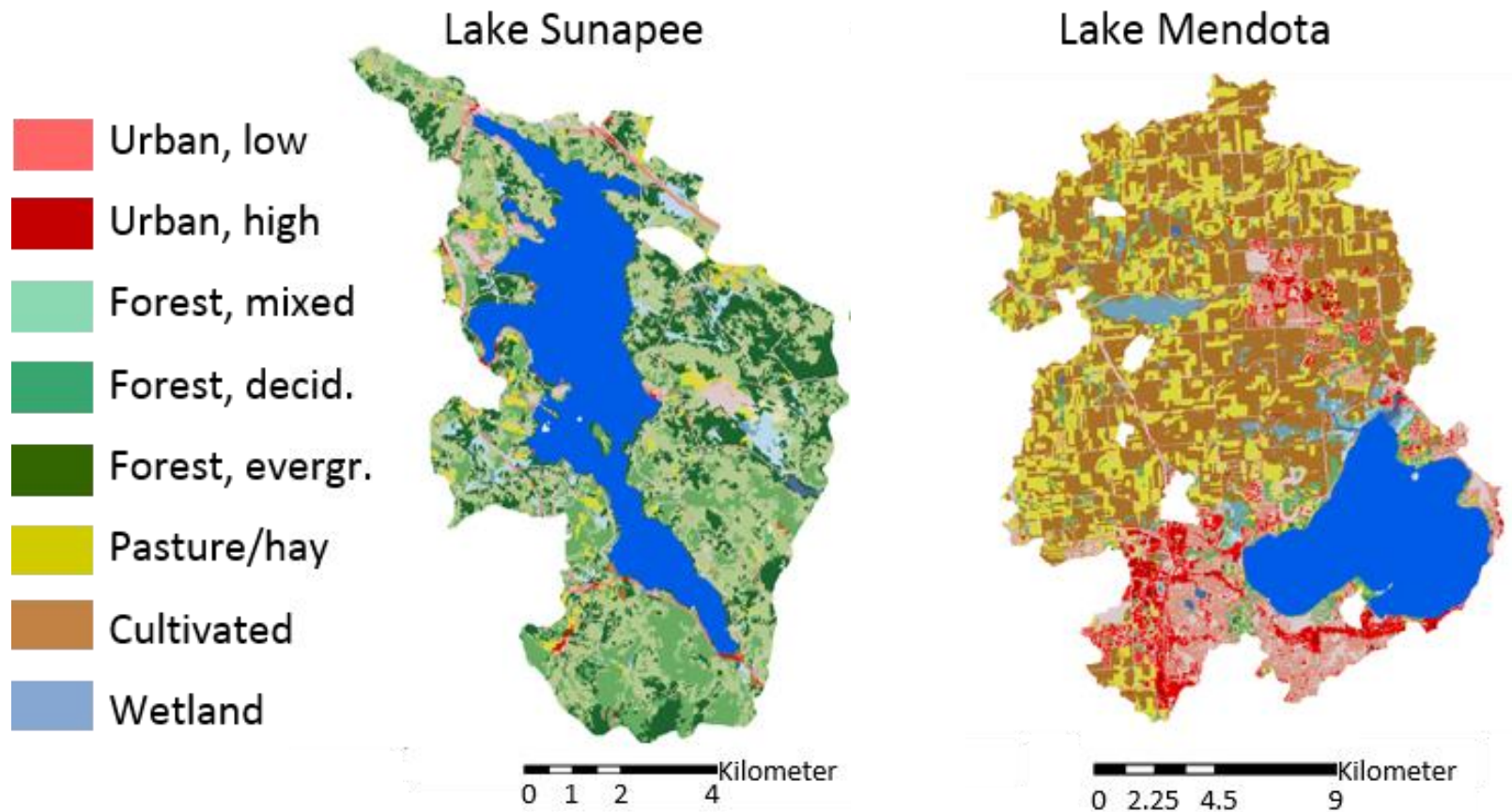
Thank you for participating!

