A multiscale analysis of the factors controlling nutrient dynamics and cyanobacteria blooms in Lake Champlain

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Andrew W. Schroth and Jason D. Stockwell, Advisors

Donna M. Rizzo, Chair

Breck Bowden, Committee member

Acknowledgements

Special thanks to Trevor Gearhart, Courtney Giles, Yaoyang Xu, and DongJoo Joung, who were instrumental in the success of this project, and to the many interns who have helped over the past 4 years. Thanks also to Steve Cluett, Saul Blocher, Mary Watzin, the entire RACC team, and the entire Rube lab team.

This work was funded by Vermont EPSCoR with funds from the National Science Foundation Grant EPS-1101317.

Key Questions:

1) *To what extent do **external nutrient inputs** or **internal nutrient processing** control nutrient concentrations and cyanobacteria blooms in Lake Champlain?*
2) *How do internal and external nutrient inputs interact with **meteorological drivers** to drive bloom development?*
3) *How is anthropogenic **climate change** likely to impact these drivers and the **risk of cyanobacteria blooms in the future**?*

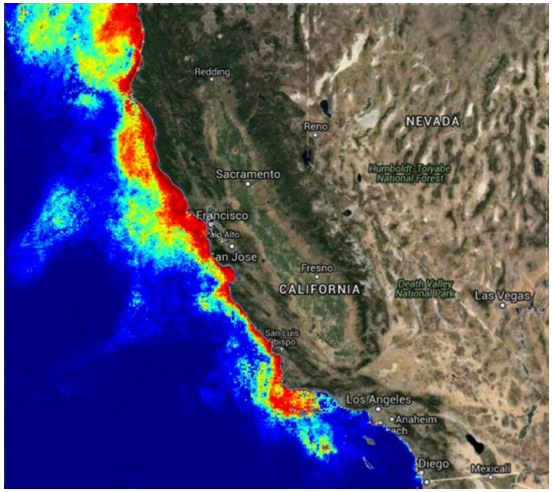
Background: Algae Blooms Worldwide

Lake Erie

Baltic Sea

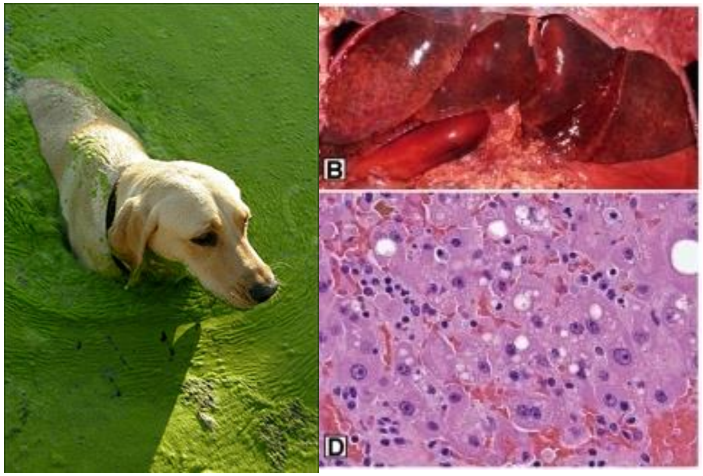
Lake Champlain

Taihu Lake, China



California Coast

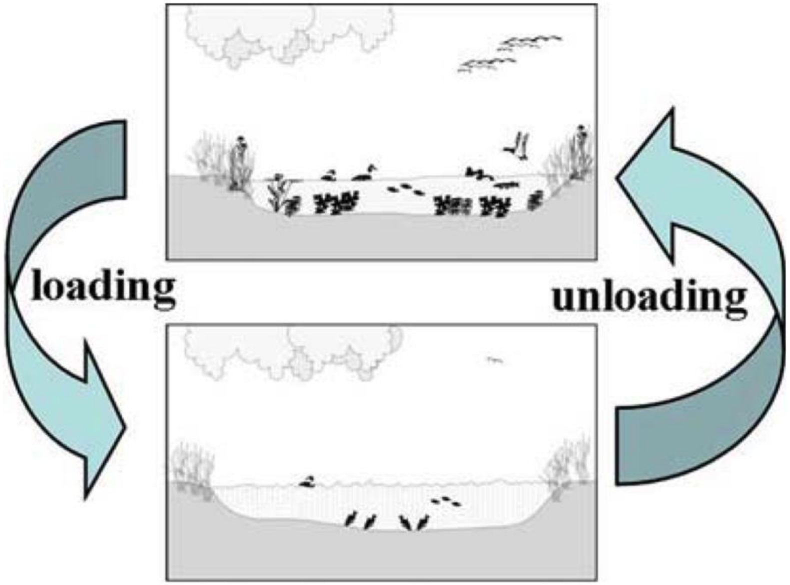
Background: Harmful Effects



Liver toxins, neurotoxins, irritants

Fish Kill, Missisquoi Bay 2012

Economic costs on recreational activities, tourism



Alternate Stable States

Background: Nutrients and Phytoplankton

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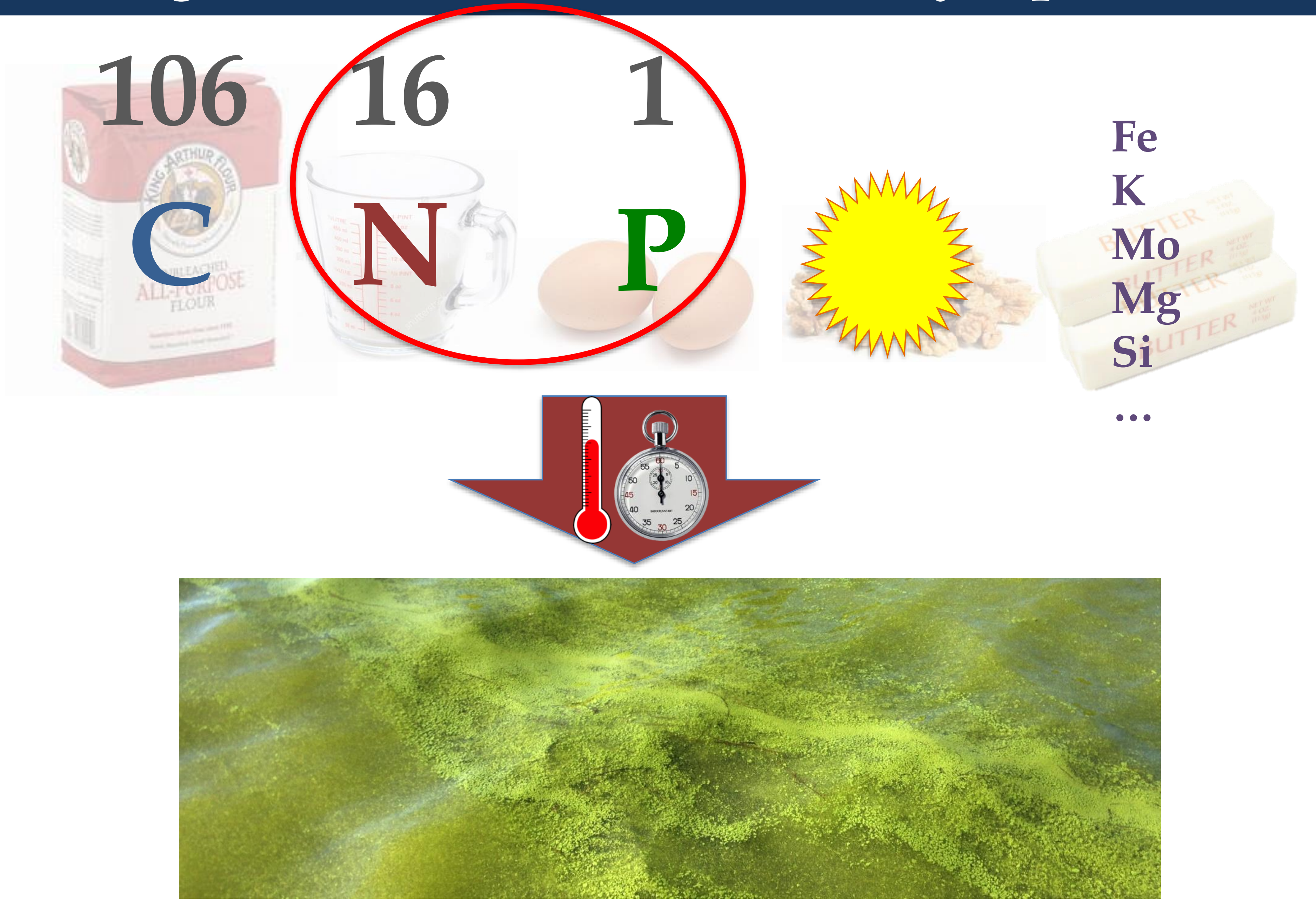
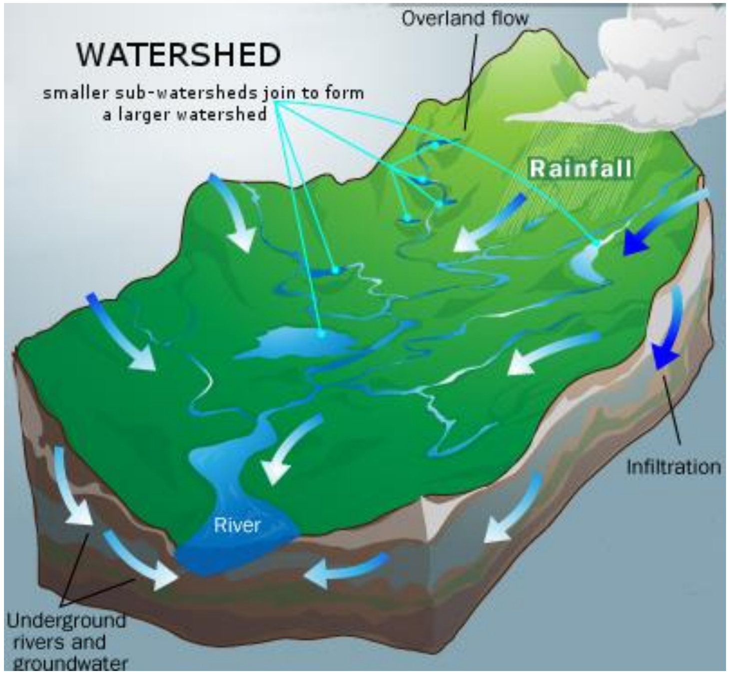
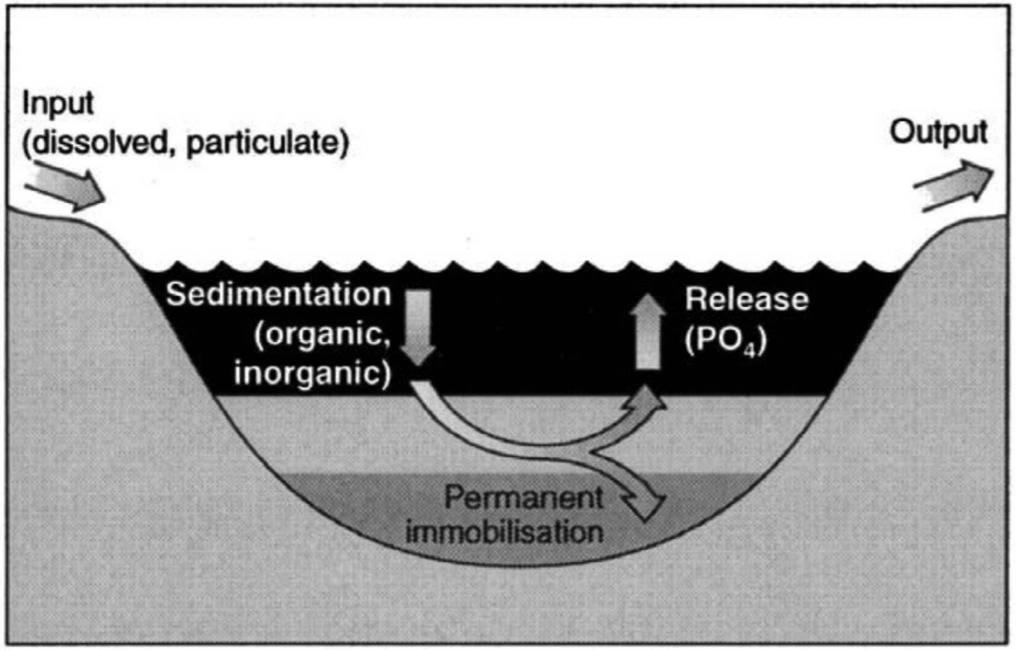


Background: Internal v. External Processes

External Loading



Internal Processes



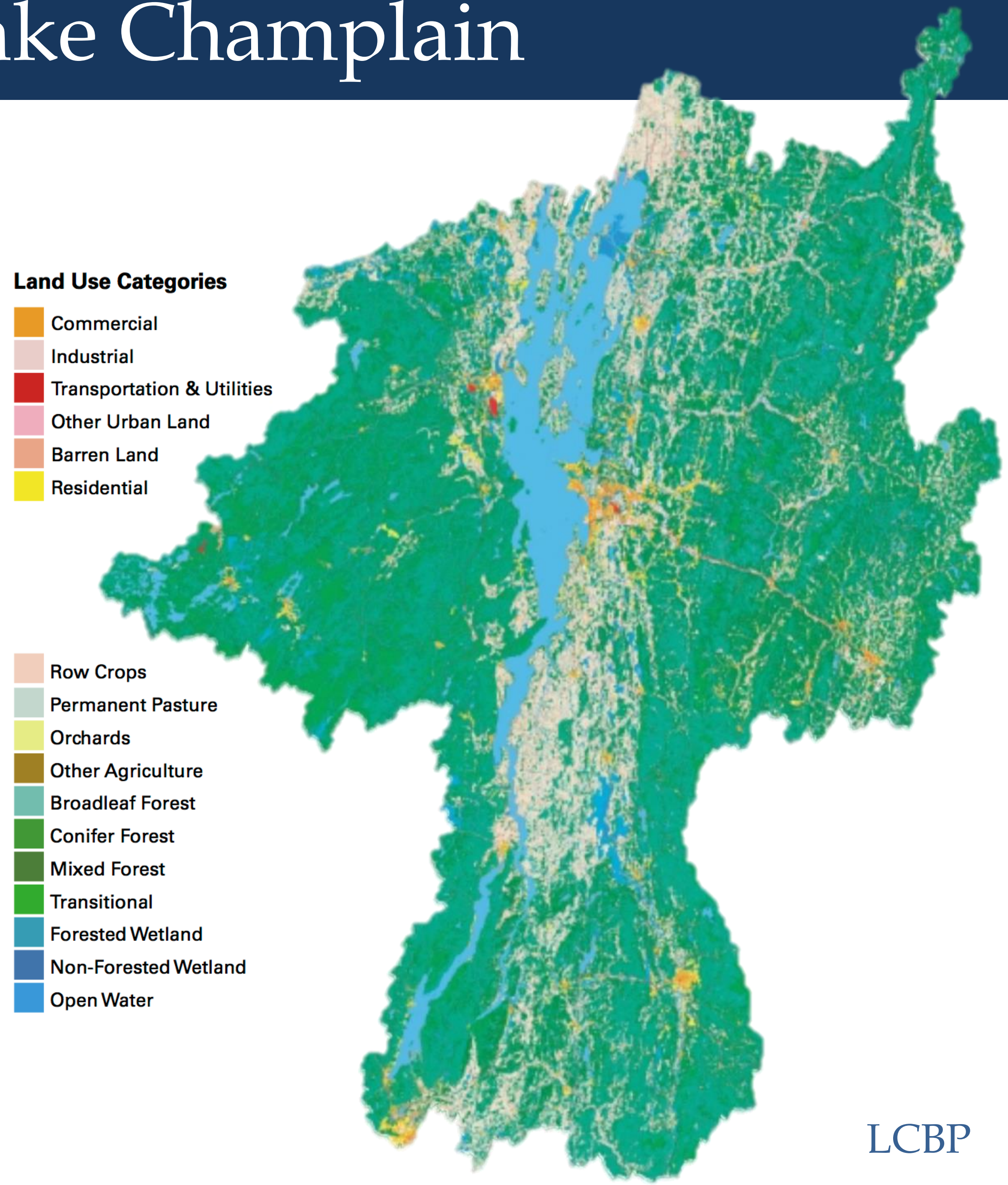
Søndergaard et al. 2003

Background: Multiple Timescales

- Hourly-Daily (diel oxygen fluctuations, water movements, phytoplankton growth)
- Seasonal (meteorological patterns, community succession)
- Inter-annual (strong v. weak bloom year)
- Decadal (responses to climate change, land-use)
- Episodic (storm events, wind mixing)

Background: Lake Champlain

- 120 miles long (193 km)
- 12 miles wide (19 km)
- Max depth 400 ft (122 m)
- Large ratio of watershed:lake area.
- Increasing TP lakewide
- Increasing frequency of HABs



Outline

1. Introduction
2. Anatomy of a strong bloom
3. Buoyancy and light limitation during blooms
4. Drivers of inter-annual variability
5. Long-term trends in N:P throughout the lake
6. Modeling the likely impact of climate change on Missisquoi Bay

Chapter 2: Dynamic internal drivers of a historically severe bloom revealed through comprehensive monitoring

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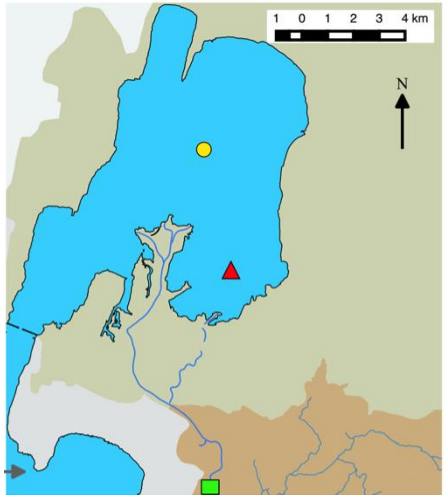
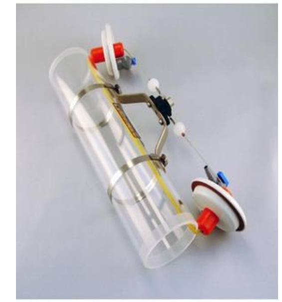
Dynamic internal drivers of a historically severe cyanobacteria bloom in Lake Champlain revealed through comprehensive monitoring

Peter D.F. Isles [a,b,*], Courtney D. Giles [b], Trevor A. Gearhart [b,c], Yaoyang Xu [b], Greg K. Druschel [b,d], Andrew W. Schroth [b,e]

Chapter 2: Data Collection



Met Station



Weekly grab samples at 5 depths
TN, TP, SRP, NH_4^+, NO_3^-, TSS, TDP, DOC, TDN, phytoplankton, zooplankton, dissolved and colloidal metals.

Weekly PAR profiles

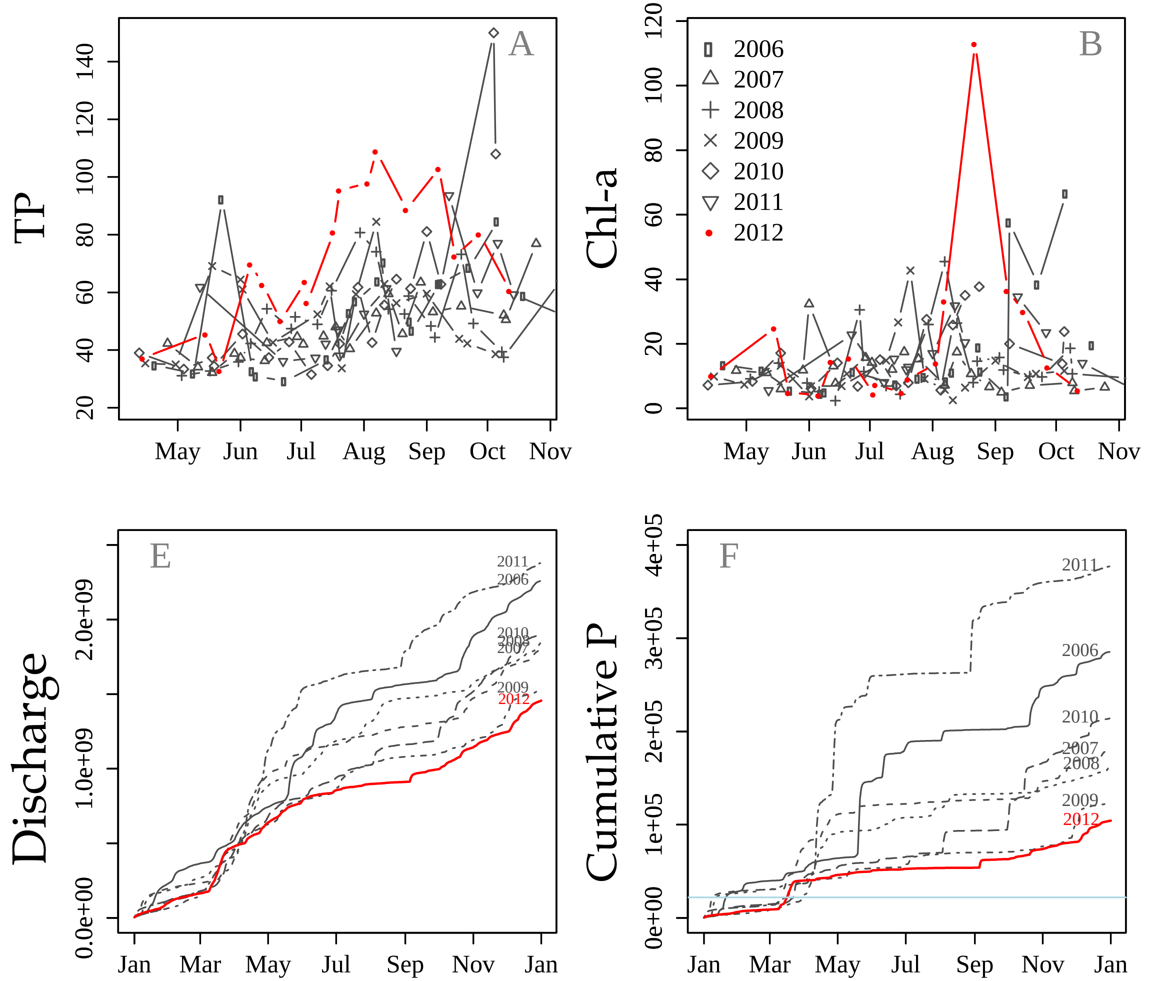
Autosamplers collect TN and TP samples every 8 hours

Hourly measurements of pH, DO, turbidity, chlorophyll *a*, phycocyanin, temperature, and conductivity

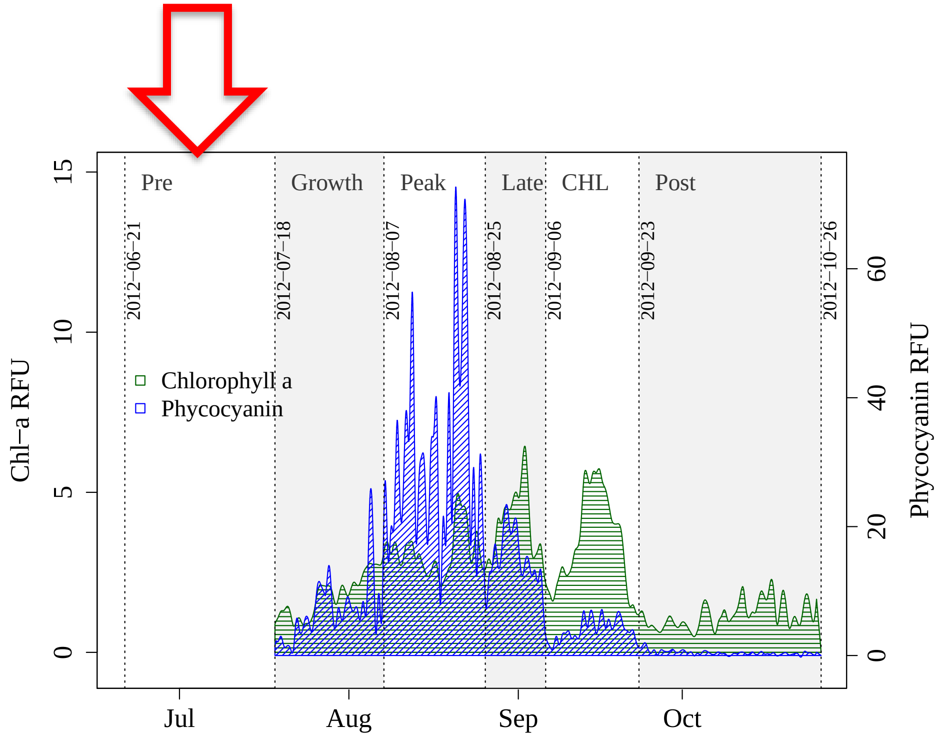
Depth to sediment-water-interface 3-4.5m

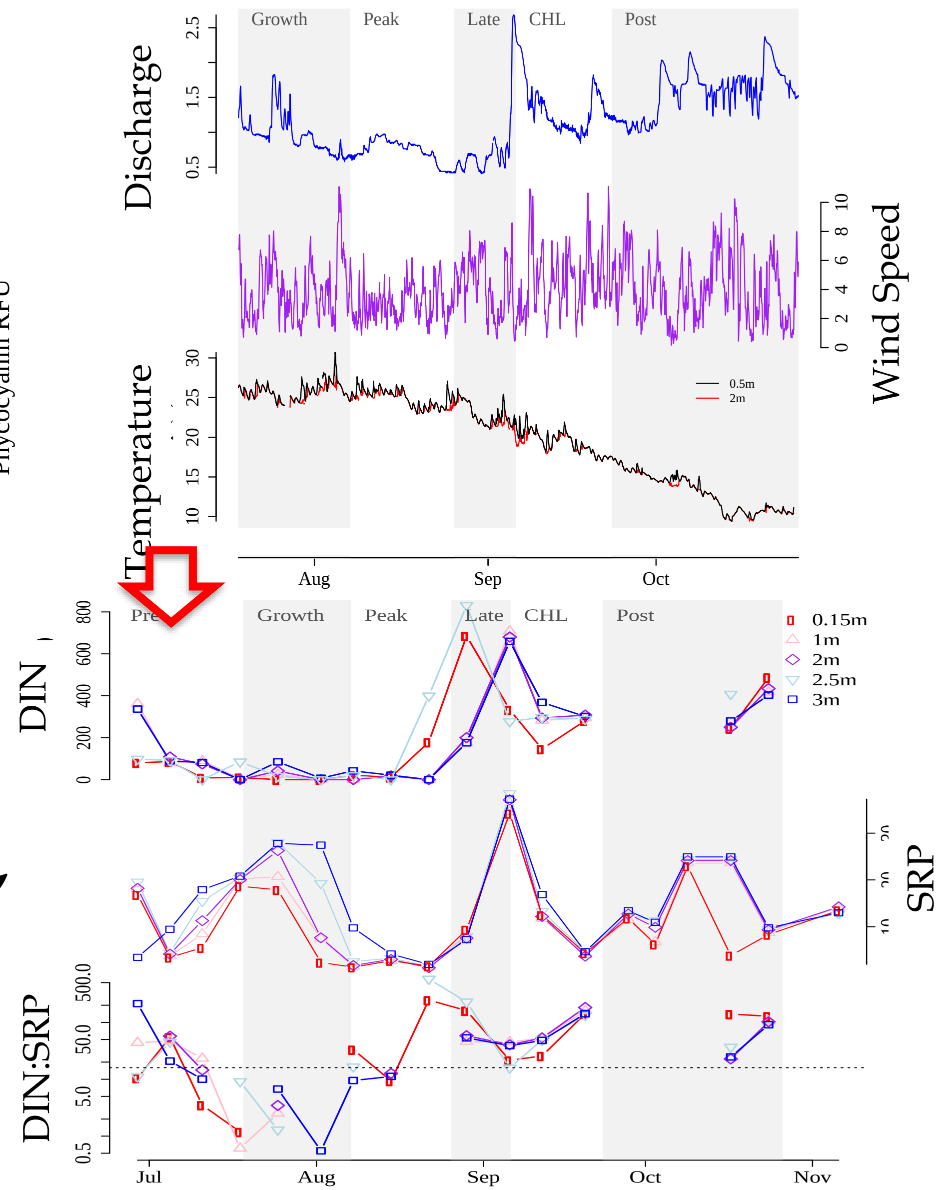
Chapter 2: Historical Context

- 2012 had the strongest bloom in recent years.
- High TP
- High Chl
- Low discharge
- Low external P load



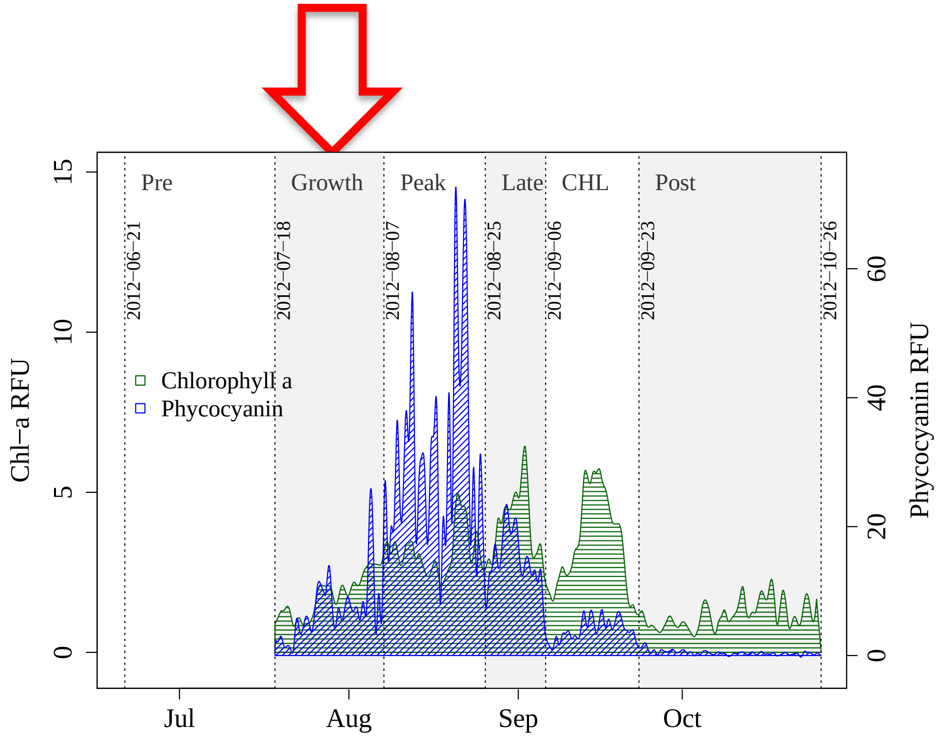
Chapter 2: Stages of a Severe Bloom

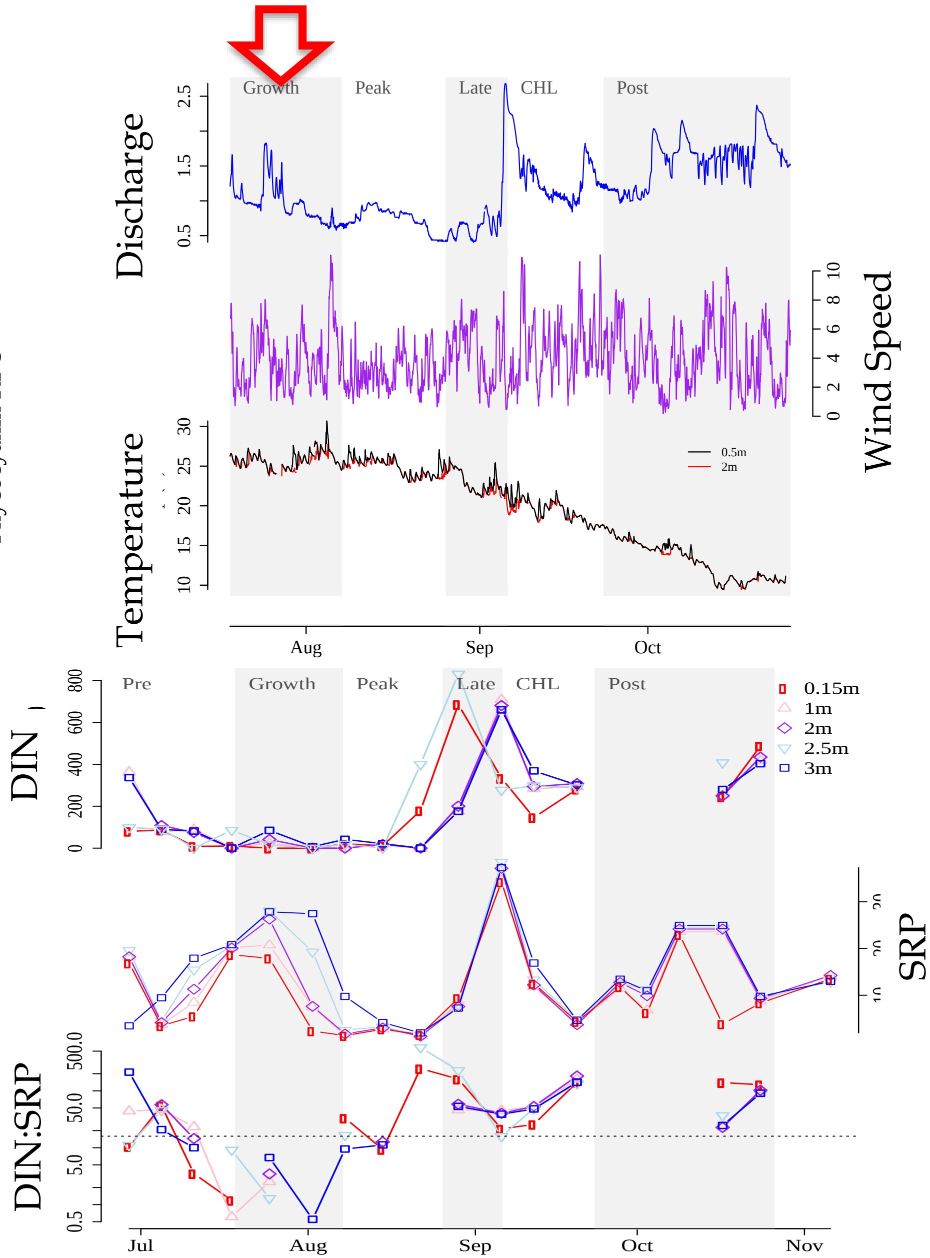




Pre-bloom: declining N:P, warming temperatures

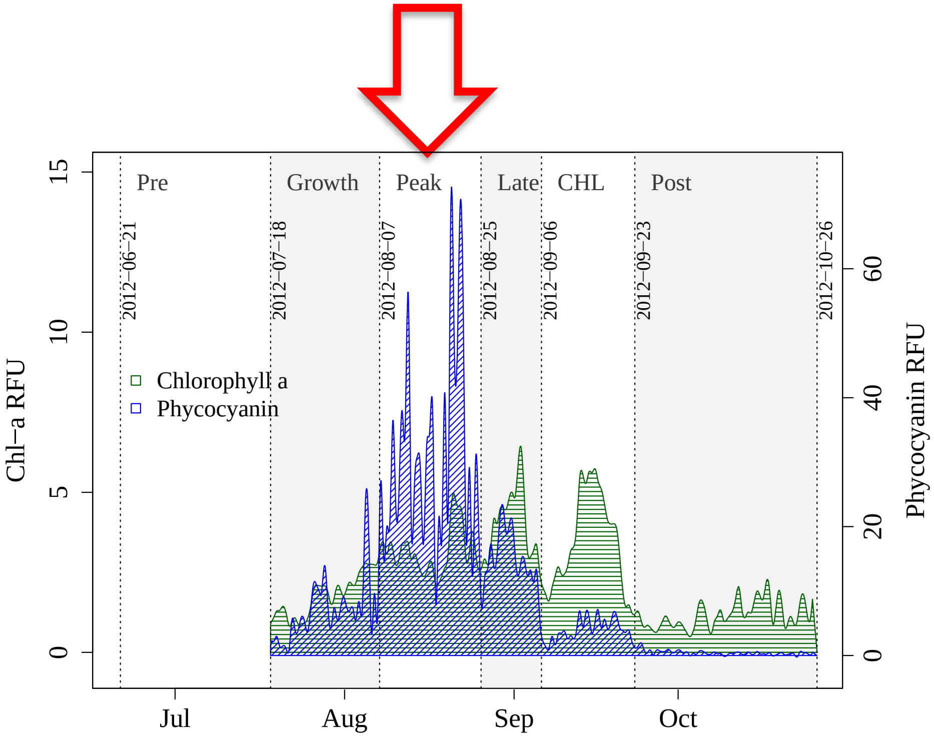
Chapter 2: Stages of a Severe Bloom

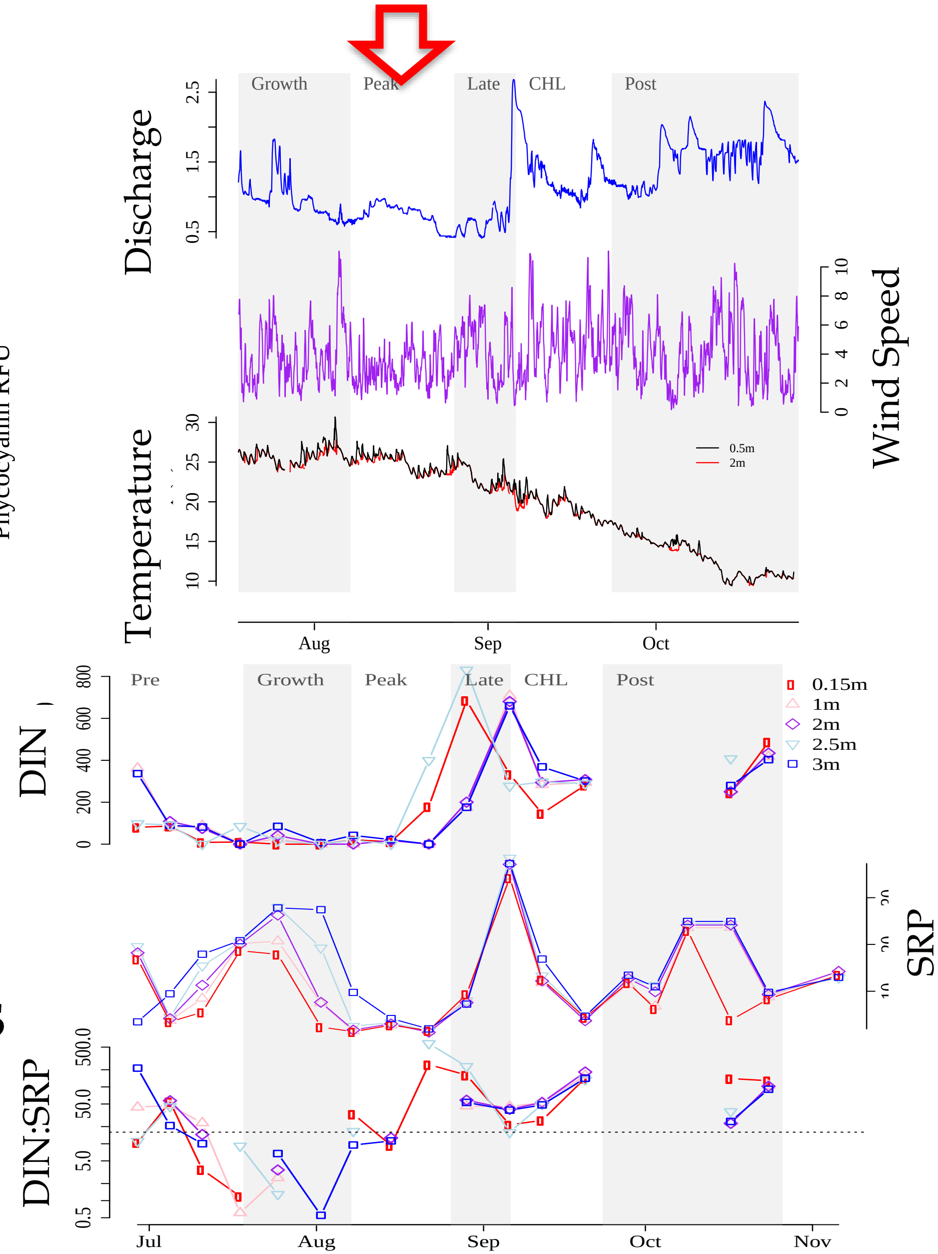




Growth period: warm water, thermal stratification, internal P loading, low available N