The General Lake Model
Figure: Hipsey et al. 2014

Wikimedia commons

Optional additional slides

- Depending on your class and the time available, you may want to include some of the following slides for discussion of the module concepts
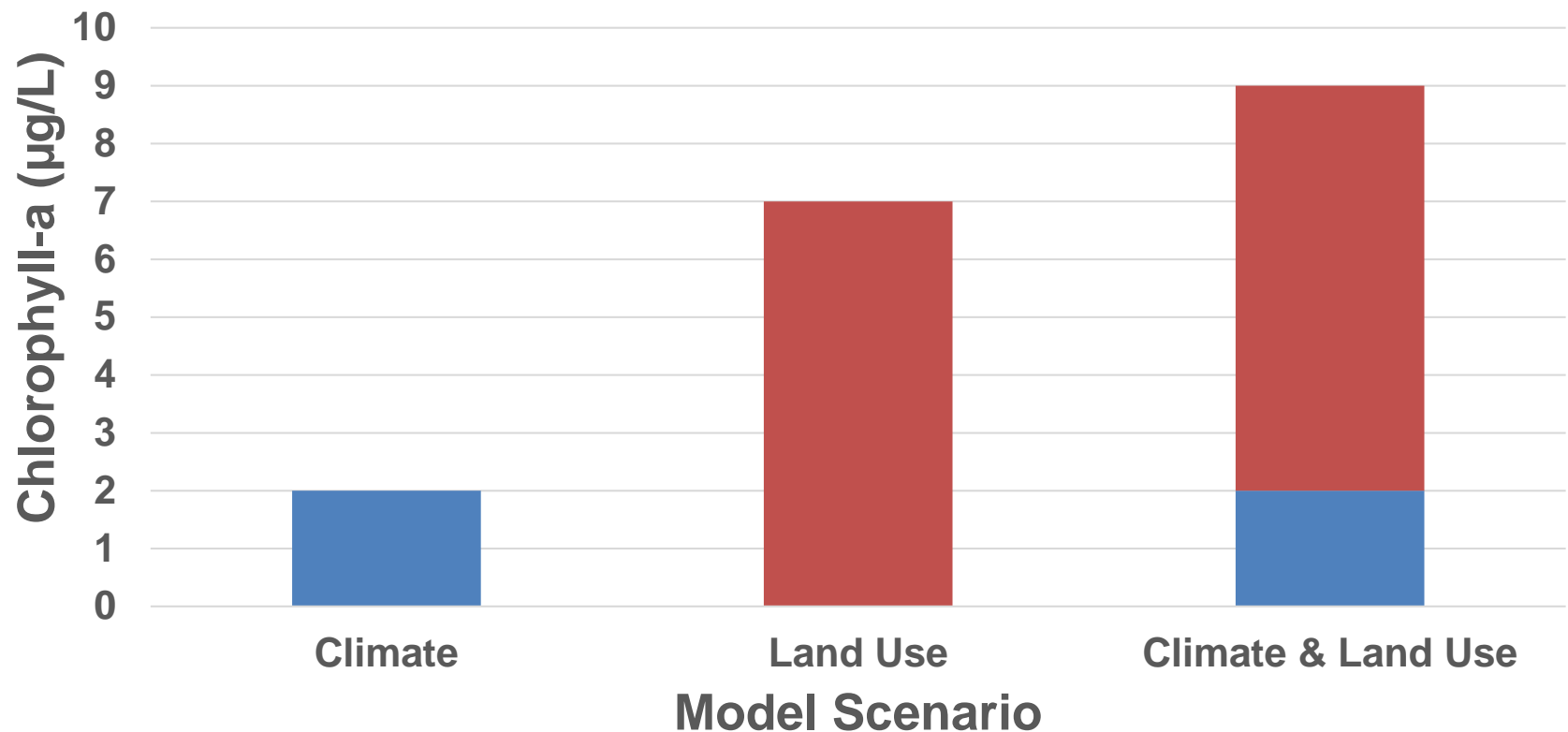
Lakes we're going to model today