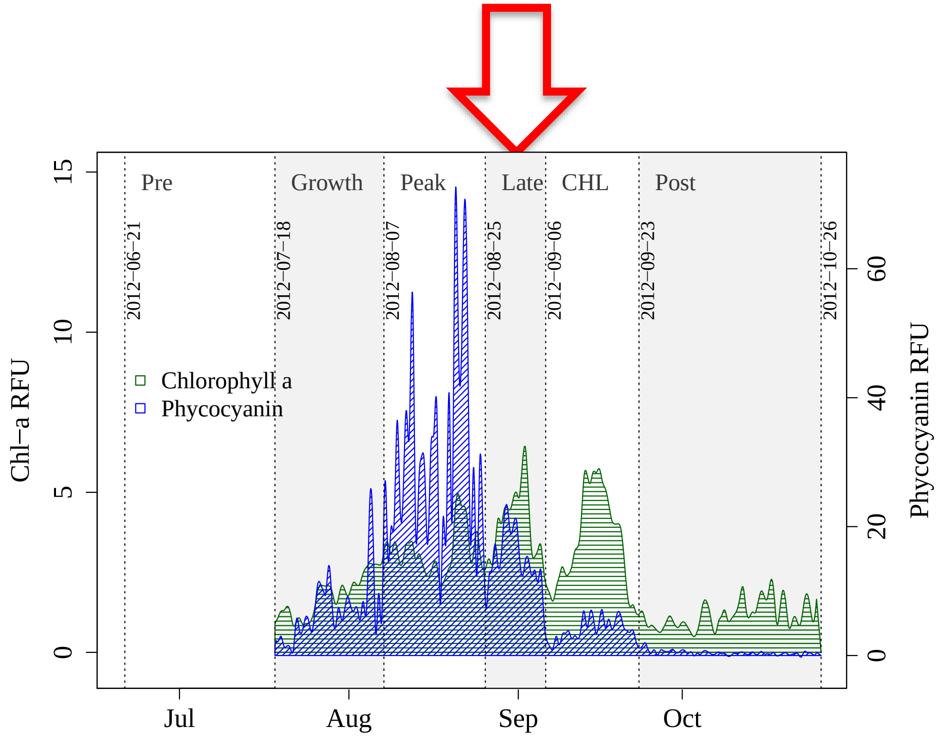
Chapter 2: Stages of a Severe Bloom

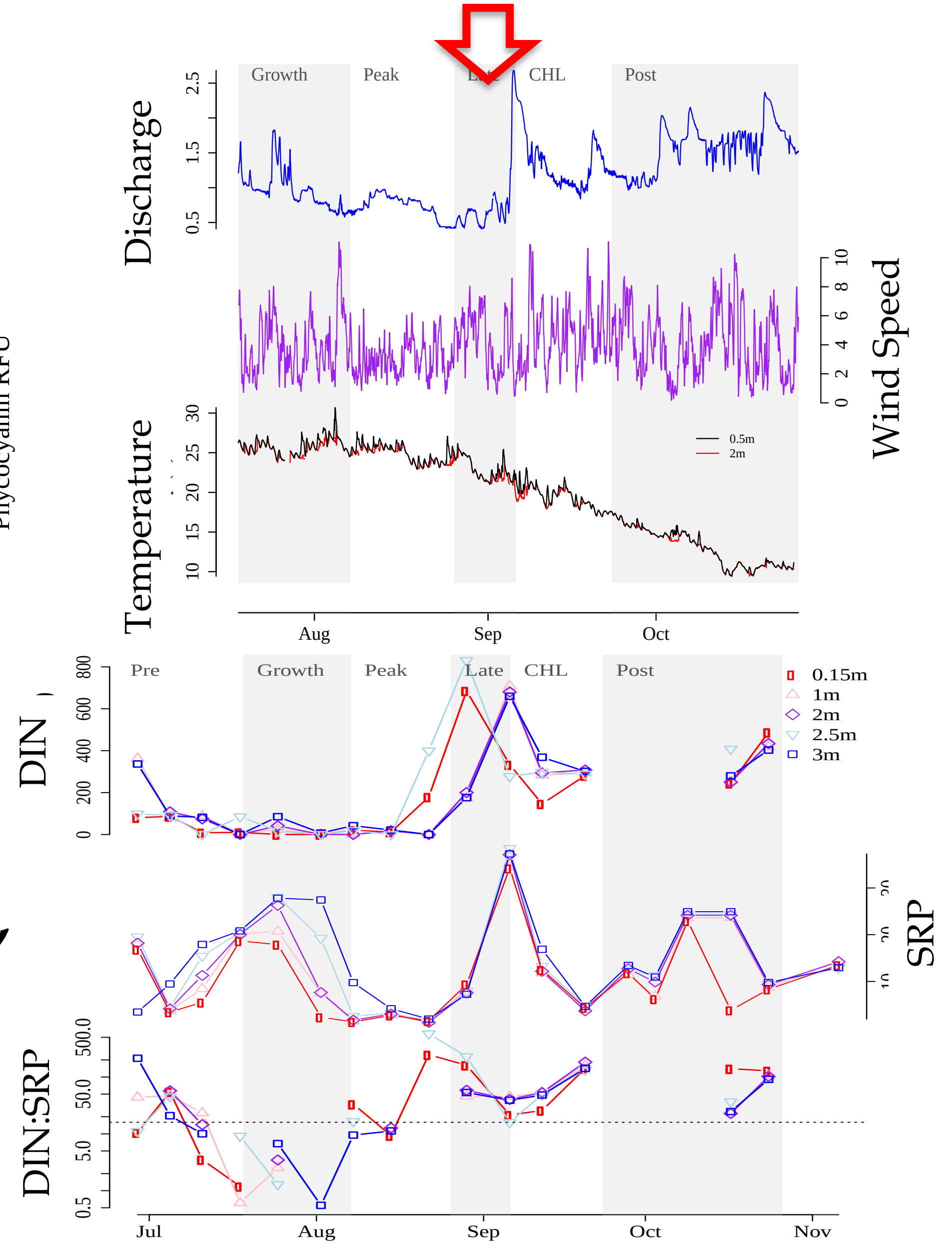




Peak bloom: low available nutrients, low wind speeds

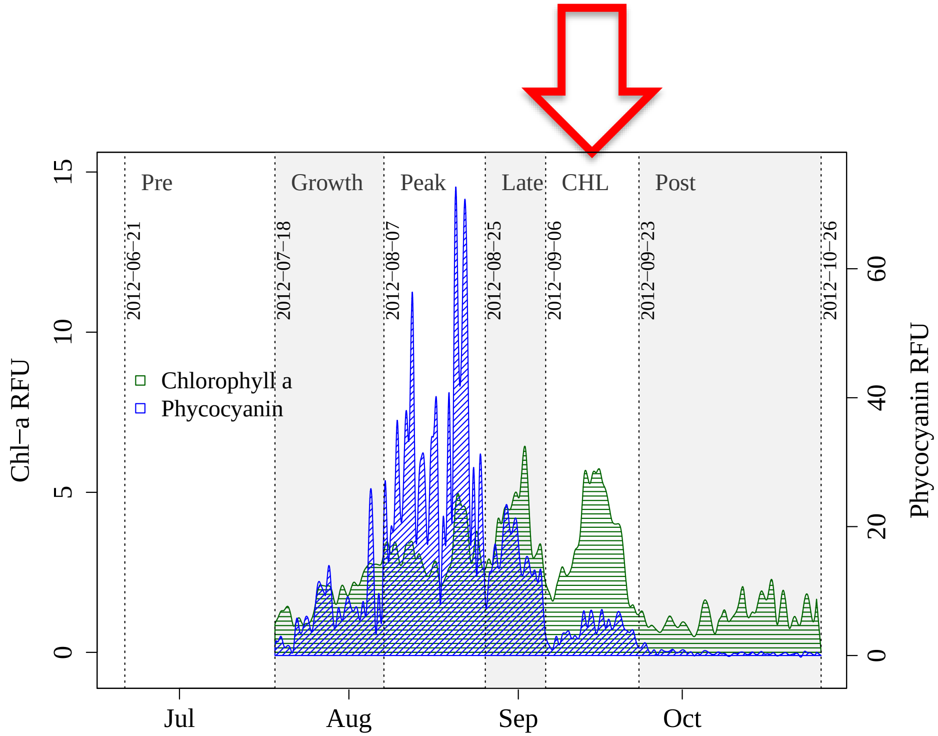
Chapter 2: Stages of a Severe Bloom

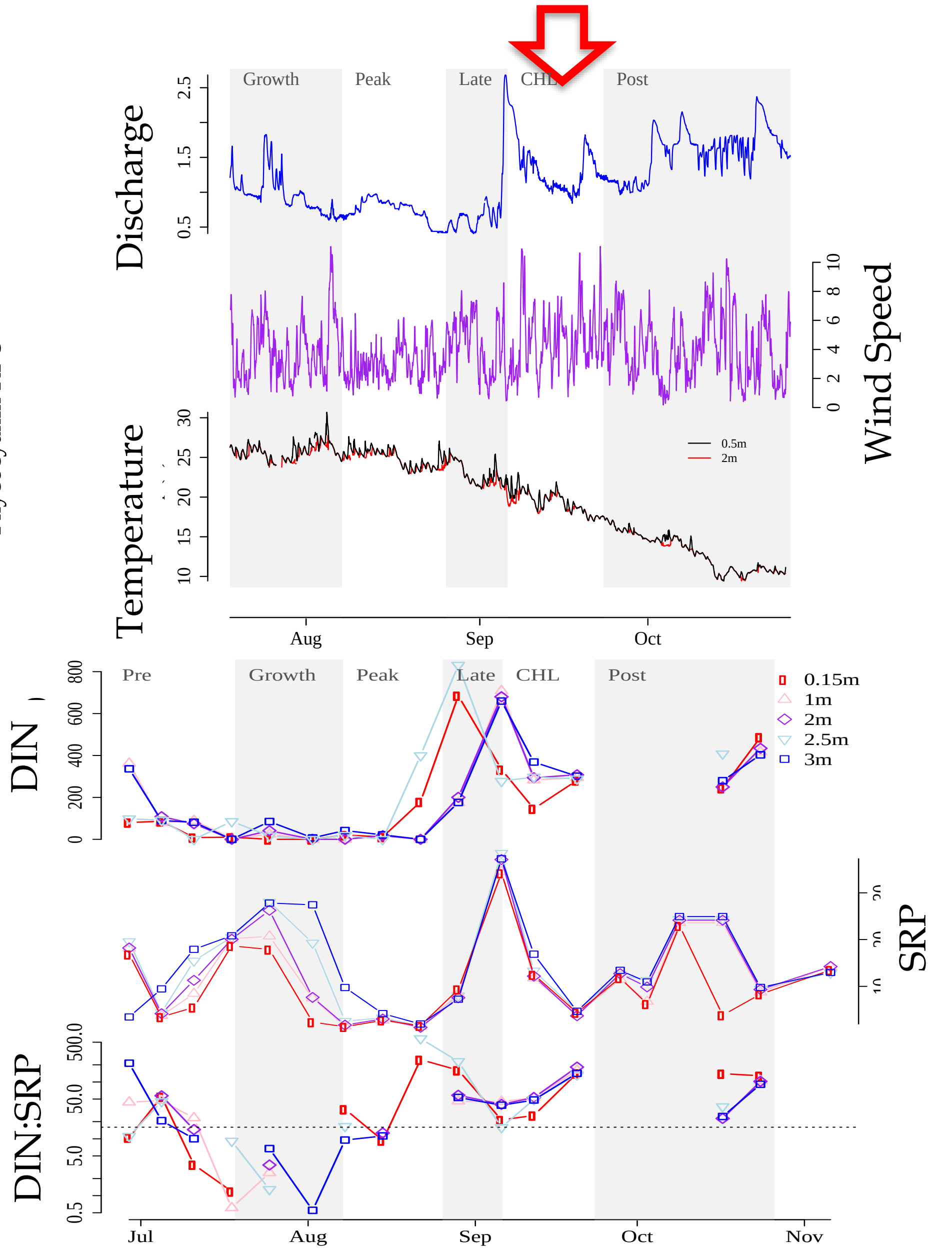




Late bloom: decline phase, increased winds, more available nutrients, strong storm event

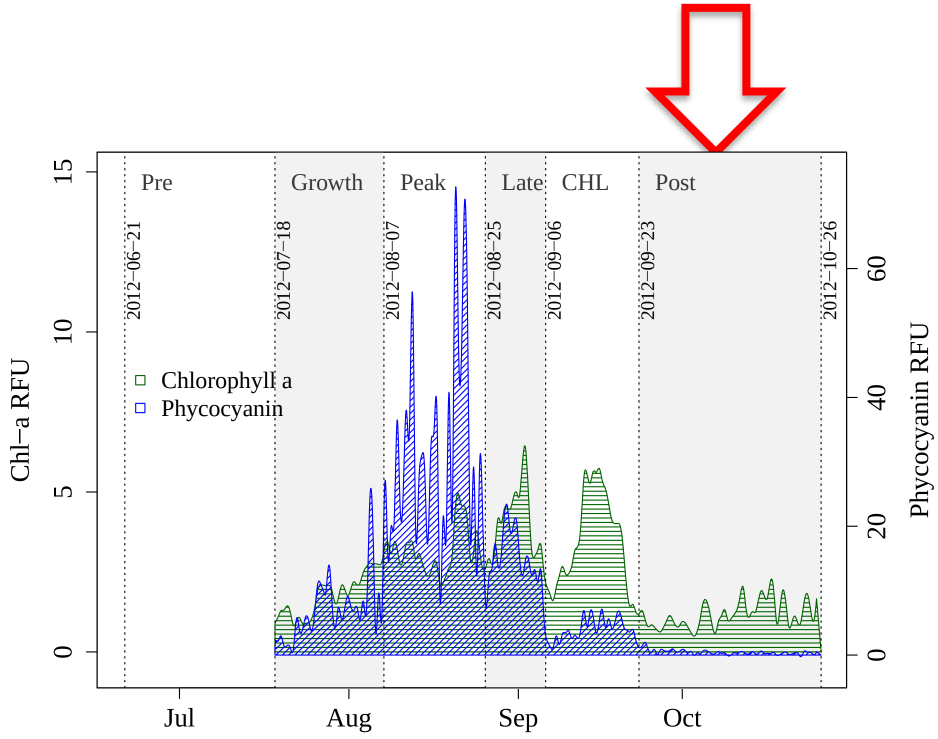
Chapter 2: Stages of a Severe Bloom

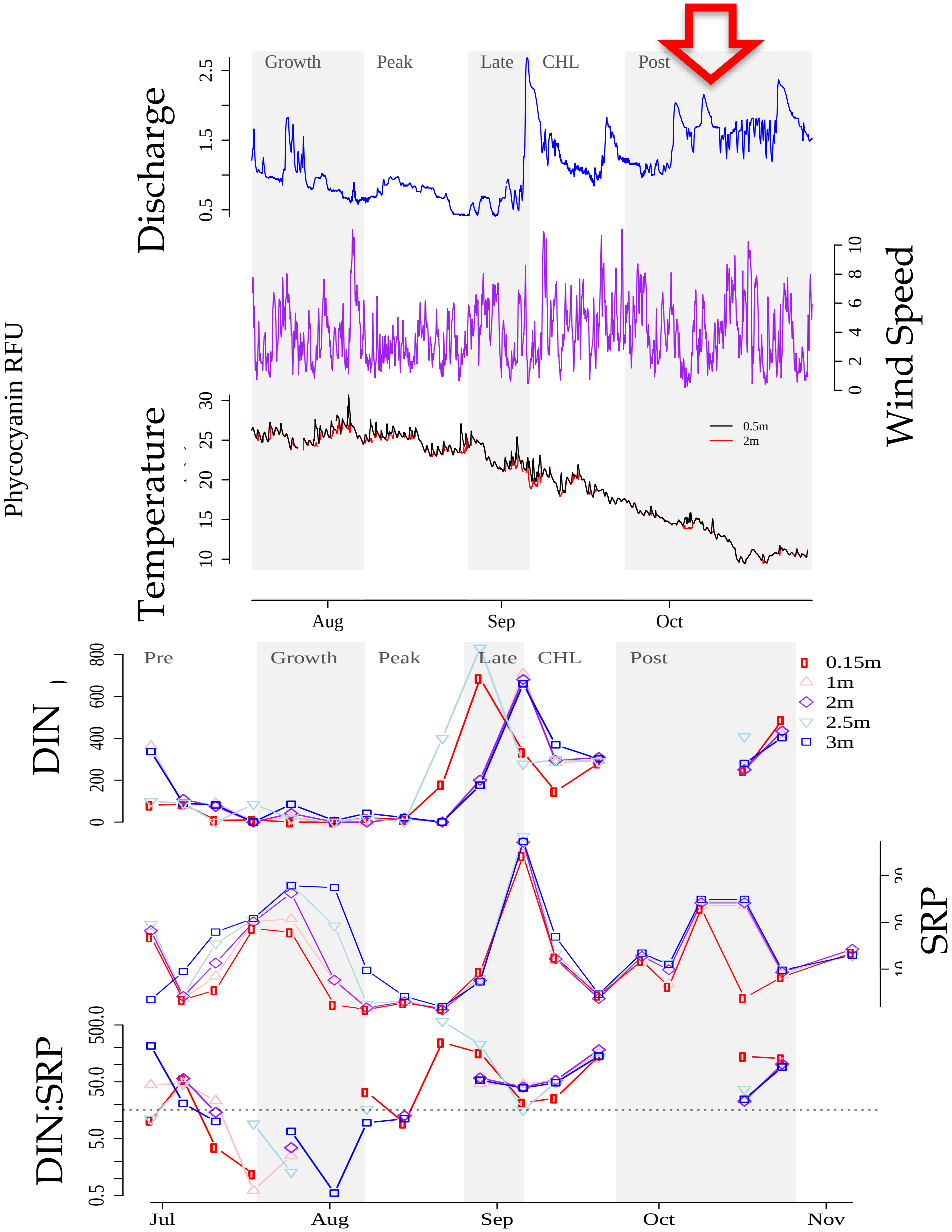




Chl-a bloom: high nutrients, decreasing temperatures

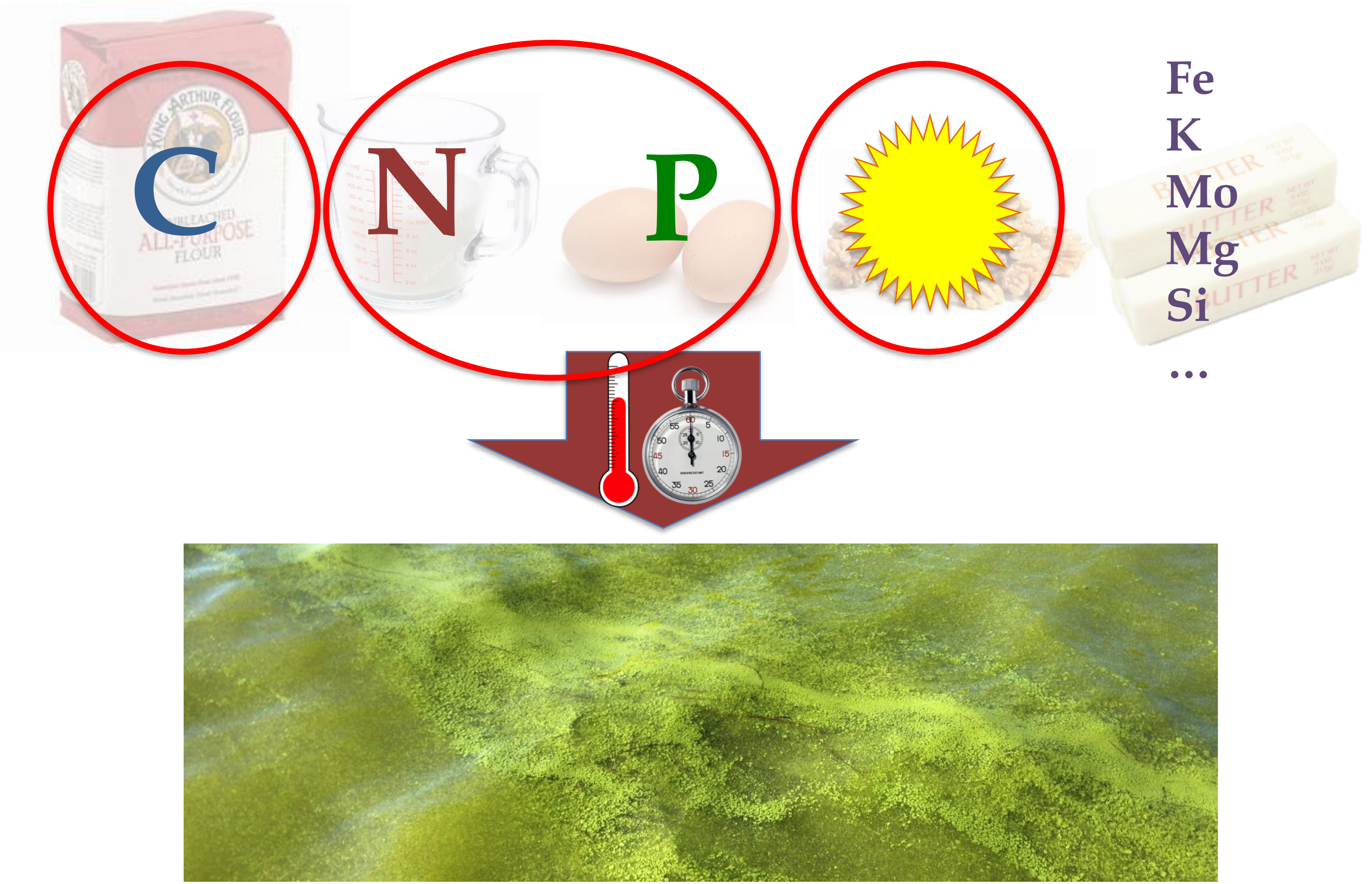
Chapter 2: Stages of a Severe Bloom



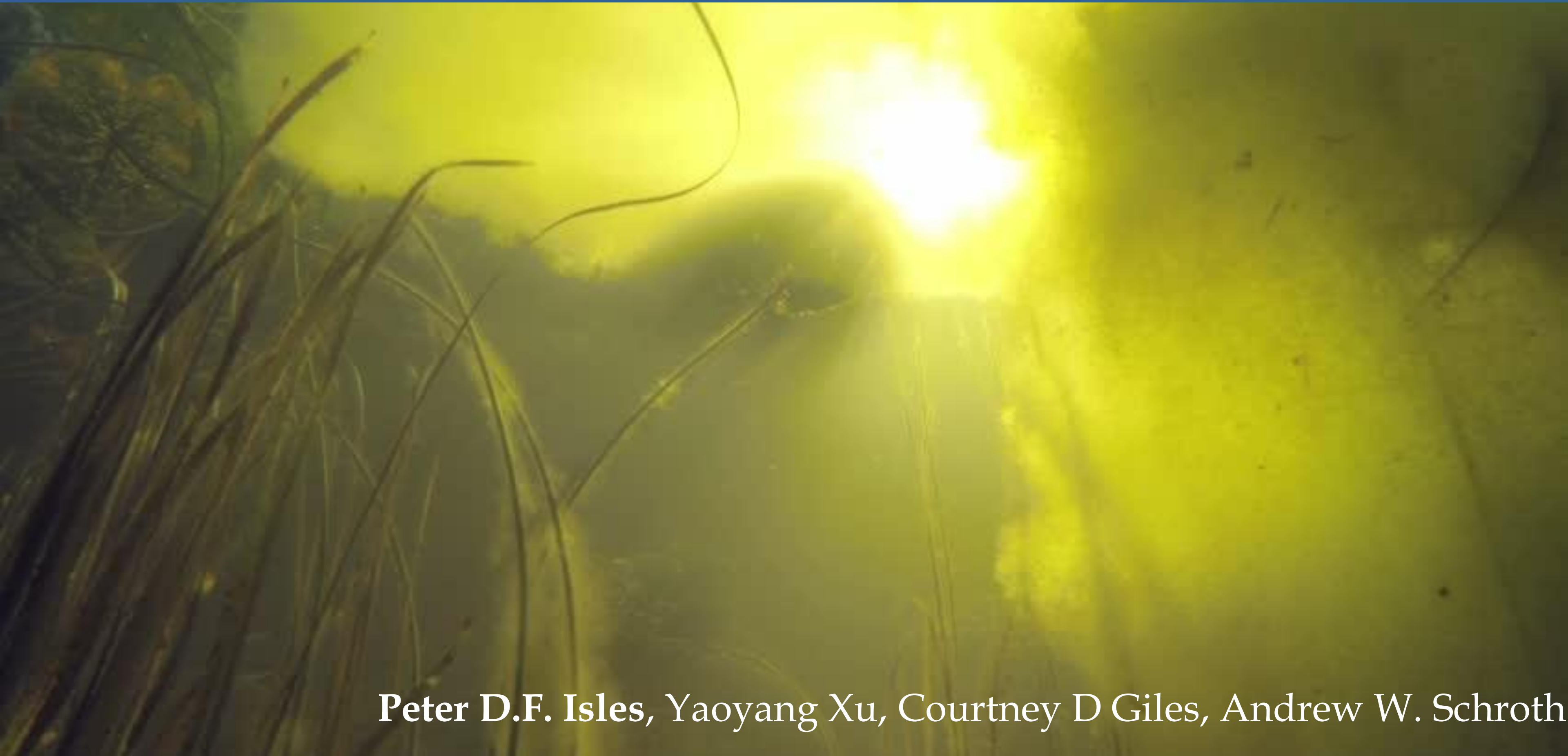


Post bloom: too cold, lots of tributary flushing

Background: Nutrients and Phytoplankton



Chapter 3: Buoyancy regulation and wind mixing control metabolism during strong blooms



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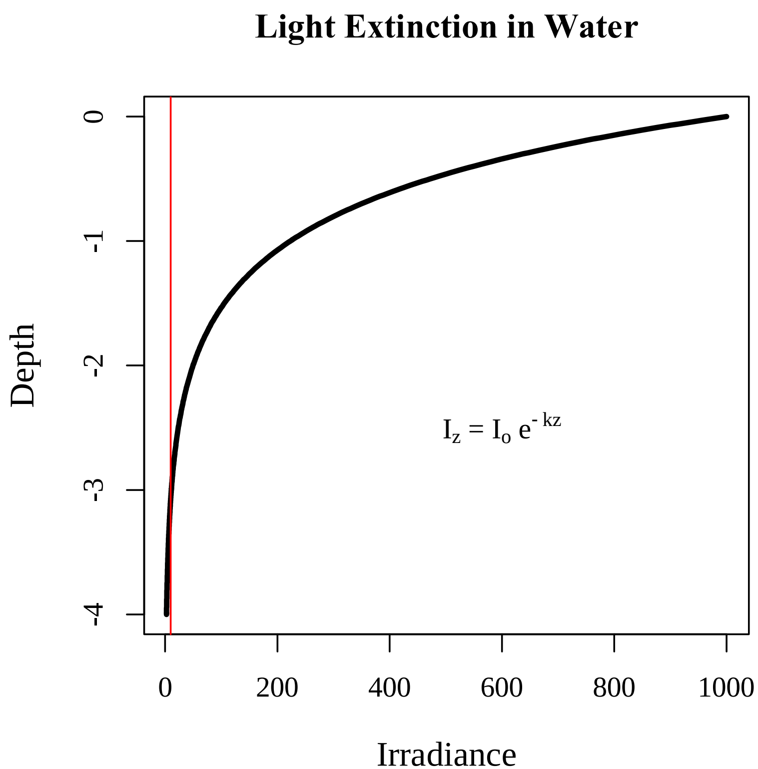
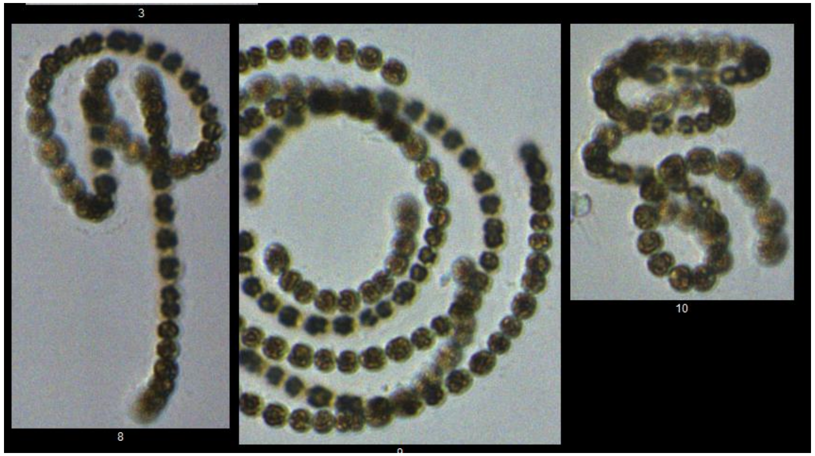
Chapter 3: The Behavior of Light in Water

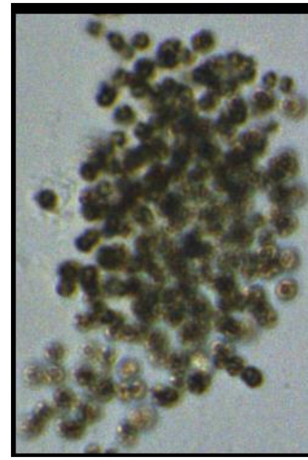
- Key Question: To what extent do buoyancy regulation and access to light control cyanobacteria bloom dynamics?