Maps: **LA**ke multi-scaled **G**e**OS**patial and temporal database (lagoslakes.org)
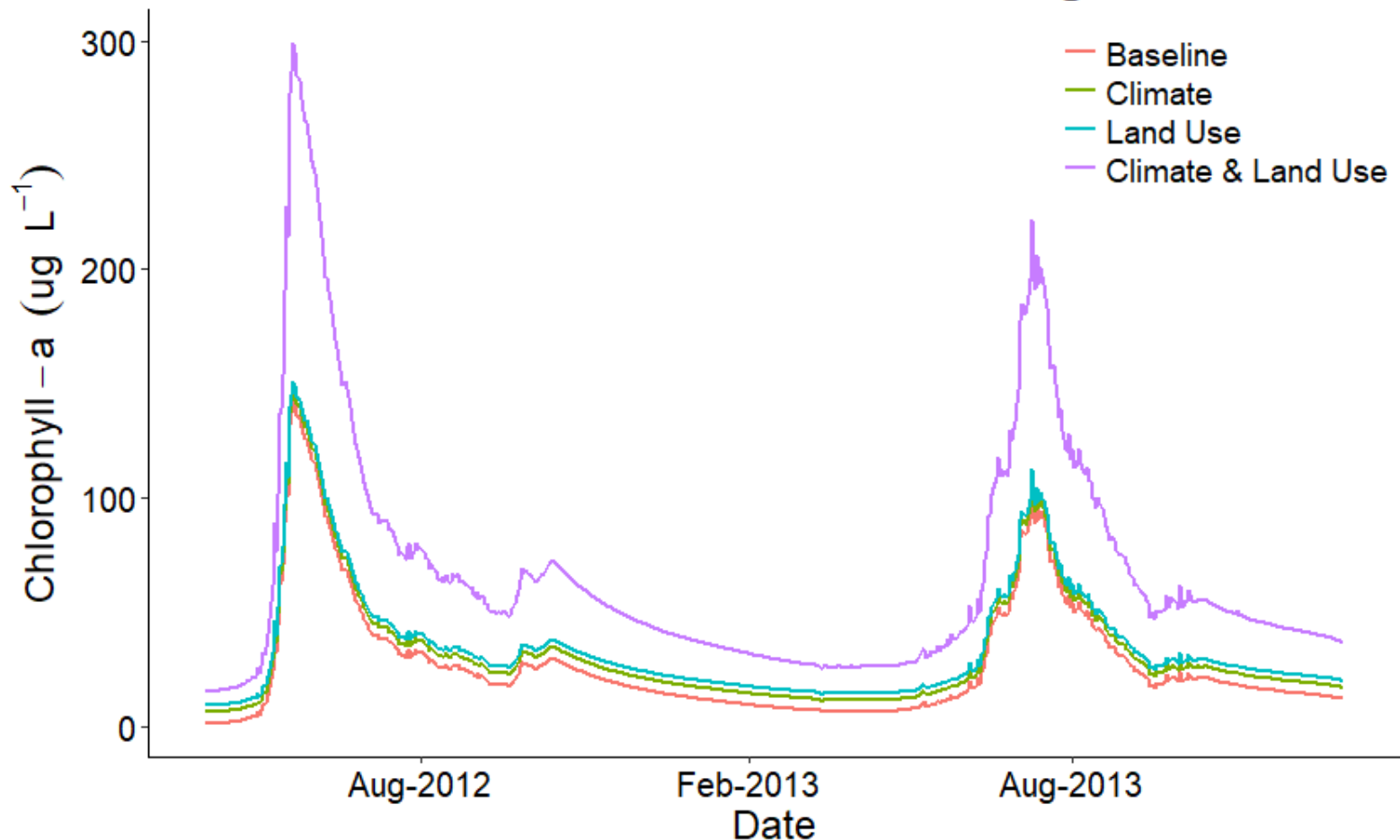
What are the possible cross-scale interactions between climate and land use?

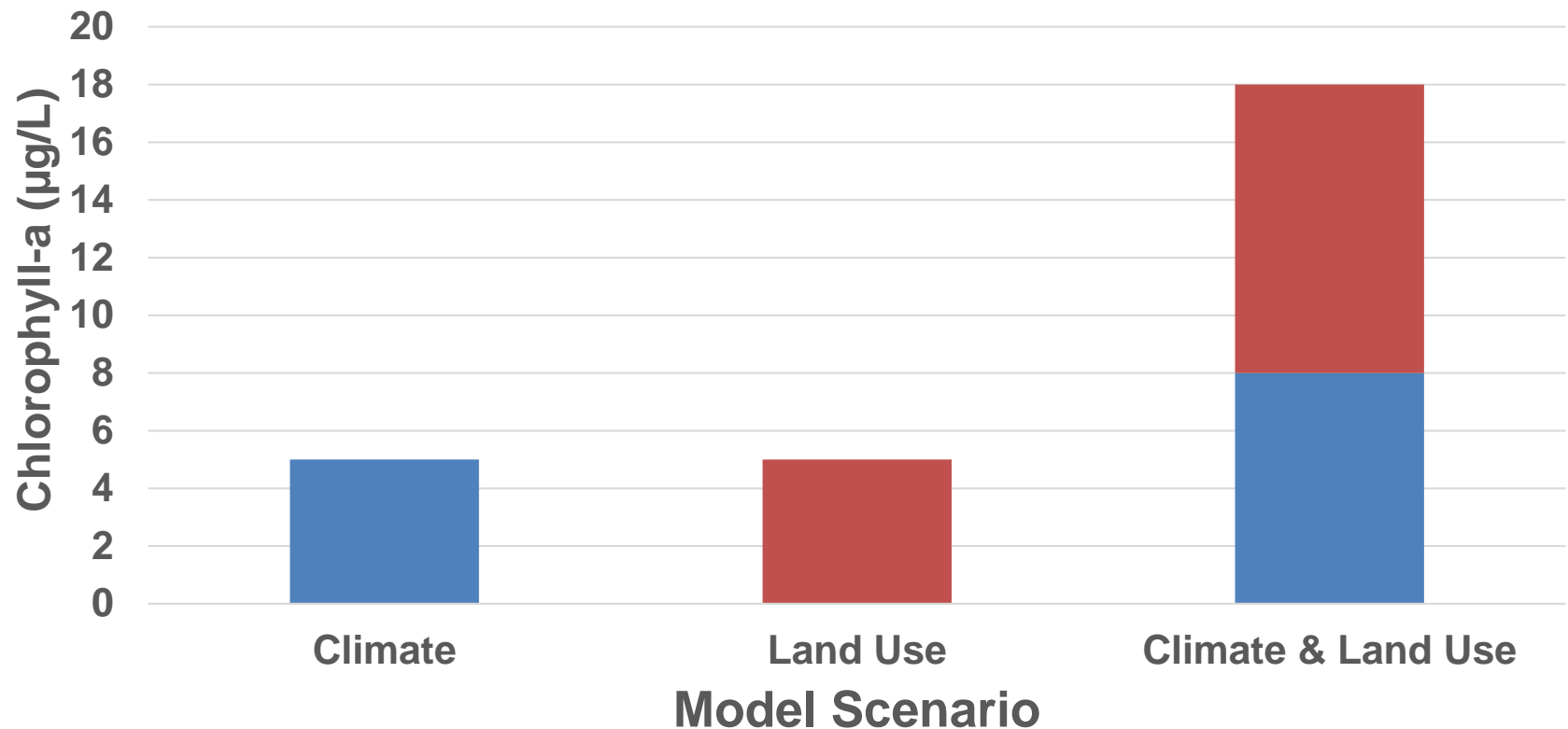*Additive* effects of climate and land use change (a linear CSI)

What are the possible cross-scale interactions between climate and land use?