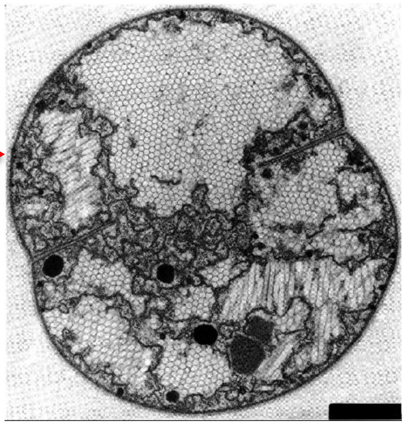
Chapter 3: Physiology of Buoyancy Regulation

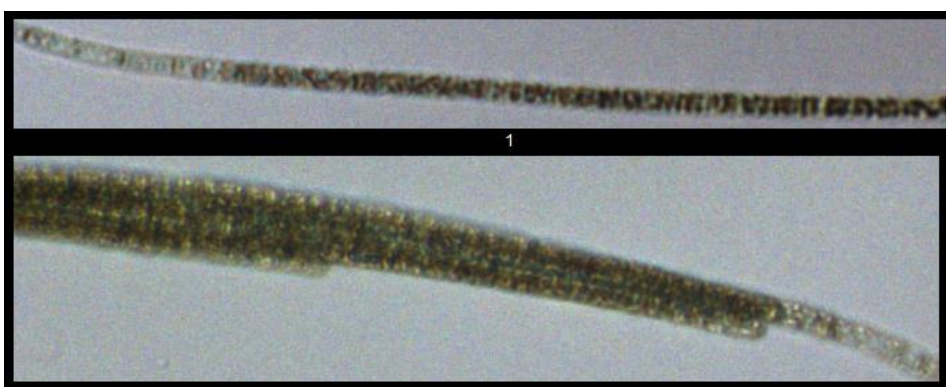


Anabaena



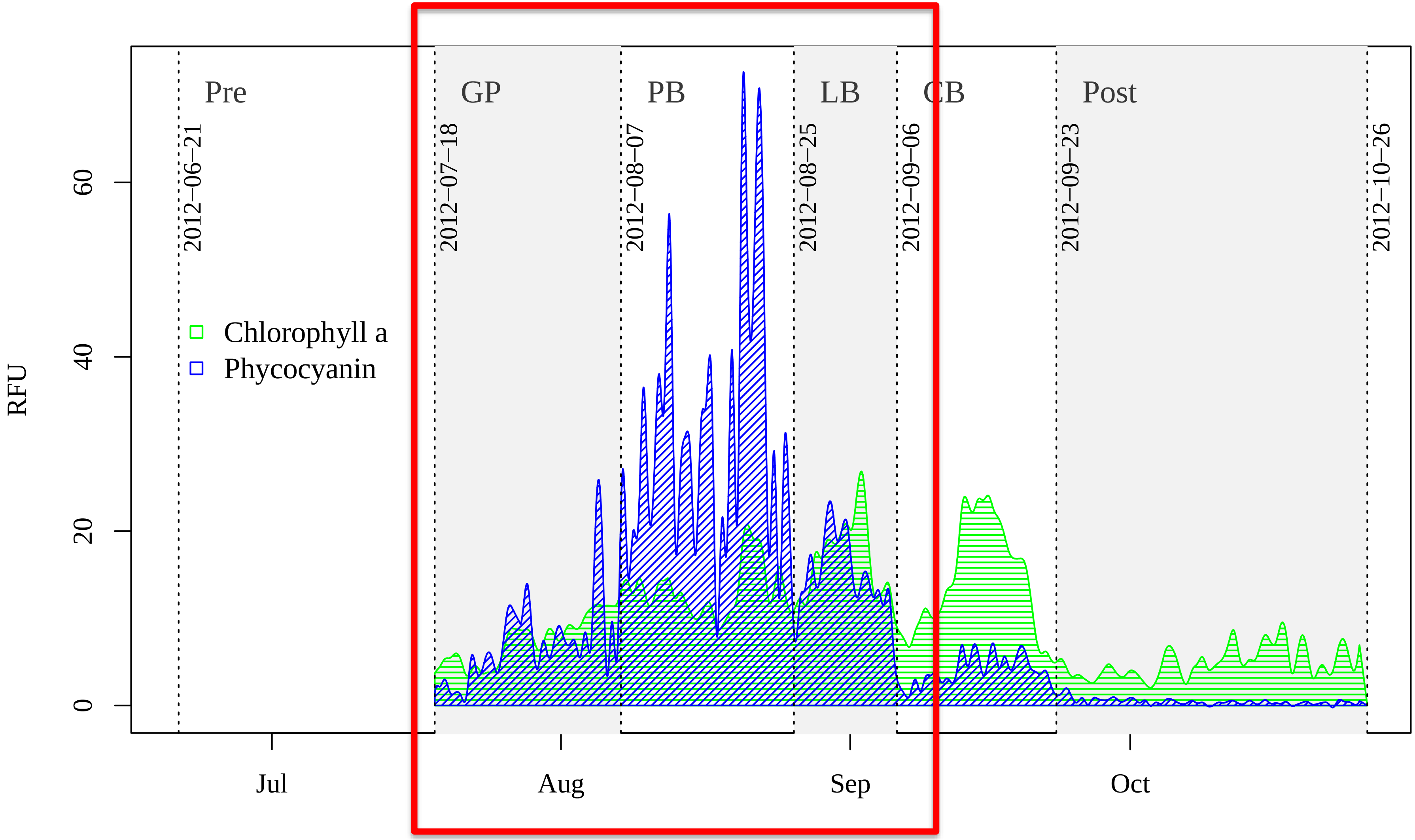
Microcystis



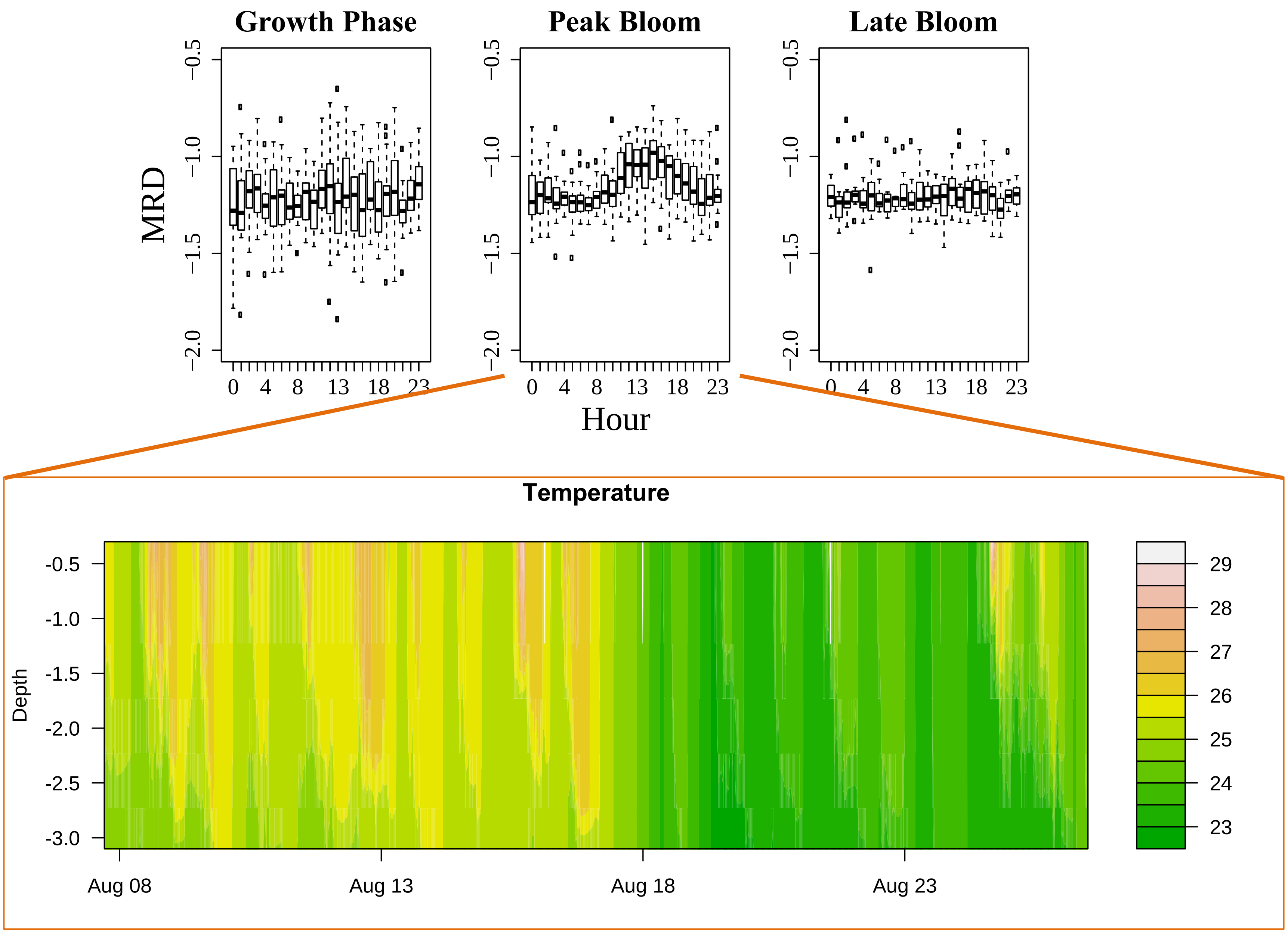


Aphanizomenon

Chapter 3: Vertical Migration and wind mixing drive lake metabolism



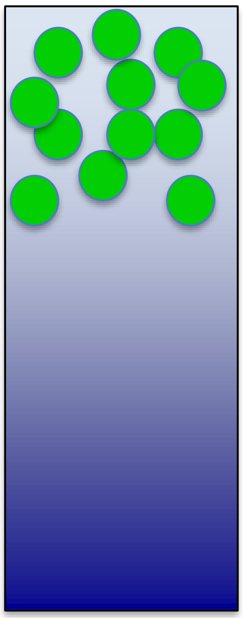
Chapter 3: Vertical Migration and wind mixing drive lake metabolism

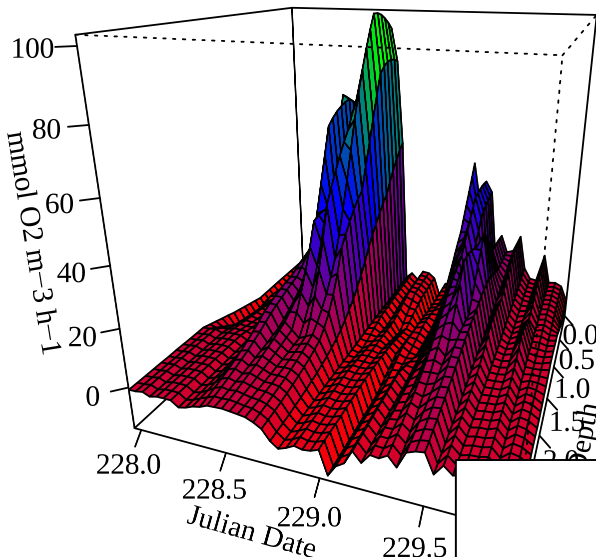


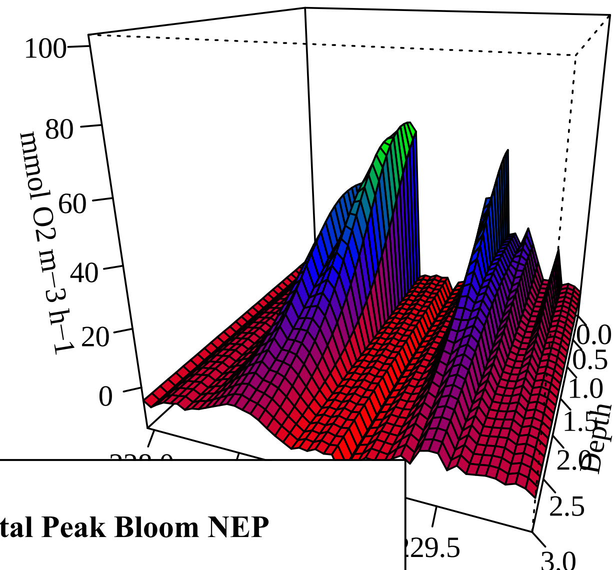
Chapter 3: The benefits of buoyancy regulation

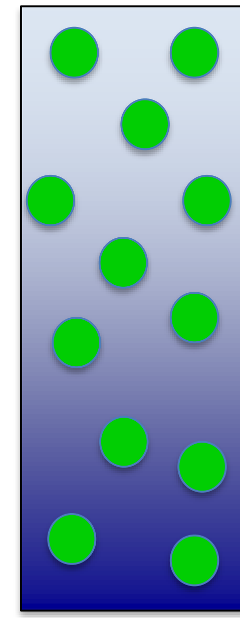
With Buoyancy Regulation

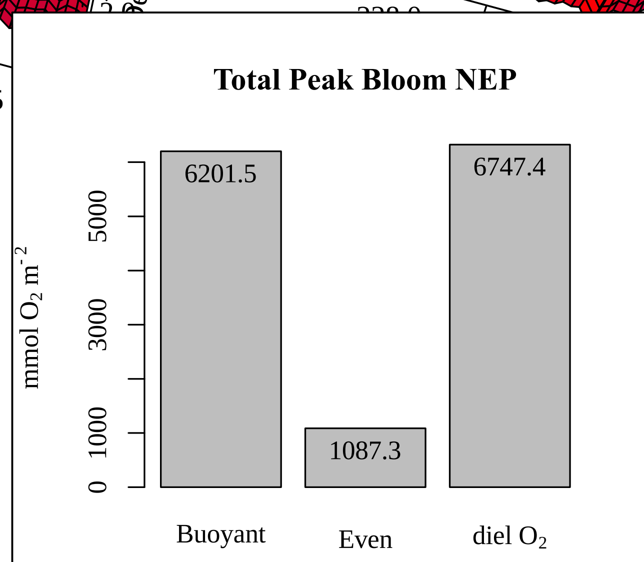
Without Buoyancy Regulation



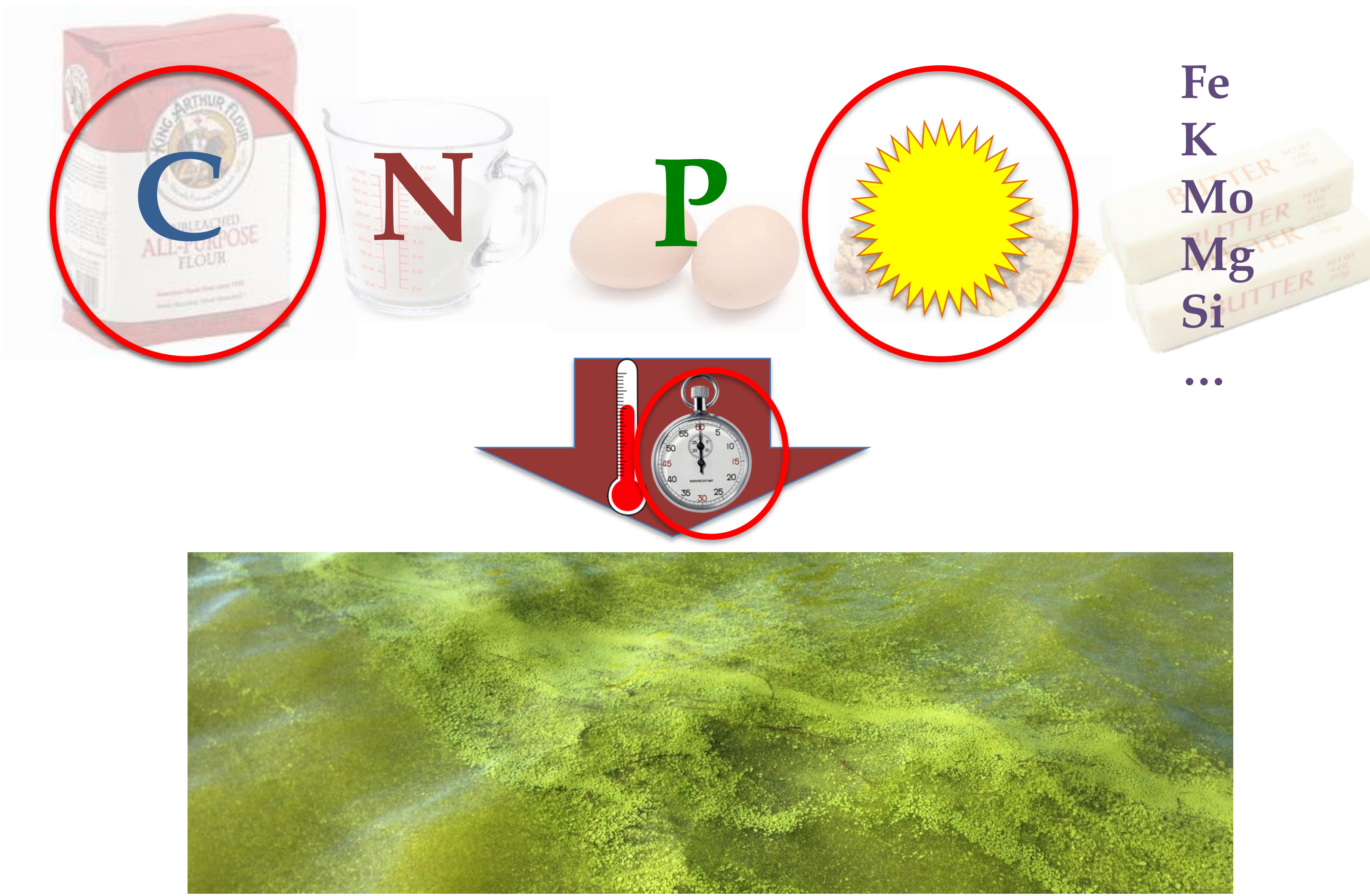




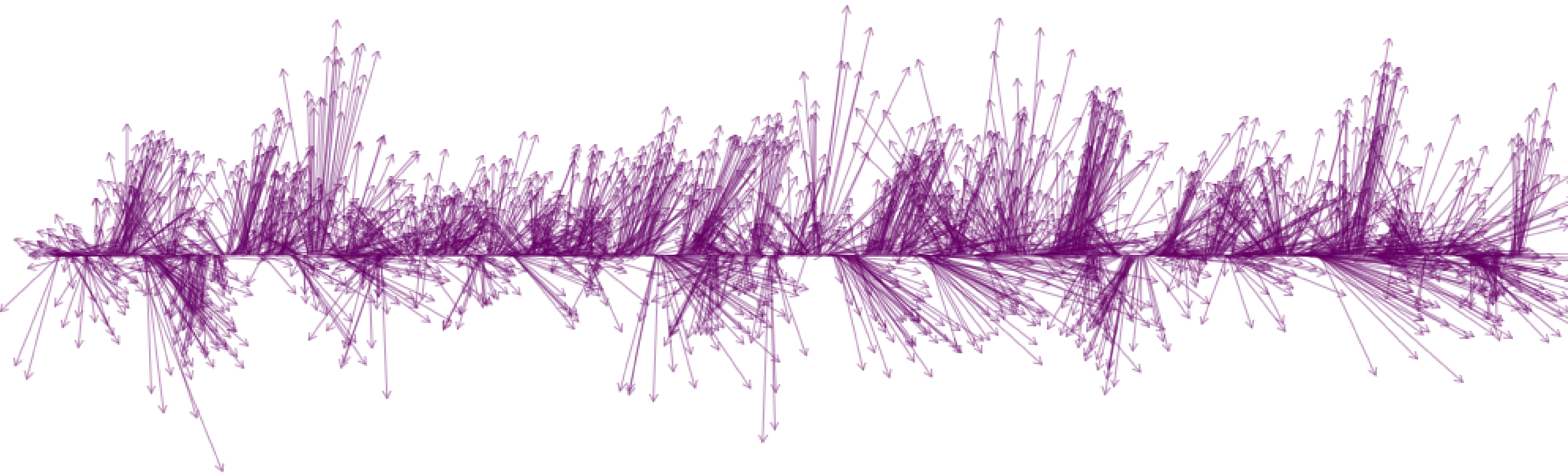




Background: Nutrients and Phytoplankton



Chapter 4: Temporal dynamics of wind mixing control inter-annual variability in cyanobacteria bloom severity