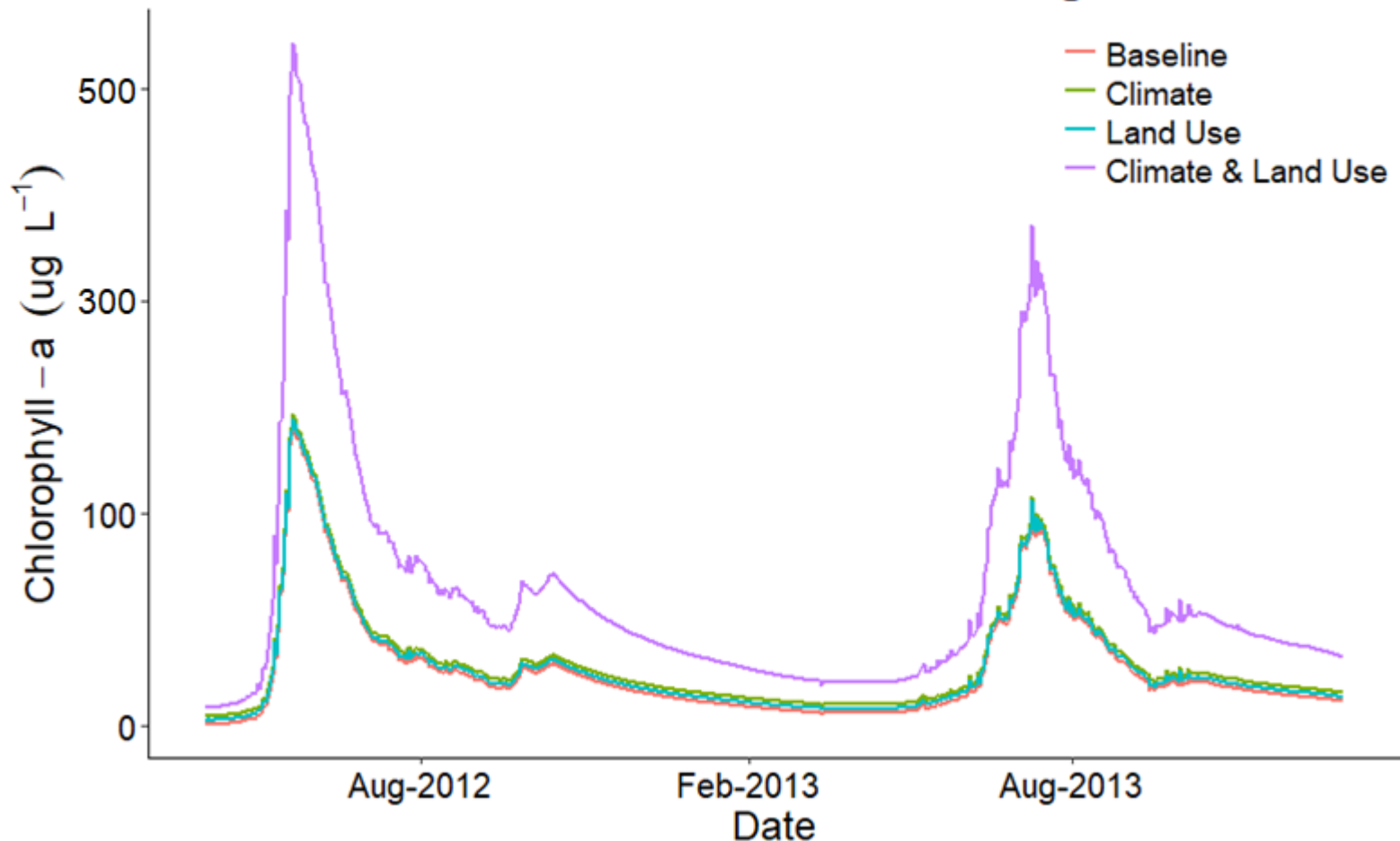Additive effects of climate and land use change

What are the possible cross-scale interactions between climate and land use?

Synergistic effects of climate and land use change (a non-linear CSI)

What are the possible cross-scale interactions between climate and land use?

What are the possible cross-scale interactions between climate and land use?

Antagonistic effects of climate and land use change (a non-linear CSI)