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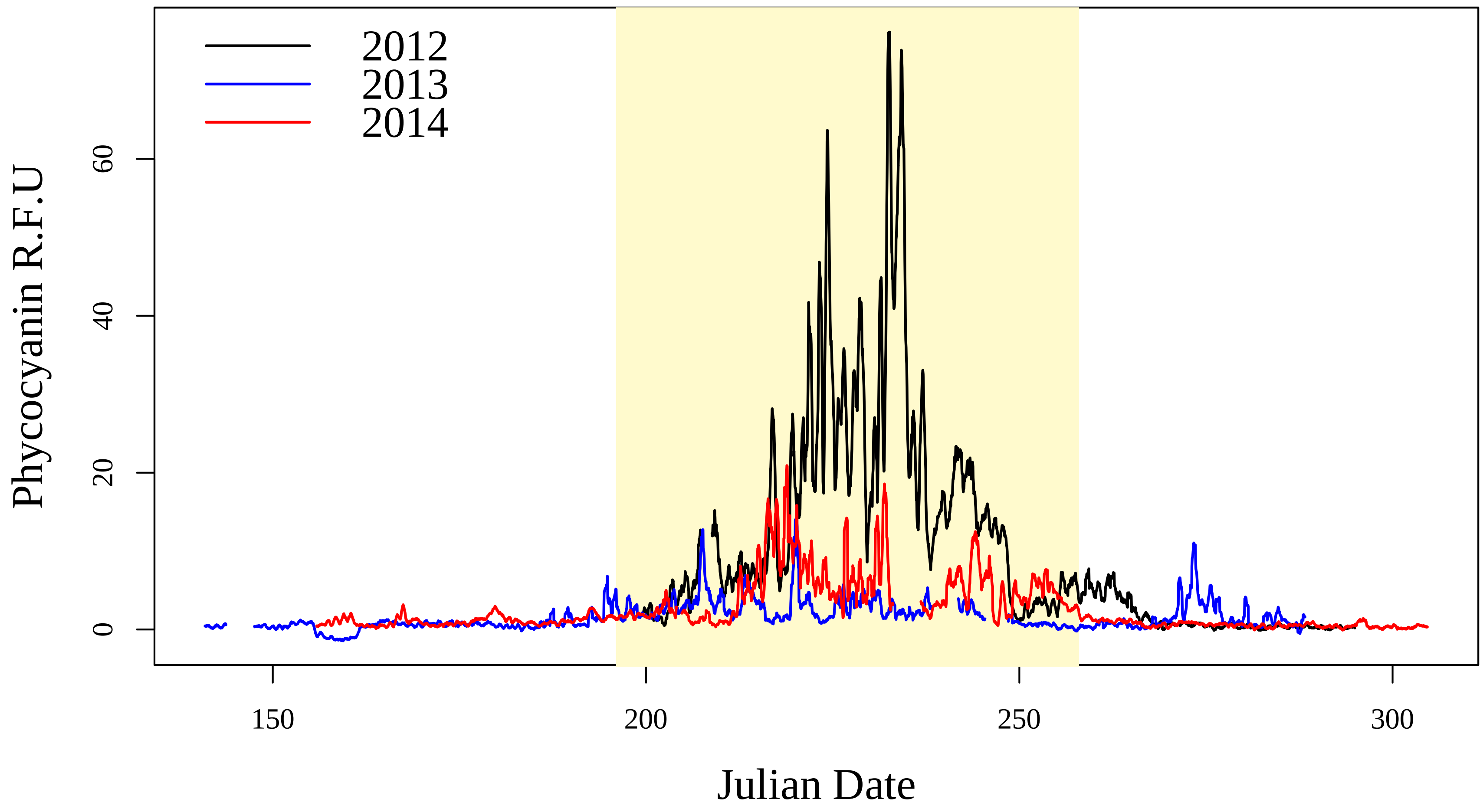
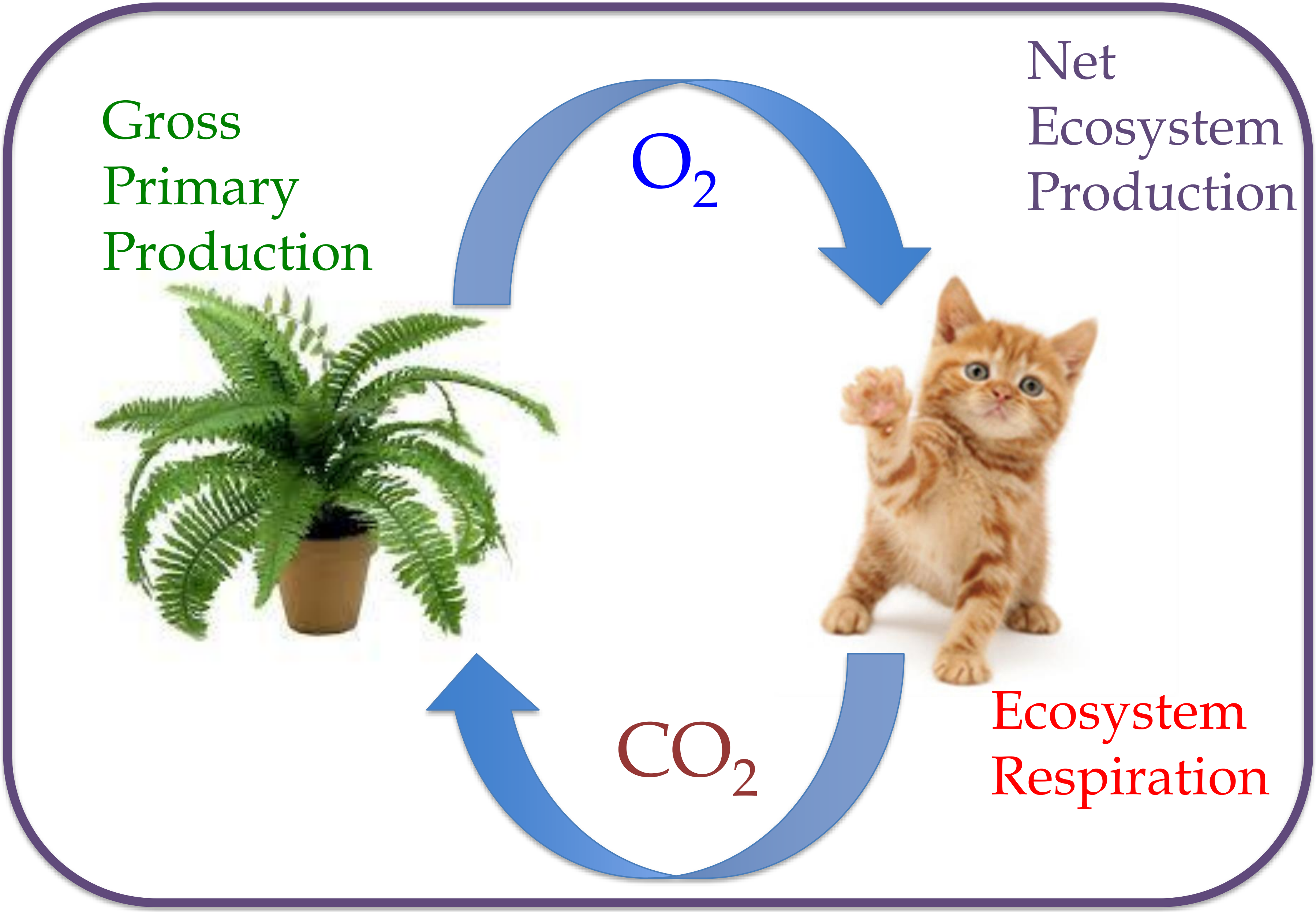
Chapter 4: Inter-annual variability in blooms



Chapter 4: Intro to Ecosystem Metabolism



Chapter 4: Drivers of Ecosystem Metabolism

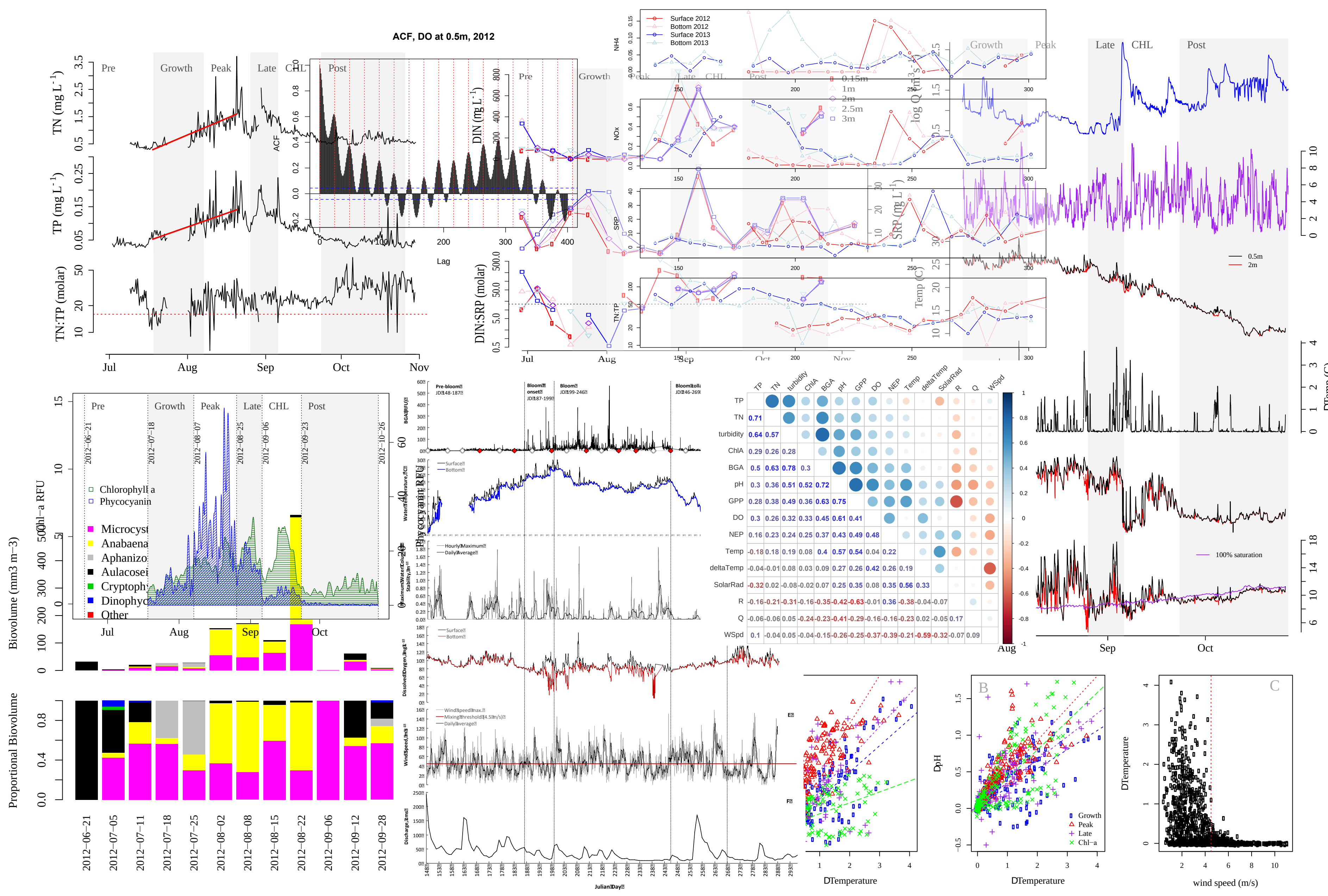
Daily NEP - R

$$\color{blue}{NEP} = \color{green}{GPP} - \color{red}{R}$$

Daily change in dissolved oxygen, corrected for atmospheric exchange

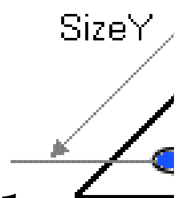
NEP at night, for each day

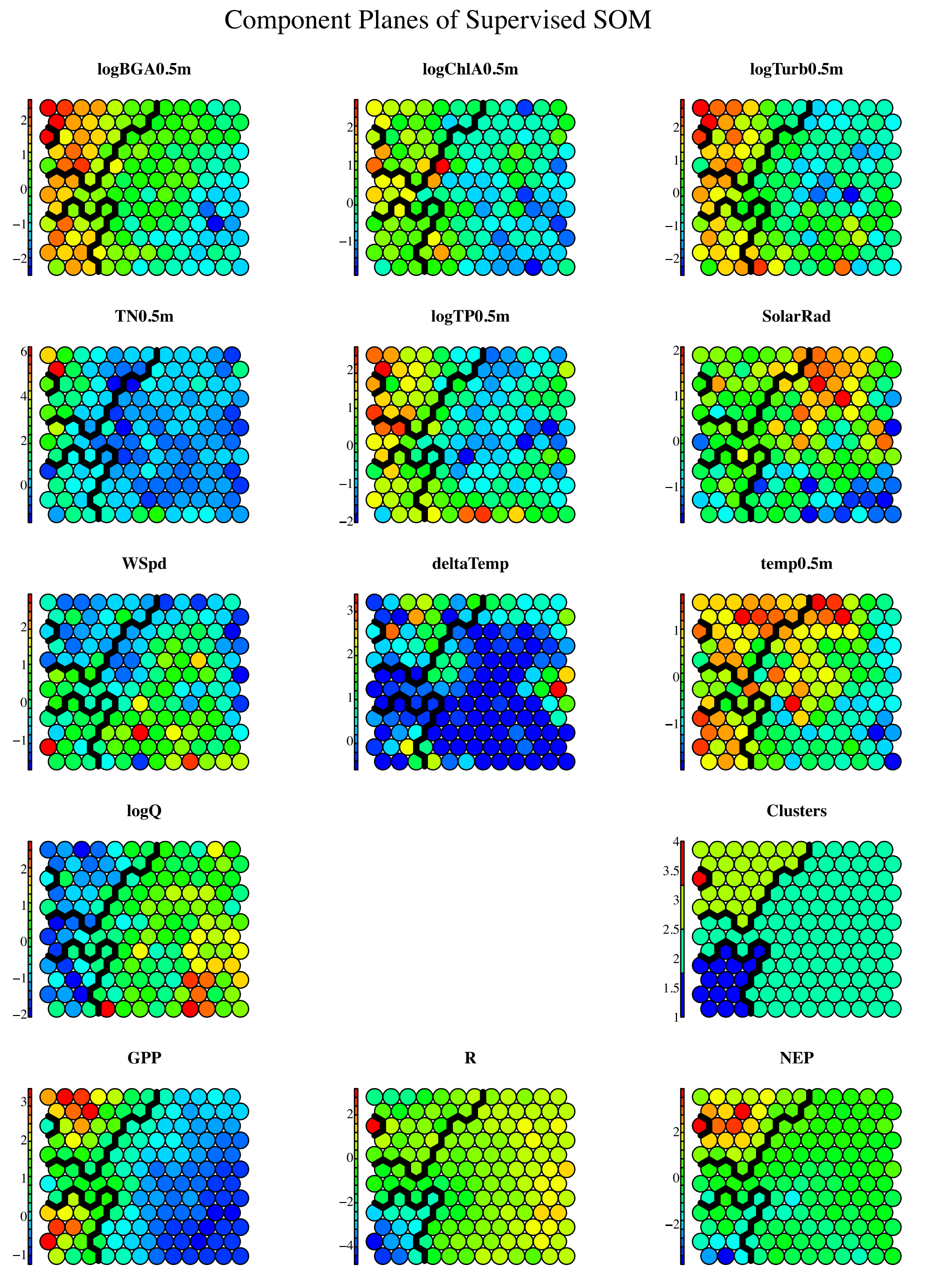
Chapter 4: Challenges of Big Data



Chapter 4: Self-Organizing Maps

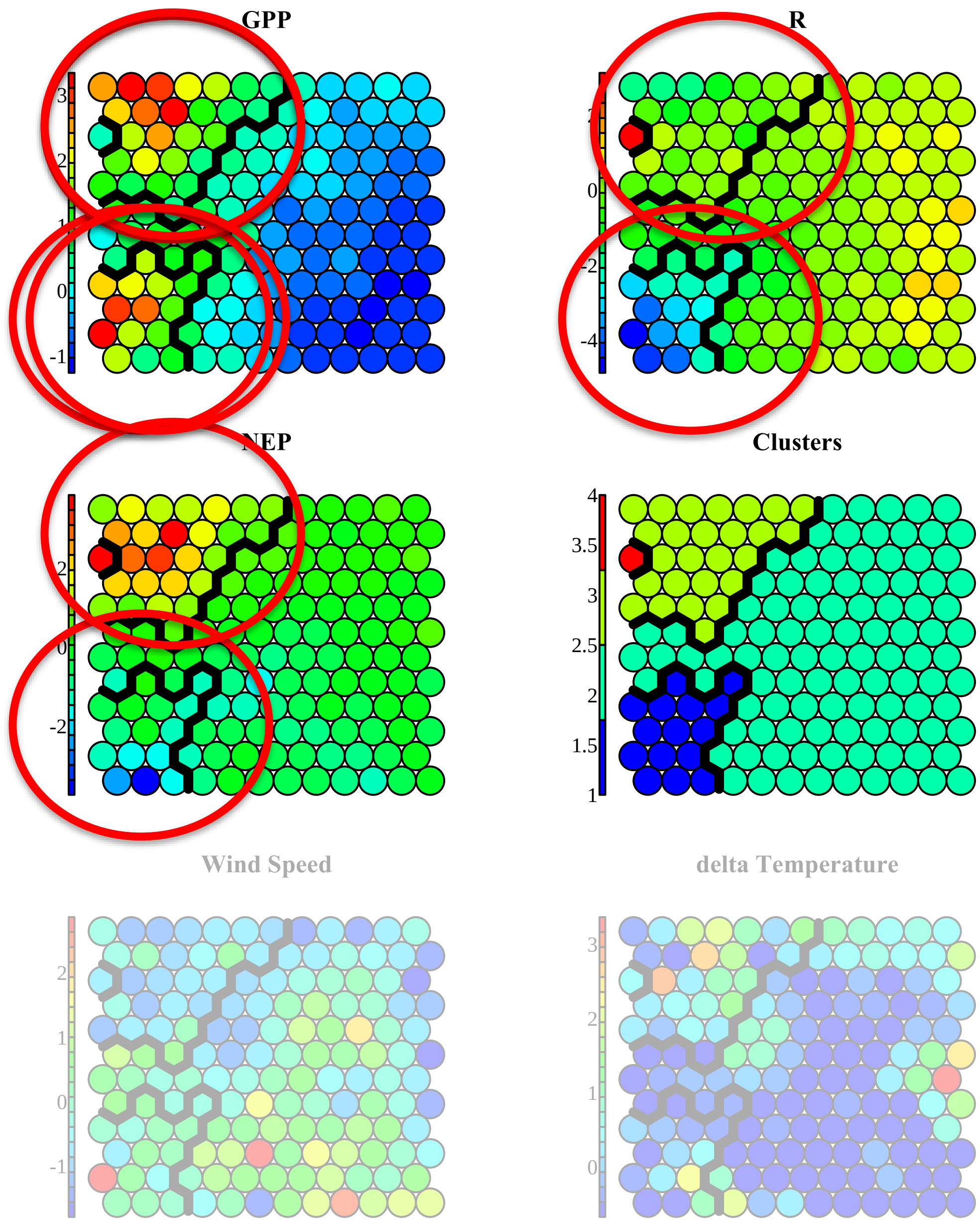
- Type of artificial neural network used for clustering, ordination, and prediction
- May outperform traditional methods with highly correlated datasets, non-linear responses
- We used supervised & unsupervised SOMs



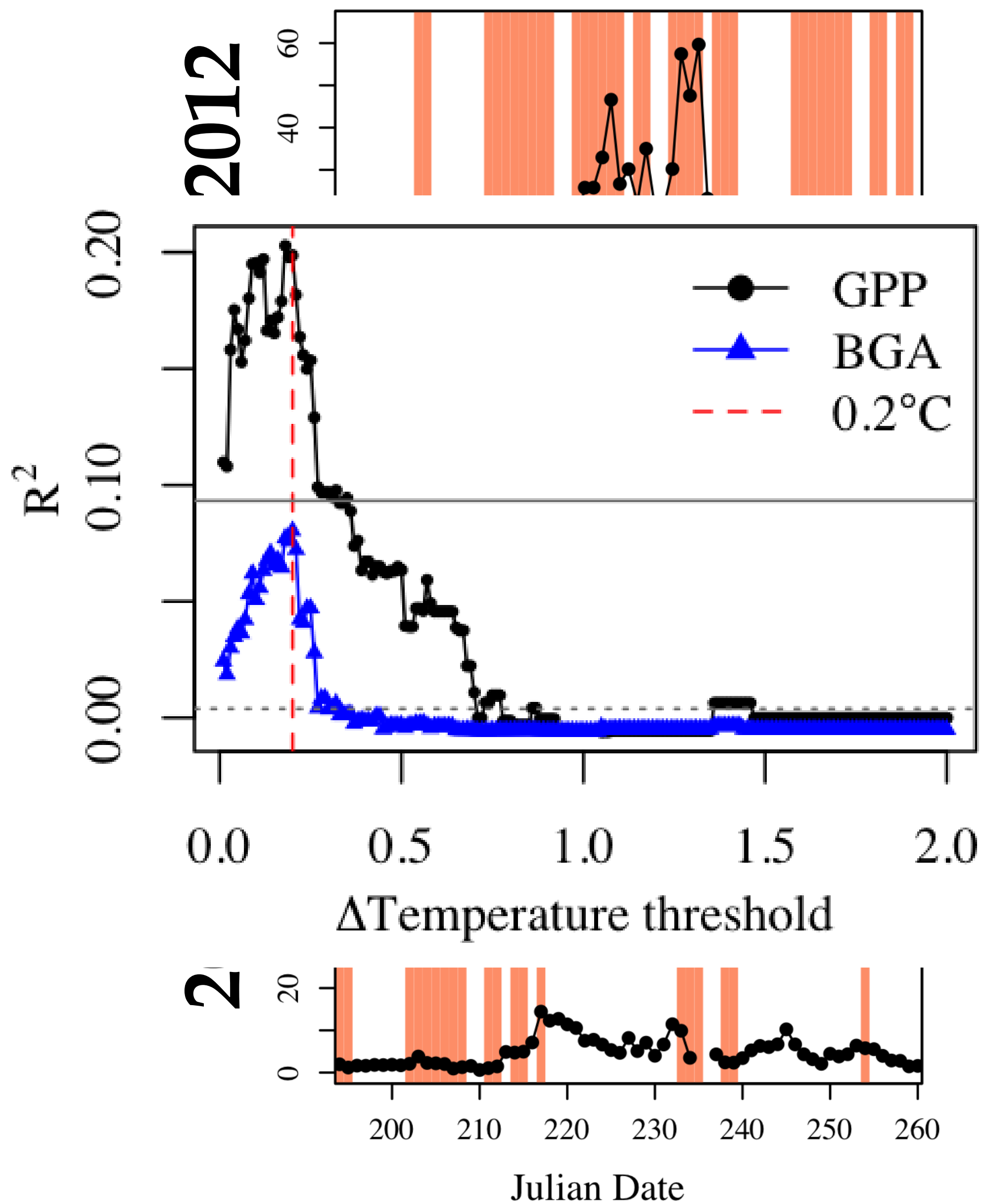


Chapter 4: SOM Results

- 2 distinct clusters with high productivity.
- One has very high respiration, negative NEP (bloom collapse).
- The other has strong positive NEP, low R
- The biggest difference between these clusters is wind mixing and stratification