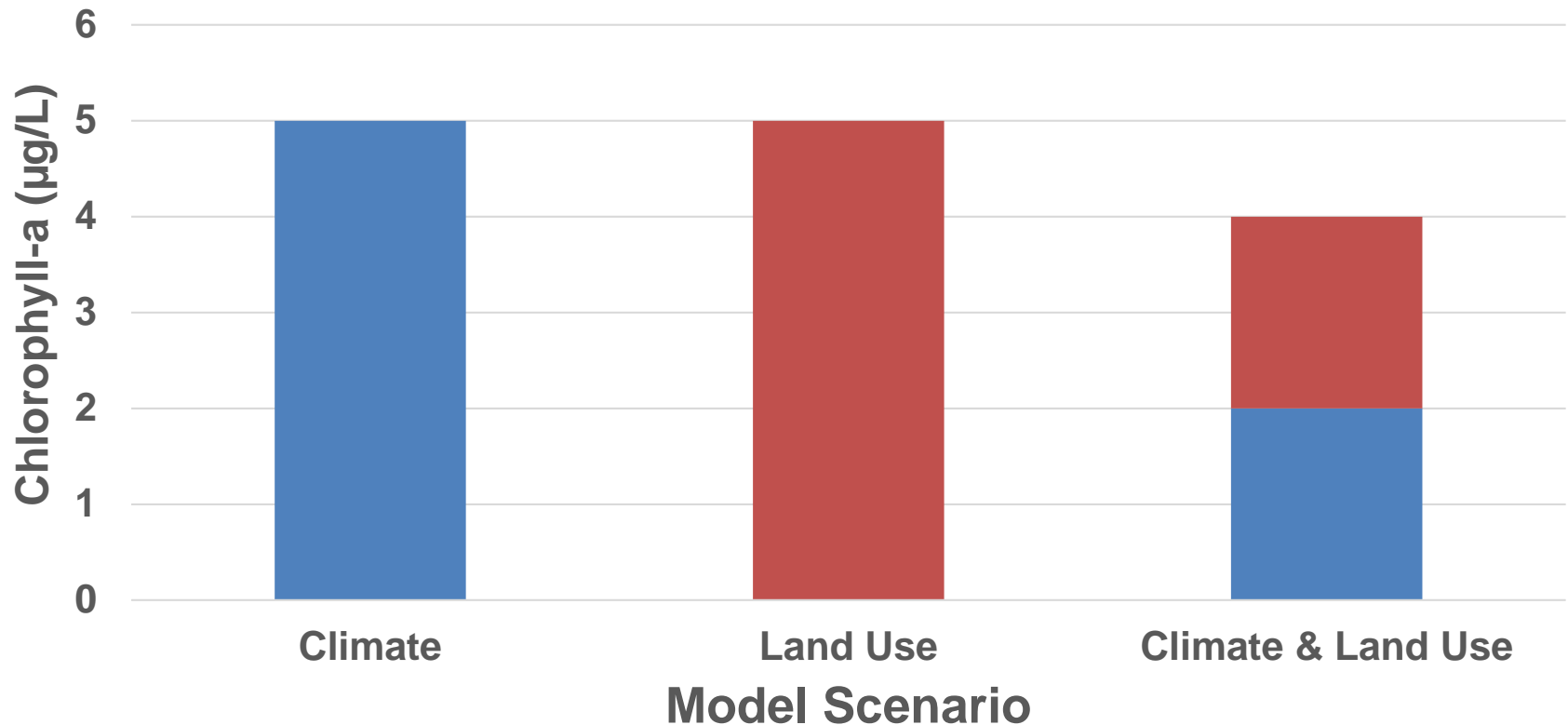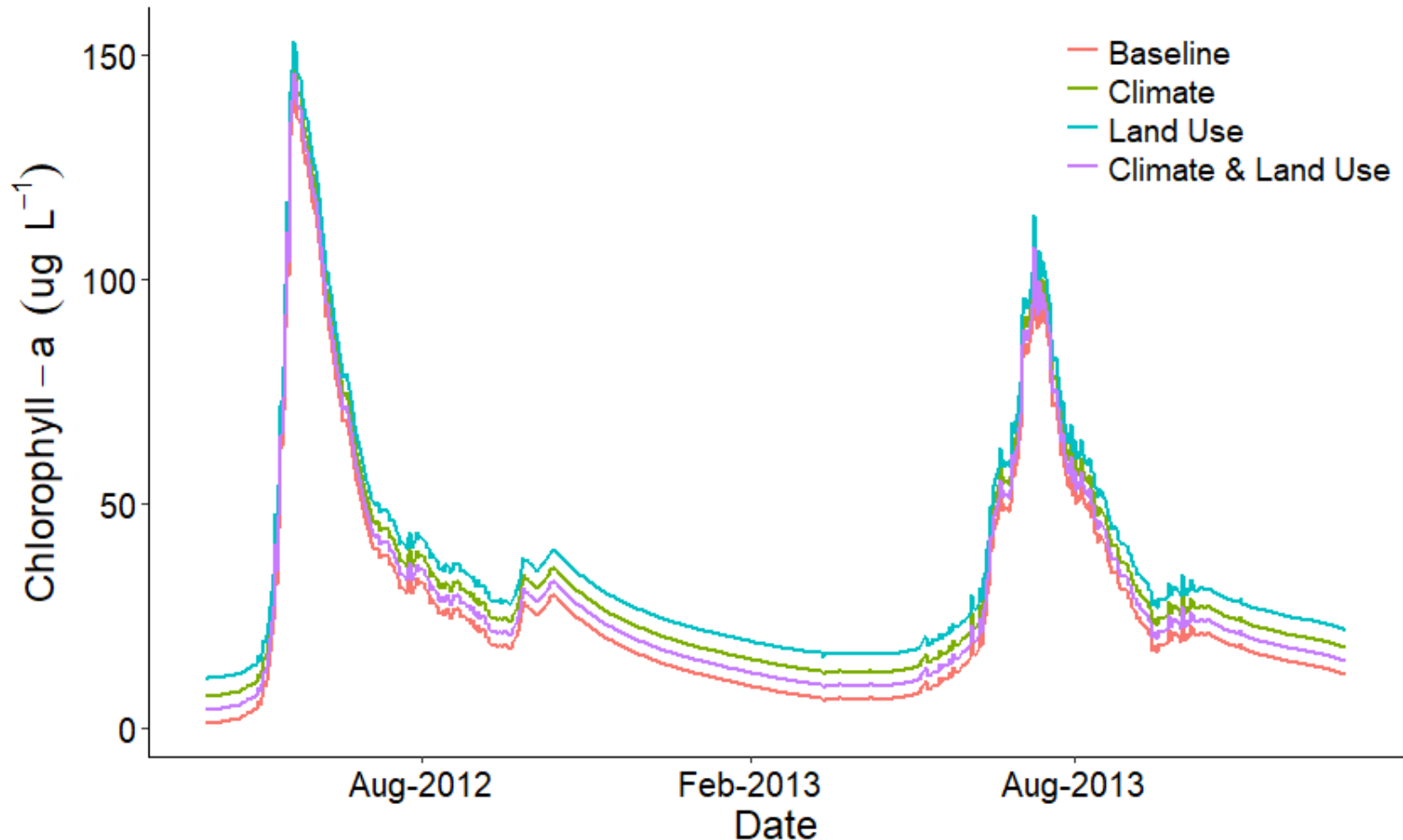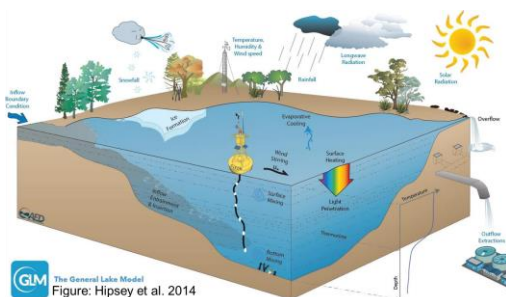# What are the possible cross-scale interactions between climate and land use?

Antagonistic effects of climate and land use change

What are the possible mechanisms underlying these patterns?

- ***Additive*** effects could happen when a lake is much more sensitive to one driver than another (linear CSI)
  - e.g., an already-warm lake with low nutrients is likely more sensitive to land use than climate change

- ***Synergistic*** effects could happen when a lake is equally sensitive to both factors, so increasing P and temperature simultaneously could trigger non-linear increases in blooms

- ***Antagonistic*** effects could happen when a lake is not sensitive to either factor, so the two factors cancel each other out non-linearly
  - e.g., adding more nutrients and increased temperatures to an already-warm lake with high nutrients may inhibit phytoplankton growth if optimal thermal and nutrient conditions are exceeded

Thank you for participating!

The General Lake Model
Figure: Hipsey et al. 2014

Wikimedia commons