Chapter 4: Critical Thresholds



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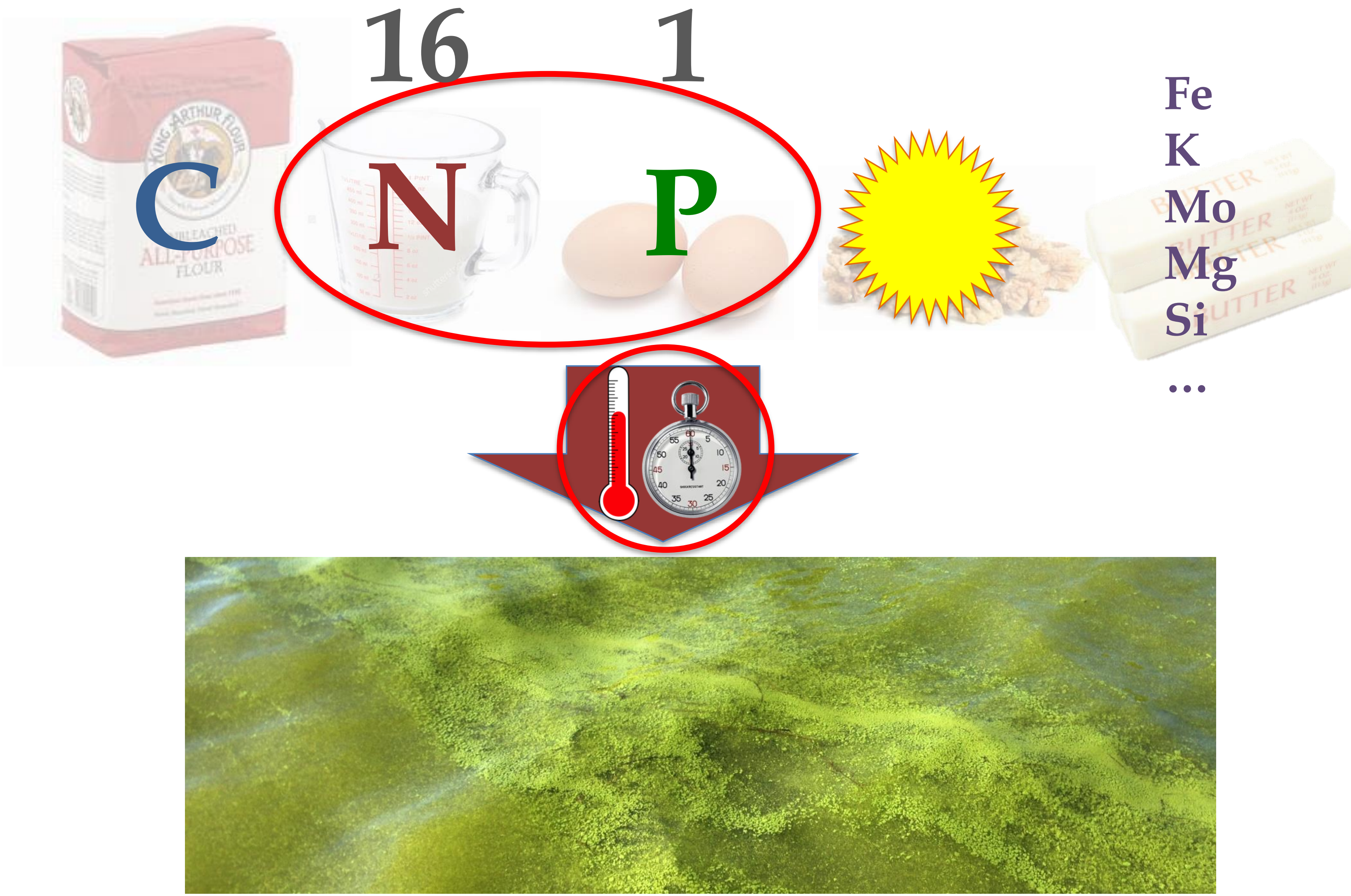
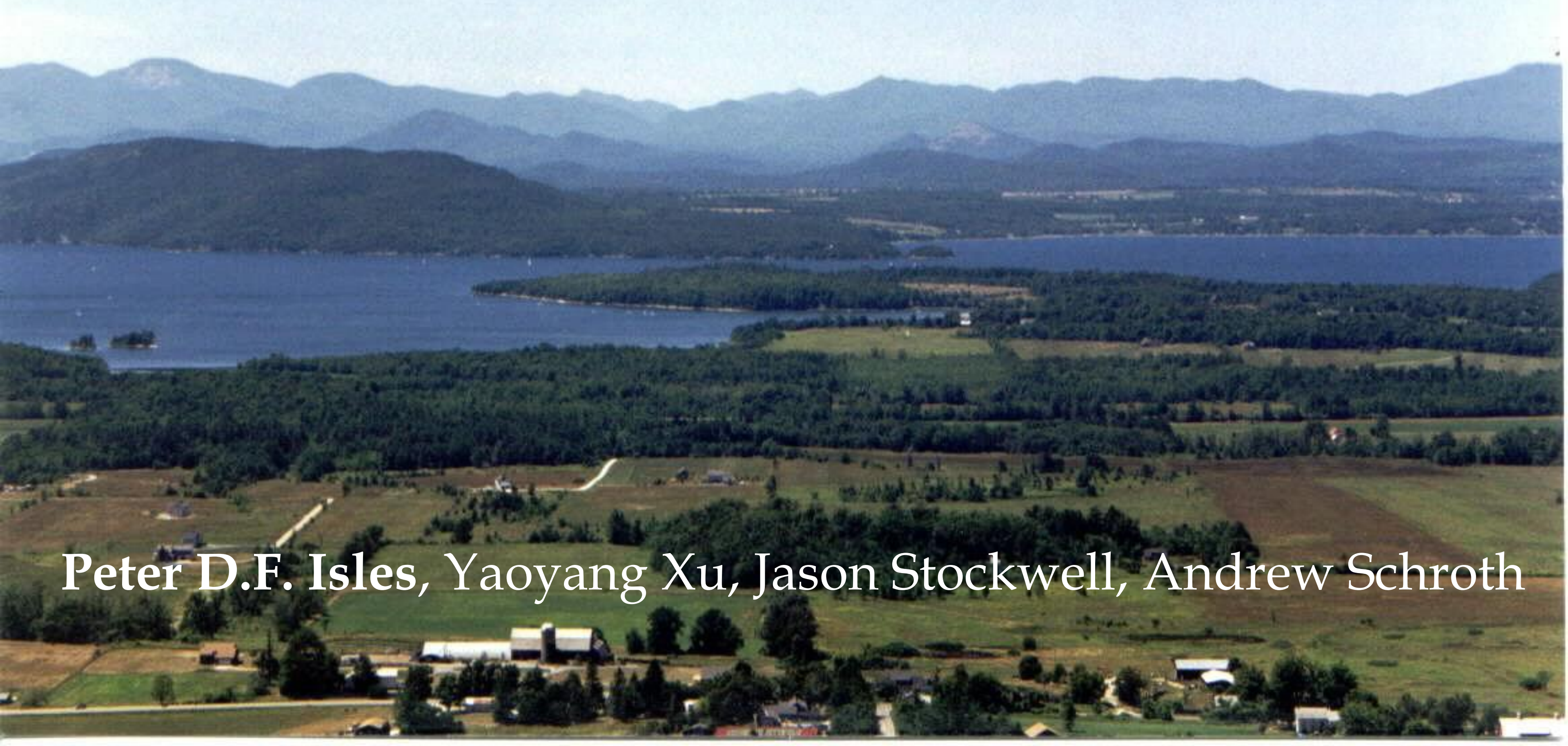


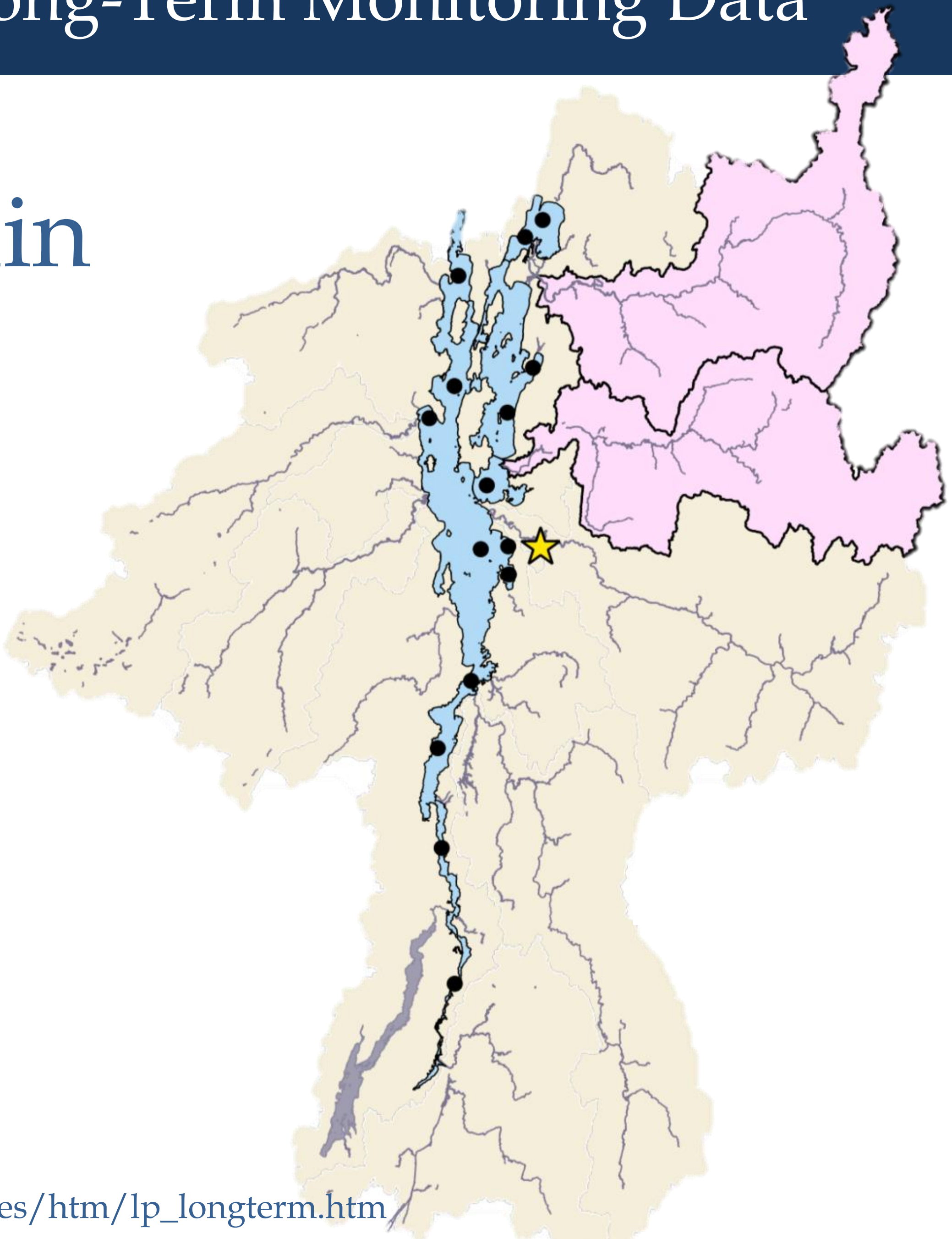
Chapter 5: Climate-driven changes in energy and mass inputs systematically alter nutrient concentration and stoichiometry in deep and shallow areas of Lake Champlain



Chapter 5: Objectives

- Low N:P makes lakes more susceptible to cyanobacteria blooms
- **How is climate change likely to affect the balance of N and P in Lake Champlain?**
- **Will changes be different in shallow and deep areas?**
- **How will this affect the frequency and severity of harmful algal blooms?**

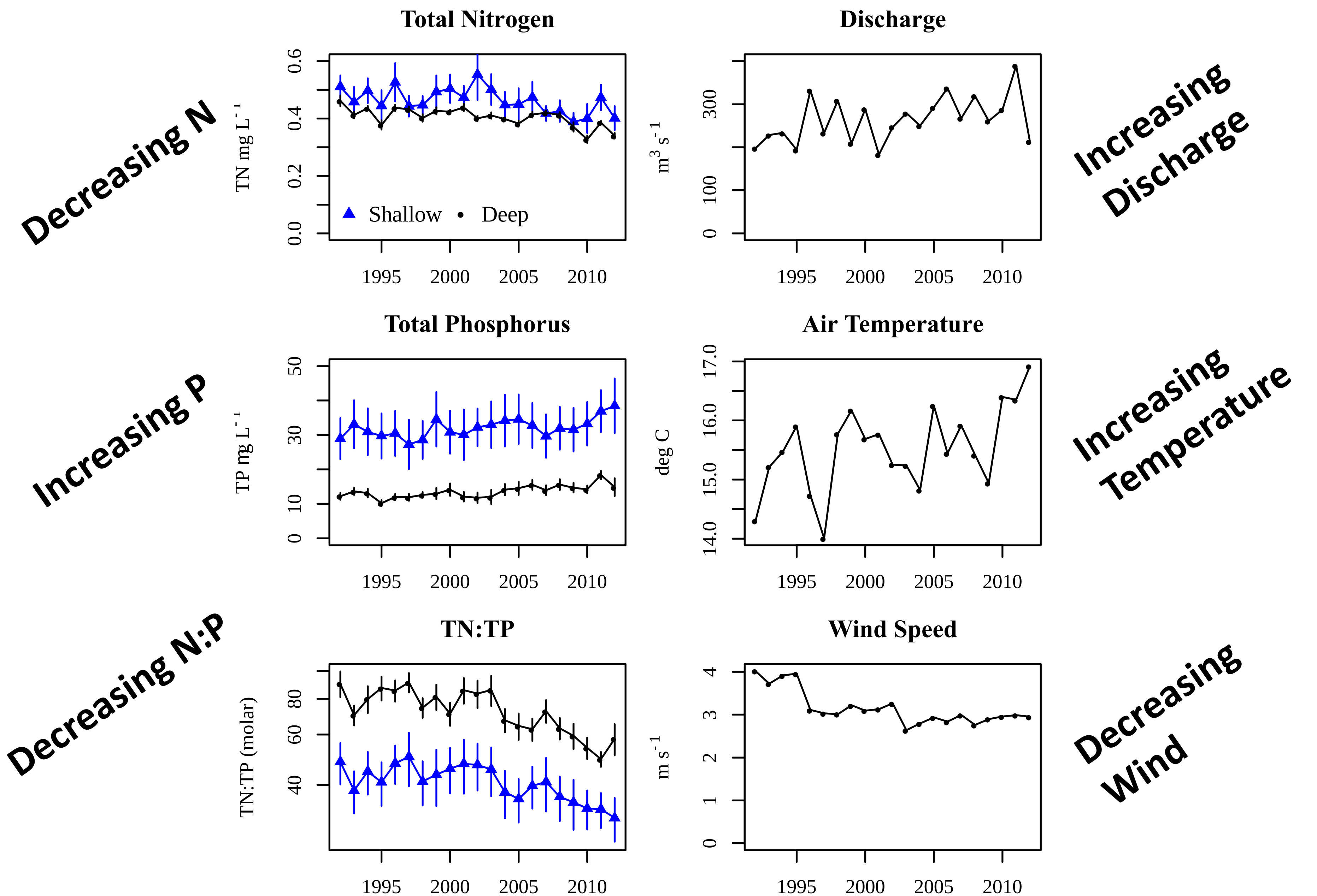
Lake Champlain LTMP



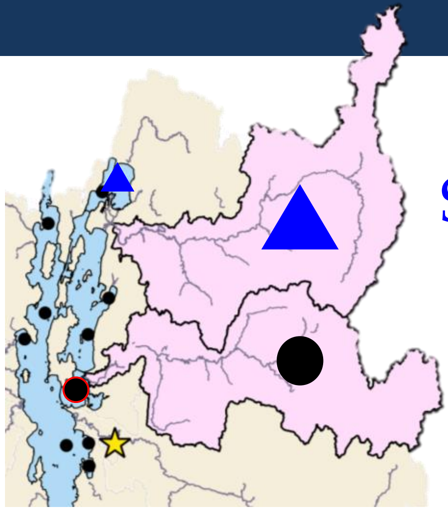
- **15 Sites**
- **1992-present**
- **Tributaries, too**

http://www.watershedmanagement.vt.gov/lakes/htm/lp_longterm.htm

Chapter 5: Long-Term Trends



Chapter 5: Effects of watershed loads and concentrations



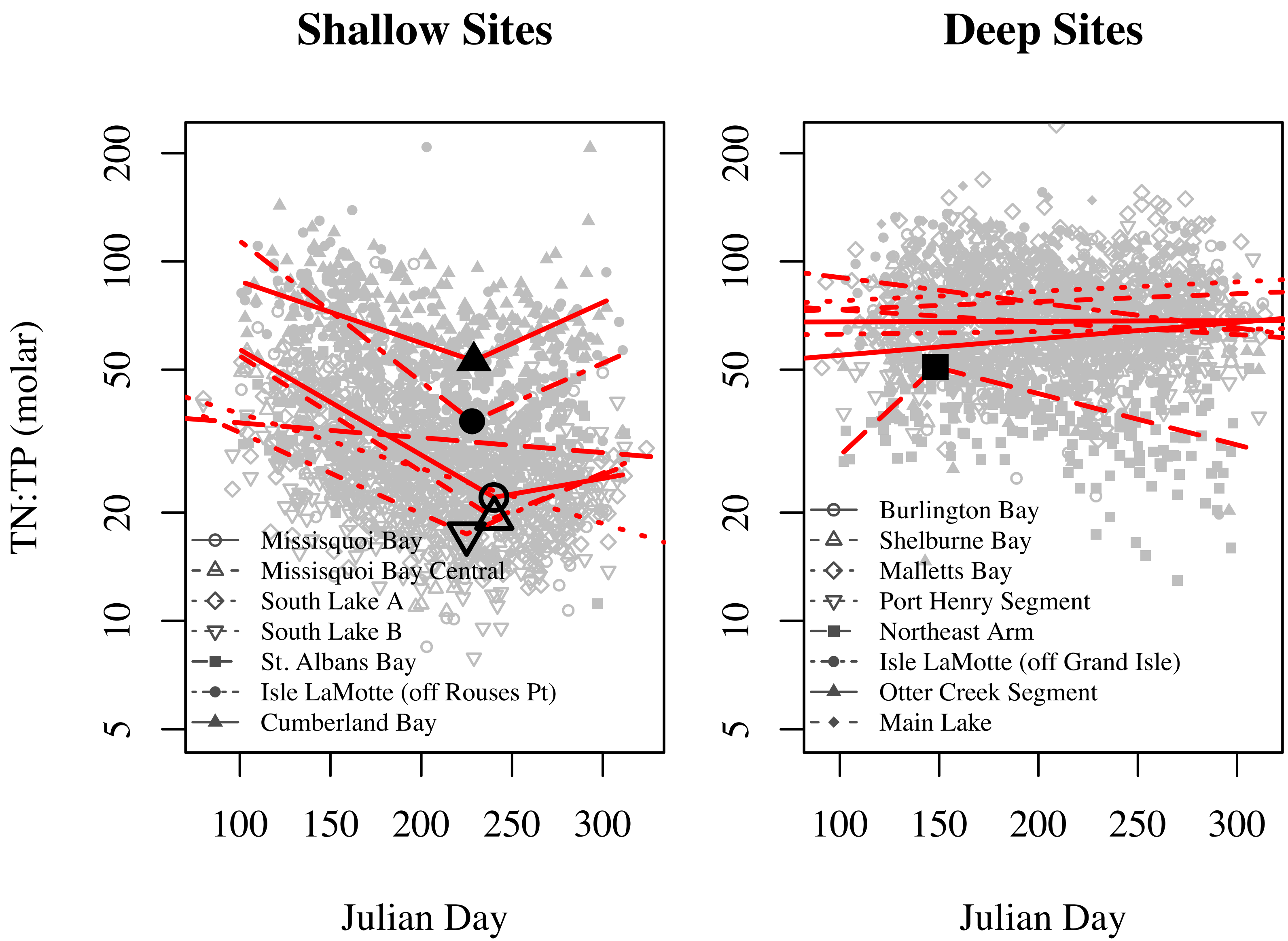
Shallow Site

Deep Site

No effect of TN:TP from rivers

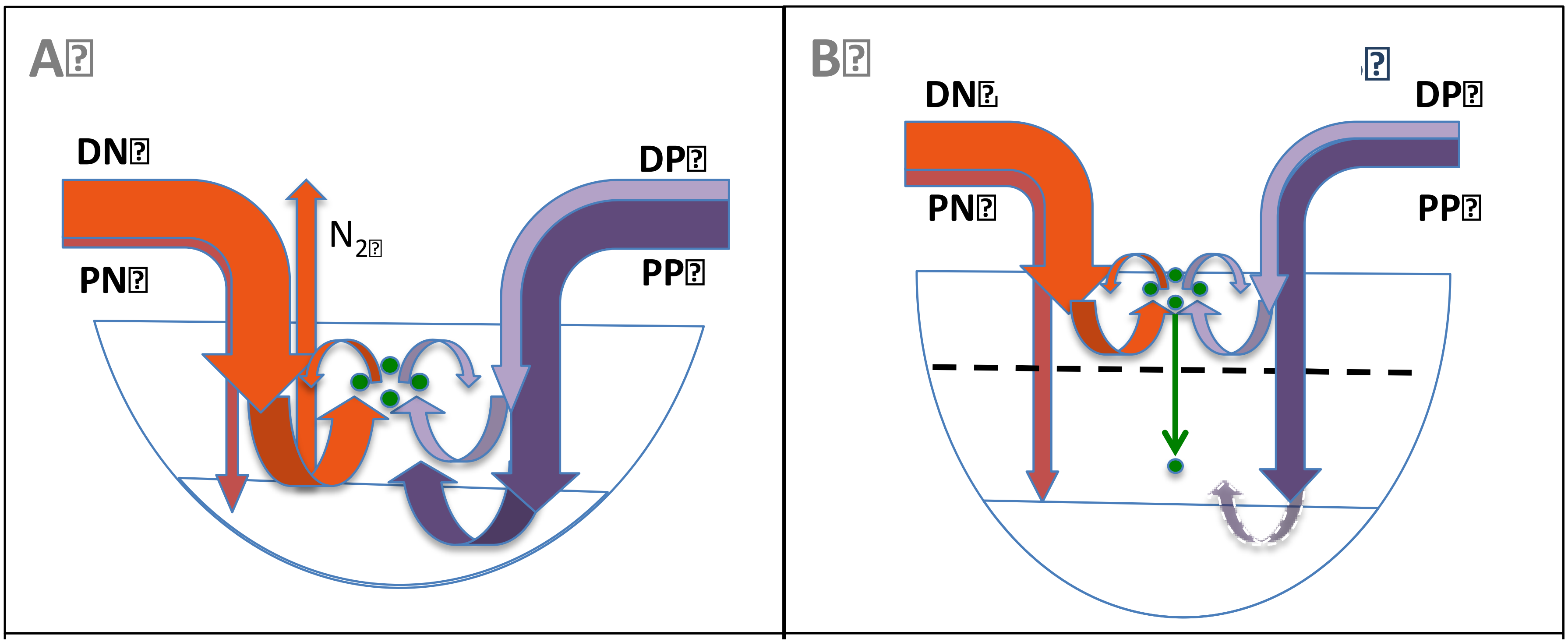
Strong effect of DN:DP from rivers in deep bay

Chapter 5: Seasonal dynamics in deep and shallow sites



Chapter 5: Conceptual Model

Shallow | Deep

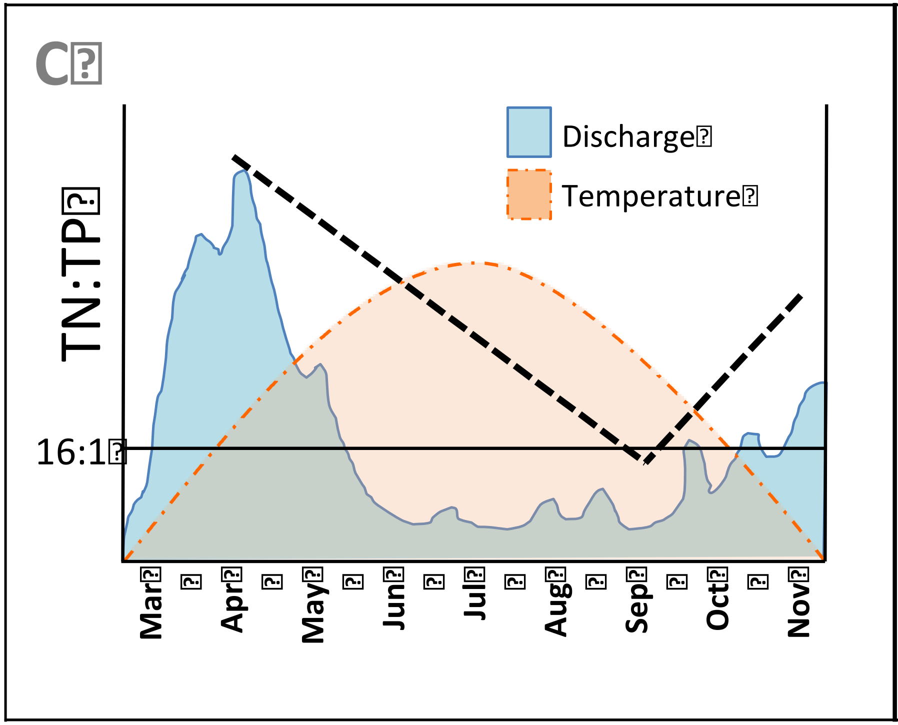


- Dissolved nutrients available immediately (in spring)
- Particulate nutrients available when Temp, O2 conditions allow

- Dissolved nutrients efficiently recycled
- Particulate nutrients mostly lost to the sediments

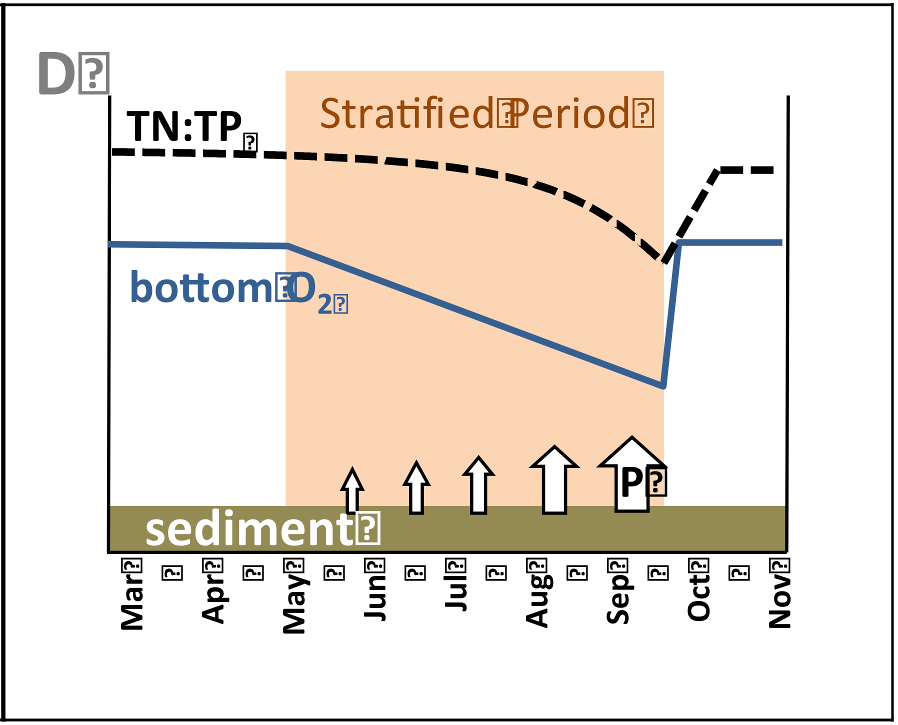
Chapter 5: Conceptual Model

Shallow



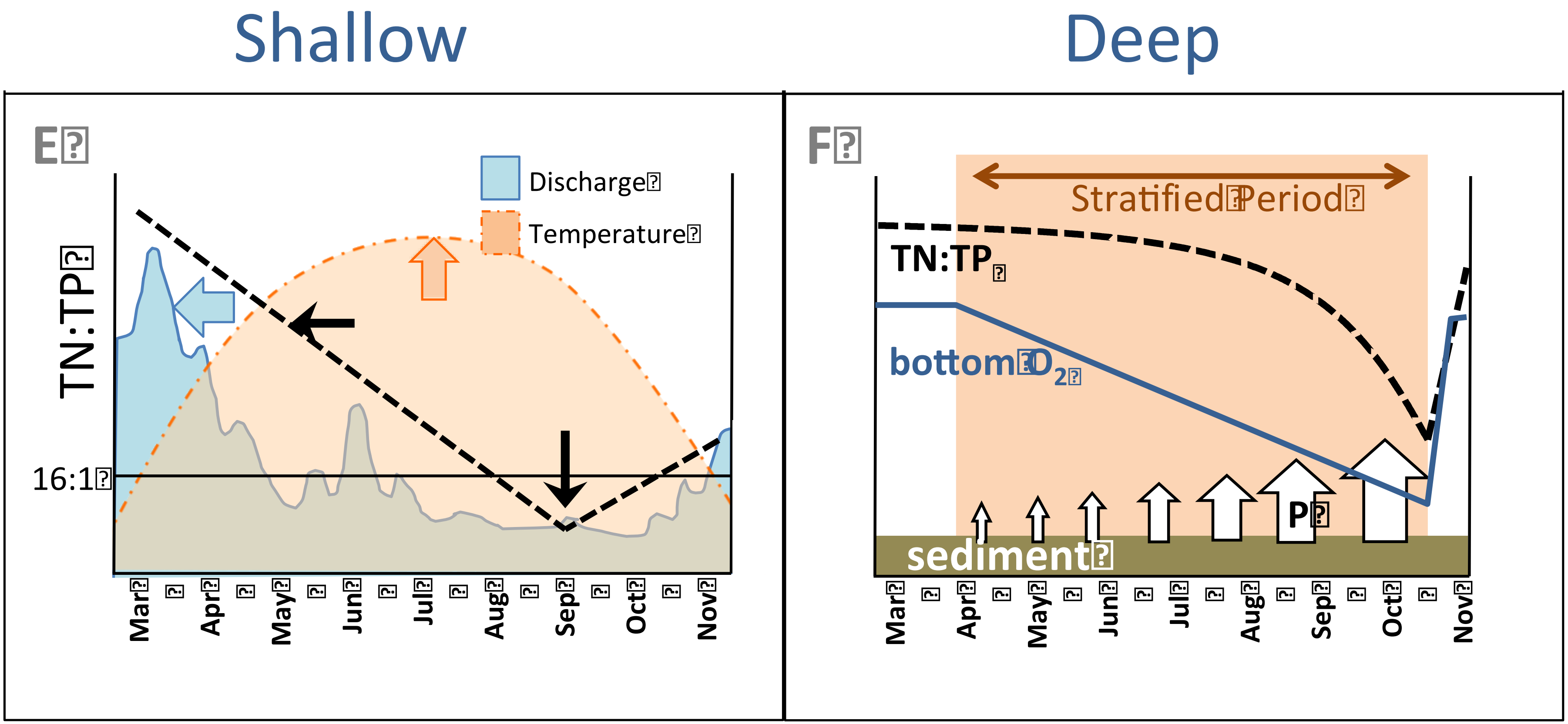
- TN:TP drops following decreasing N inputs and increasing temperatures during the summer
- TN:TP usually approaches Redfield ratio in late summer (Missisquoi)

Deep



- Bottom water O2 gradually declines during summer stratification due to sedimenting OM from epilimnion
- If O2 falls enough, pulse of P from sediment in late summer drops N:P

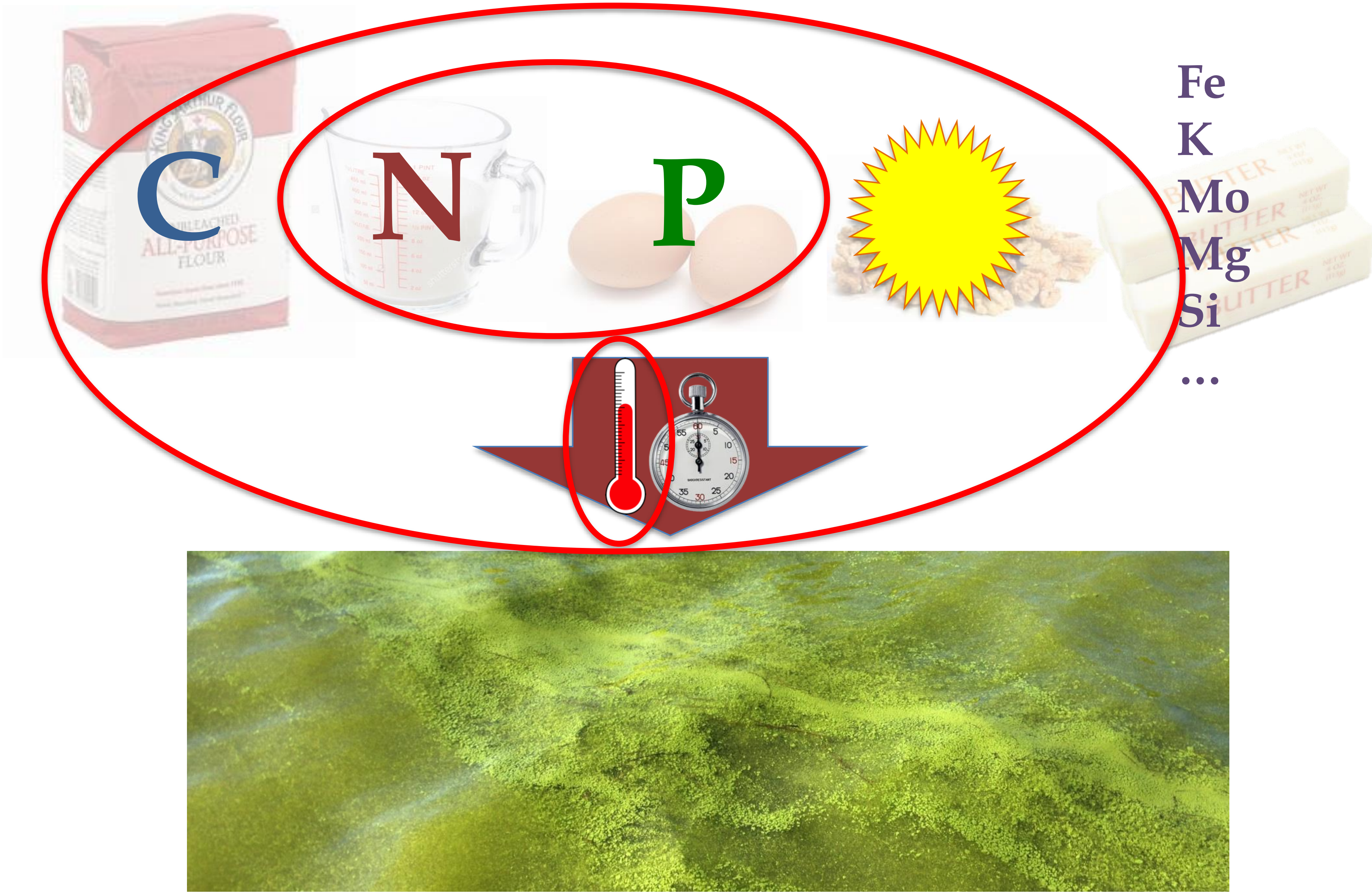
Chapter 5: Conceptual Model



- With climate change, peak discharge is earlier, and warm temps start earlier and last longer
- This leads to prolonged period of declining N:P

- Longer stratified period leads to more bottom O2 depletion and consequent P release in late summer (also more denitrification).

Background: Nutrients and Phytoplankton



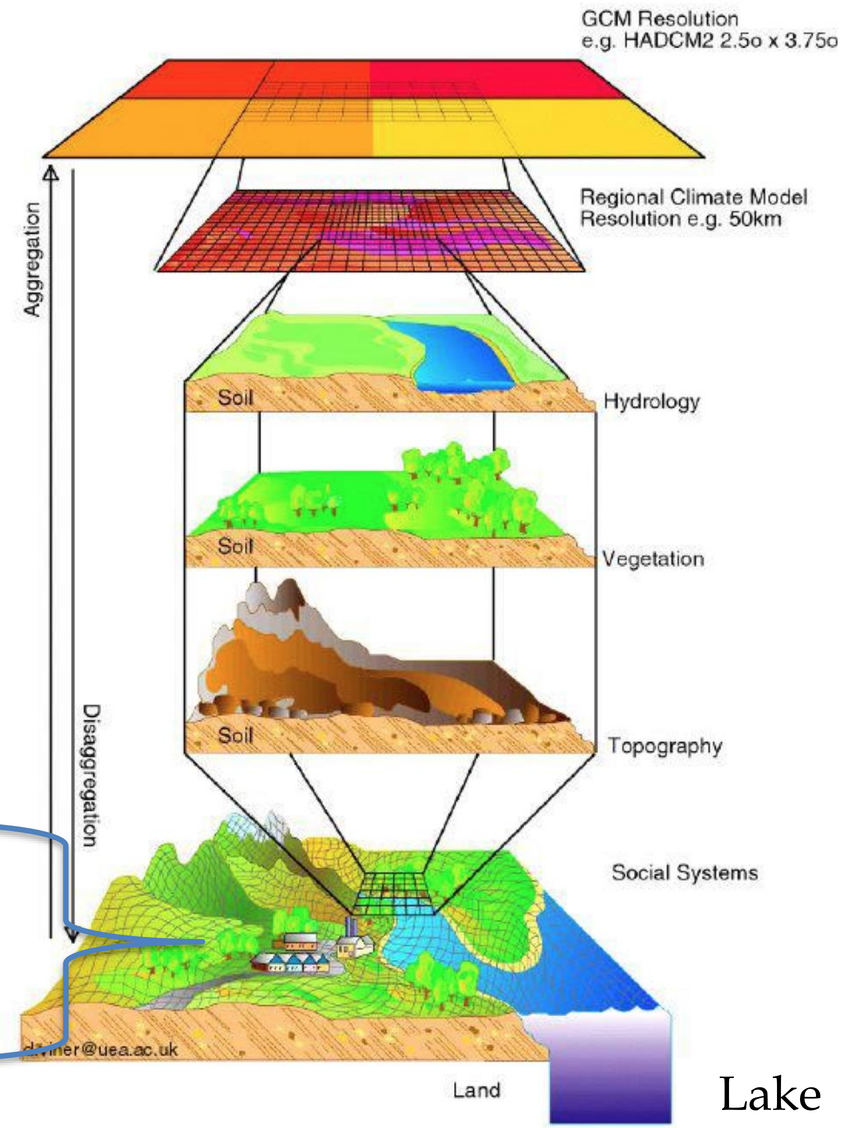
Chapter 6: Modeling Climate Change Impacts on Water Quality in Missisquoi Bay

Chapter 6: Integrated Assessment Model

Climate Downscaling

Hydrological Modeling

Land-Use and Governance Modeling

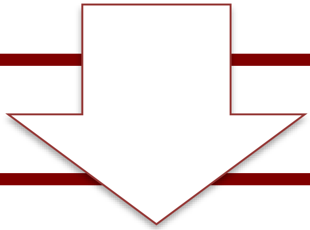


RACC
Research on Adaptation to Climate Change

Chapter 6: Lake Modeling Framework

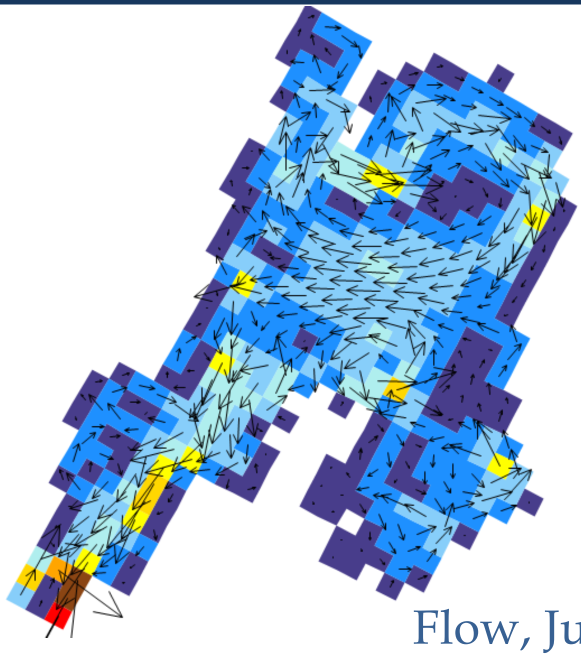
Environmental Fluid Dynamics Code (EFDC)

- 3-D hydrodynamic model
- Water temperature, flow patterns

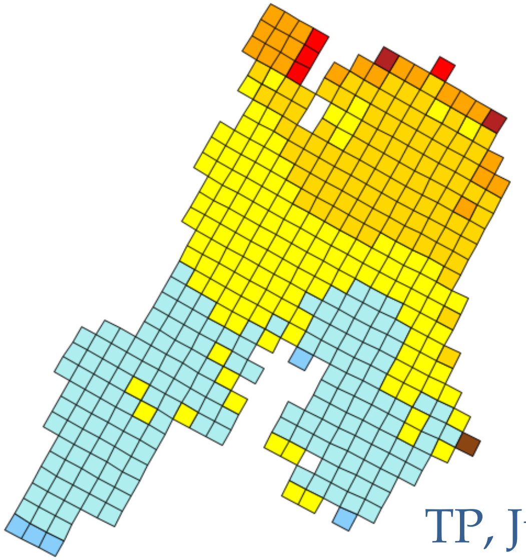


Row-Column AESOP (RCA)

- Water Quality Model
- Sediment diagenesis

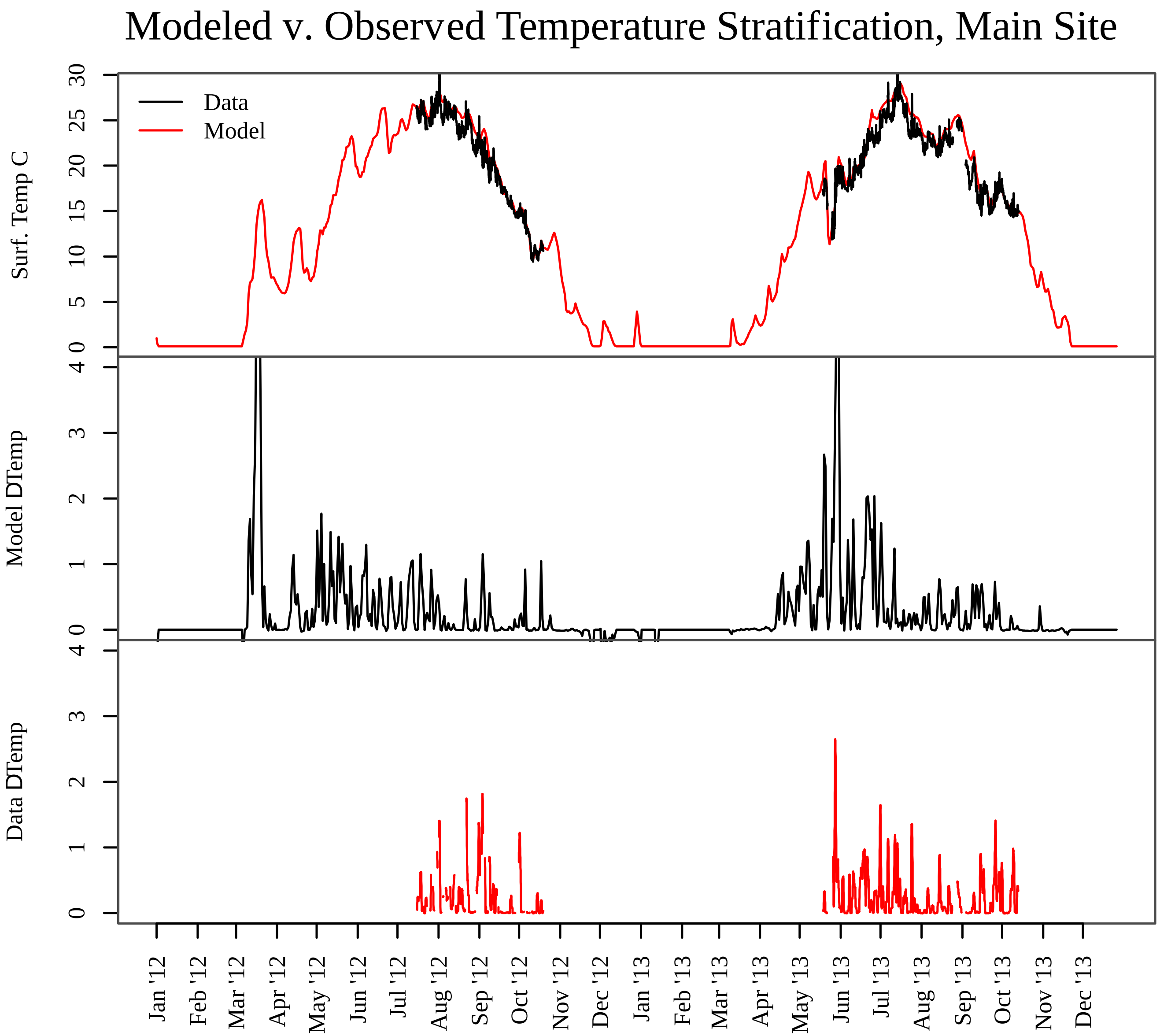


Flow, July 2012

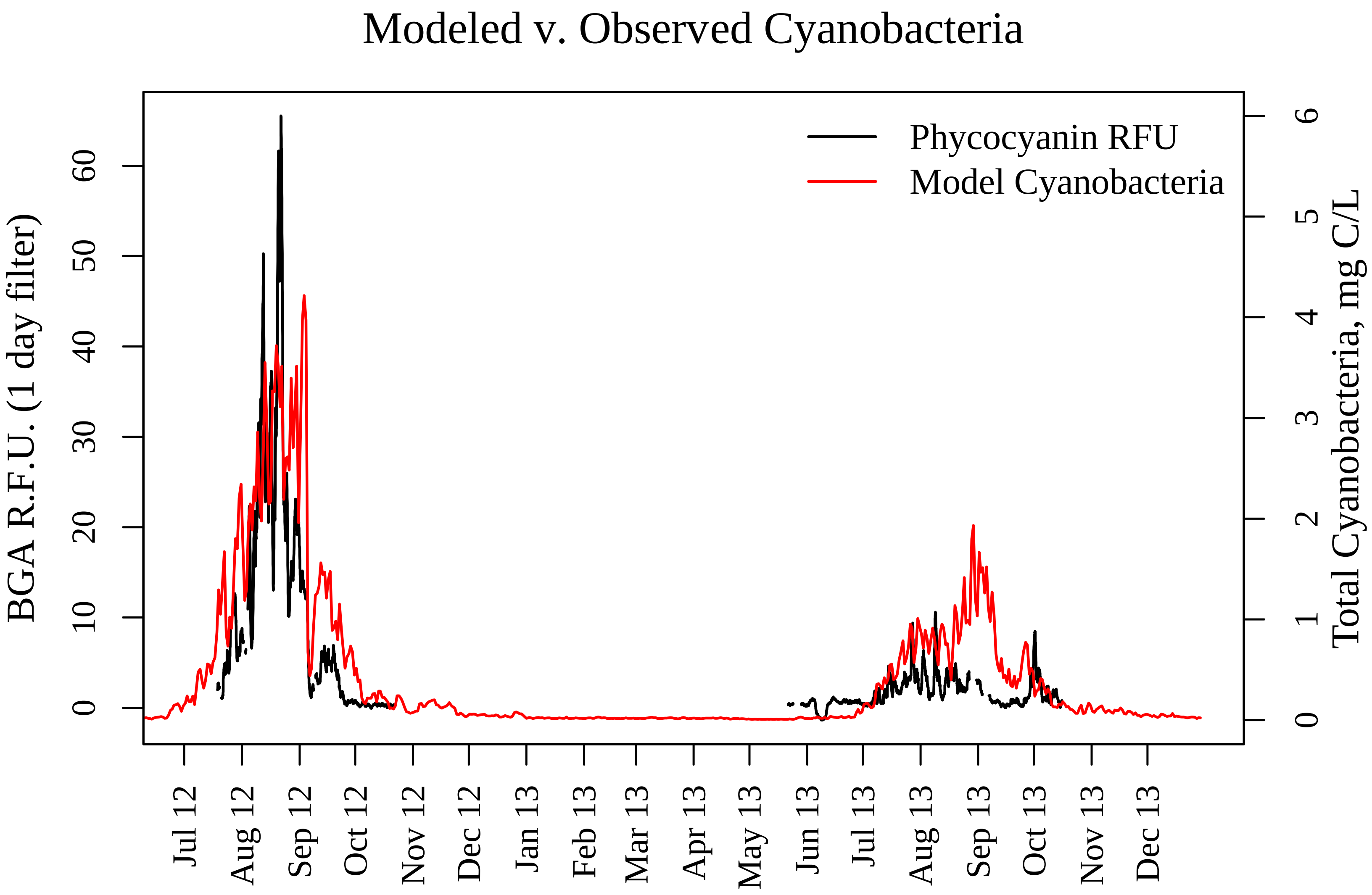


TP, July 2012

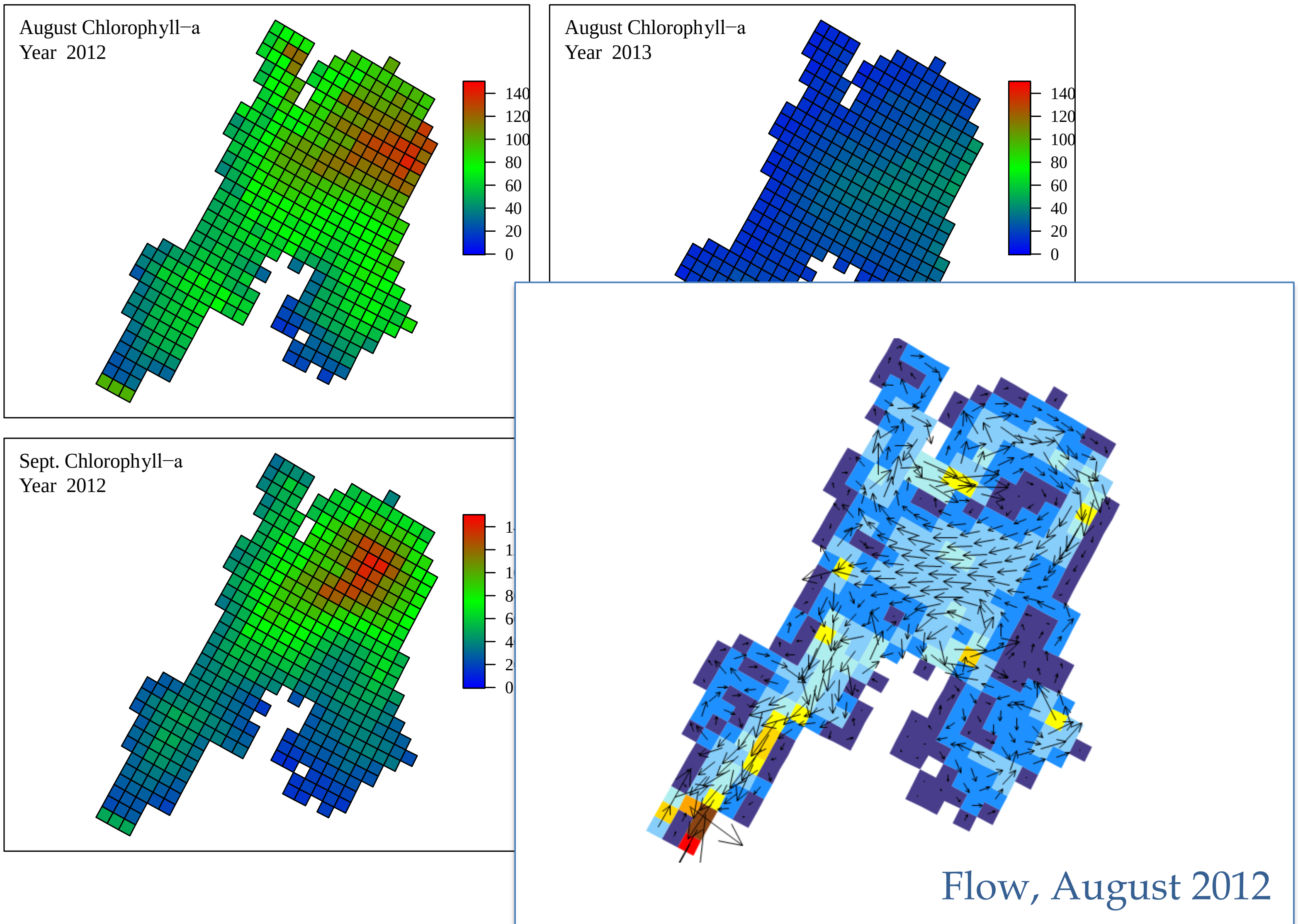
Chapter 6: High-frequency calibration



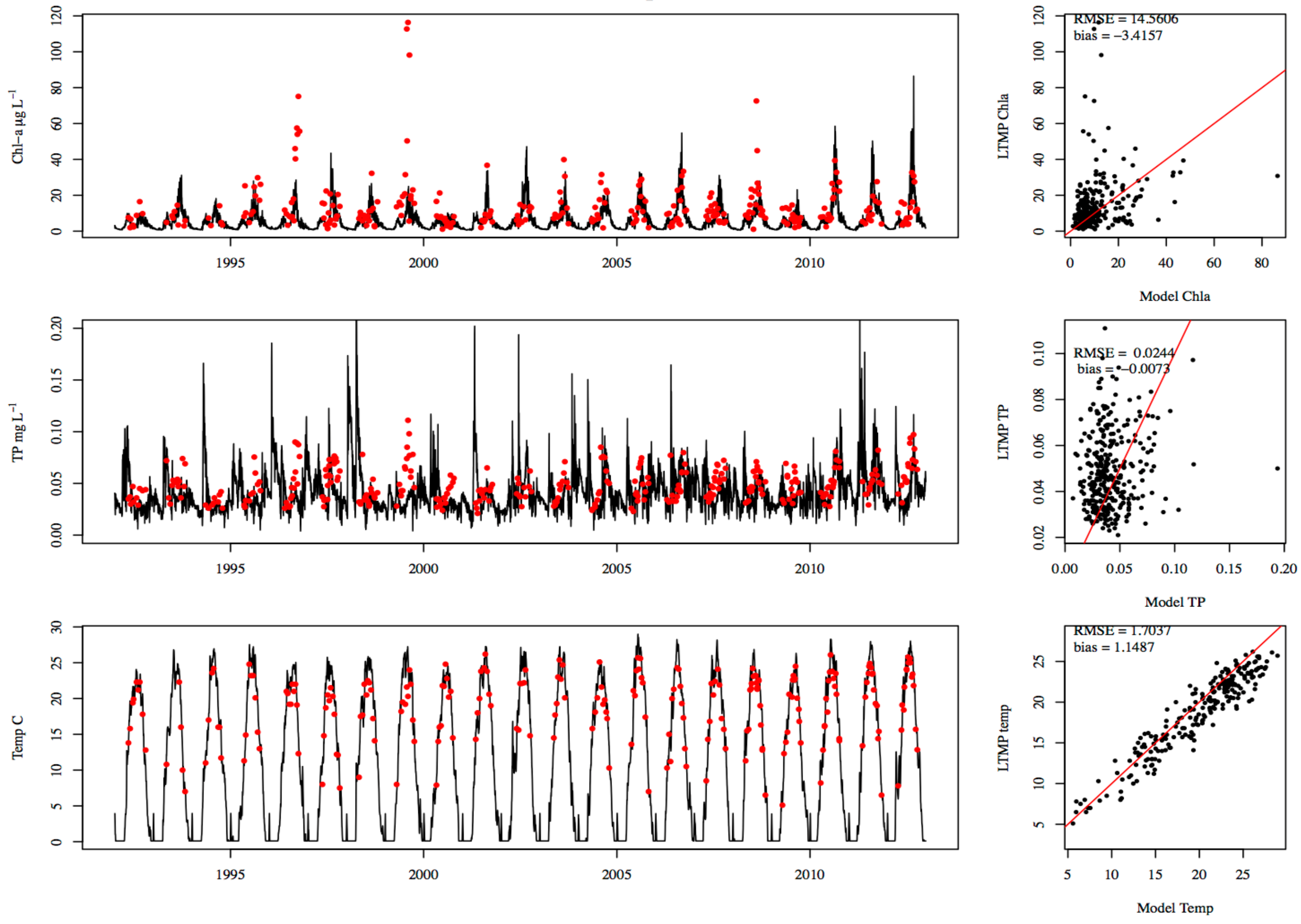
Chapter 6: High-frequency calibration



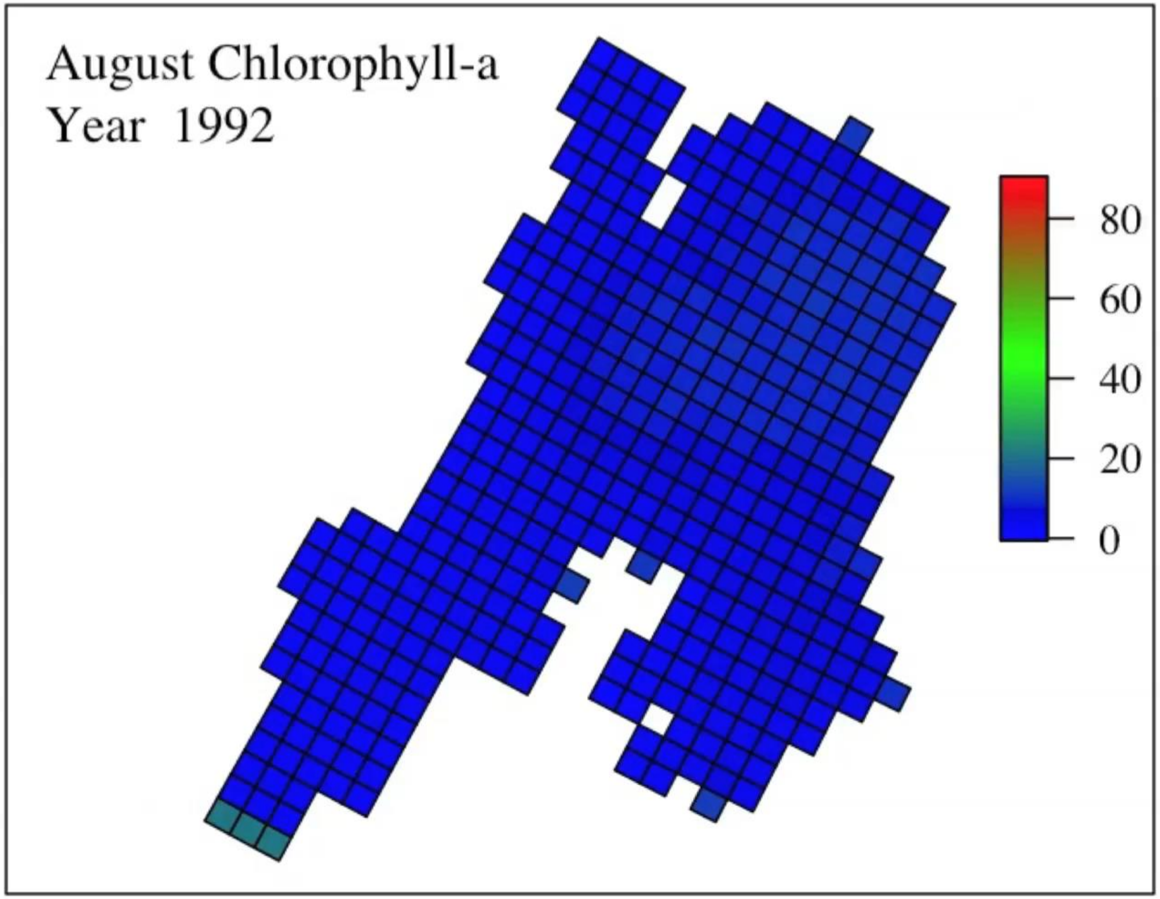
Chapter 6: High-frequency calibration



Chapter 6: Long-term calibration



Chapter 6: Long-term calibration

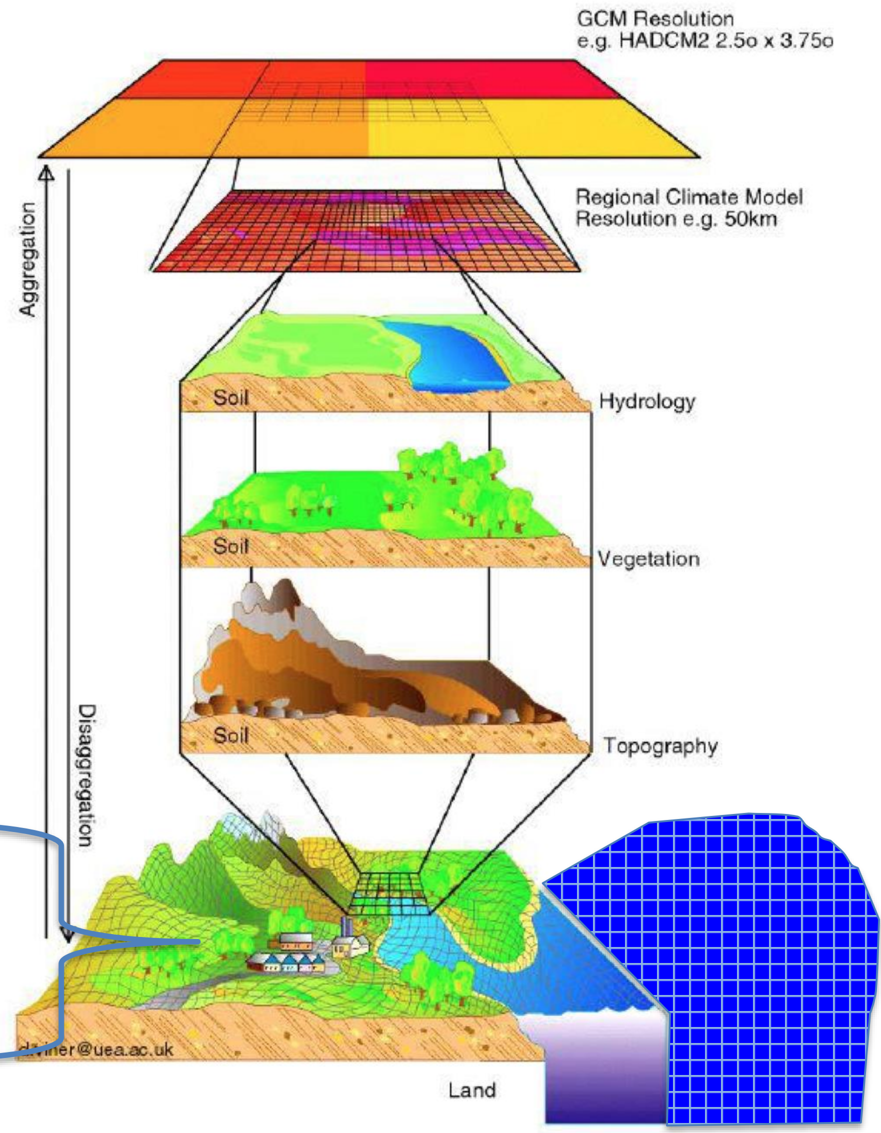


Chapter 6: Integrated Assessment Model

Climate Downscaling

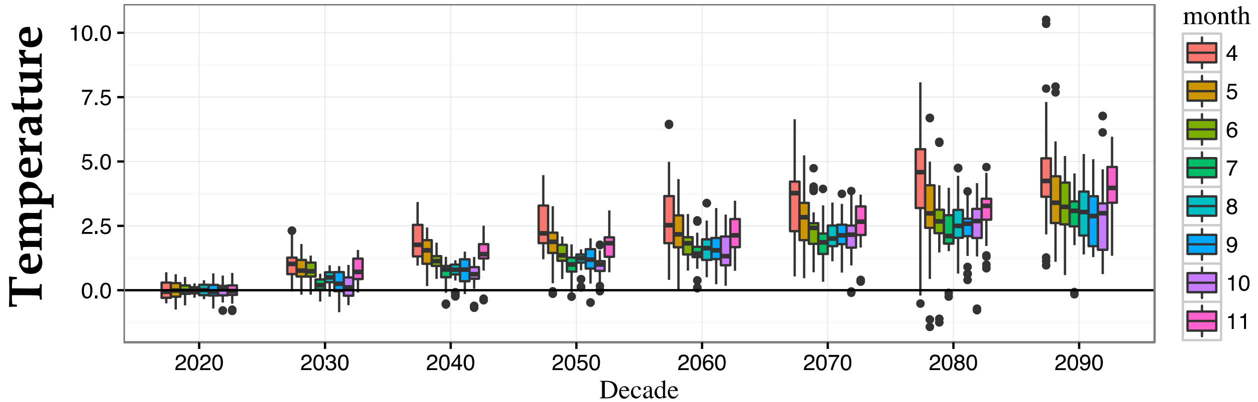
Hydrological Modeling

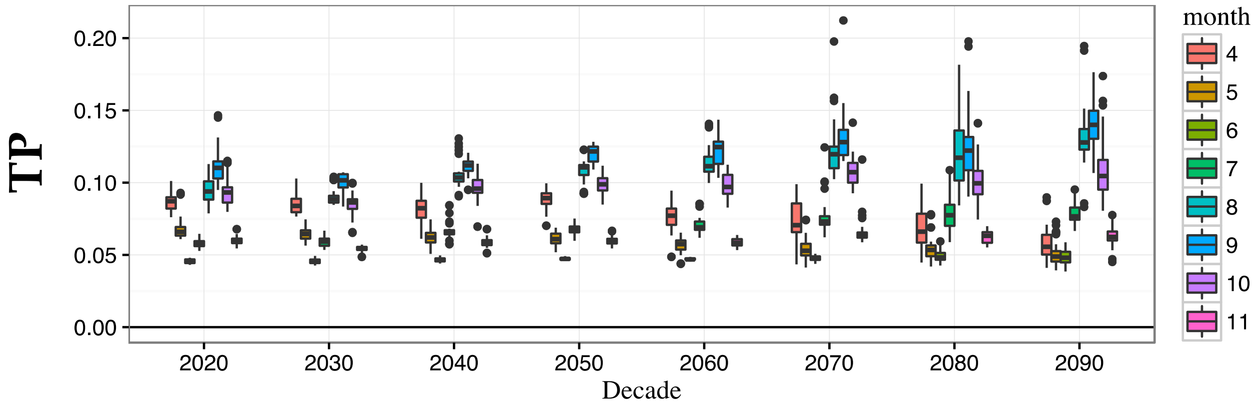
Land-Use and Governance Modeling

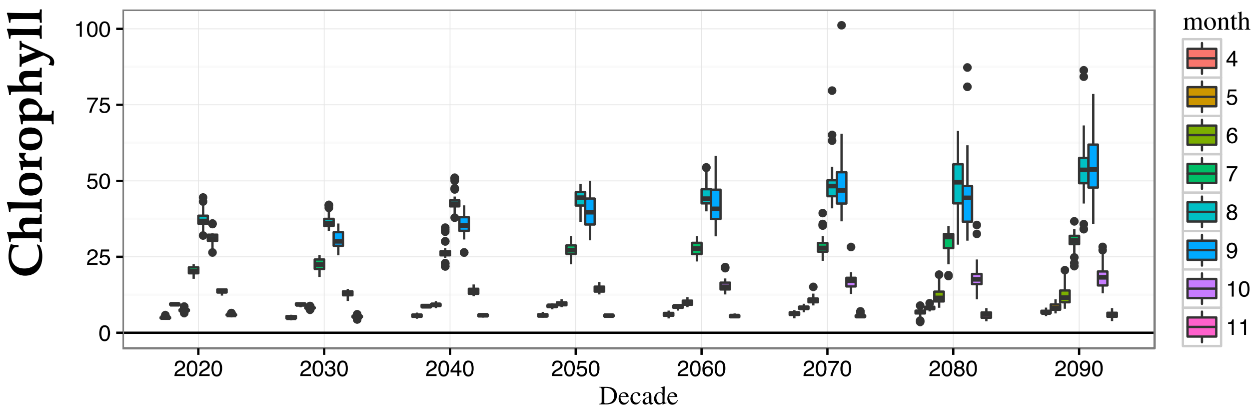


RACC
Research on Adaptation to Climate Change

Chapter 6: Future Climate Scenarios







What have we learned?

- Multiple resources con
  bloom processes at mu
- During bloom periods,
  critical for controlling b
- Long-term changes are
  inputs and climate tren

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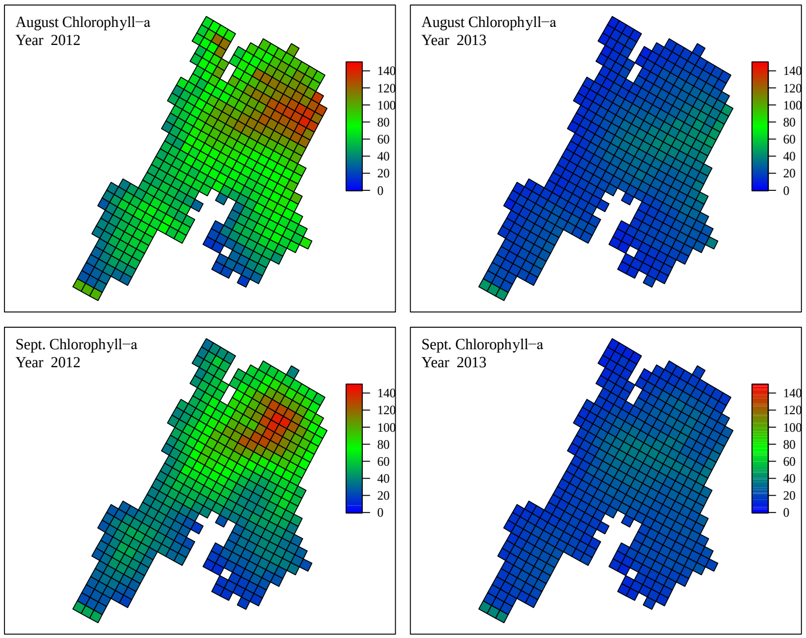

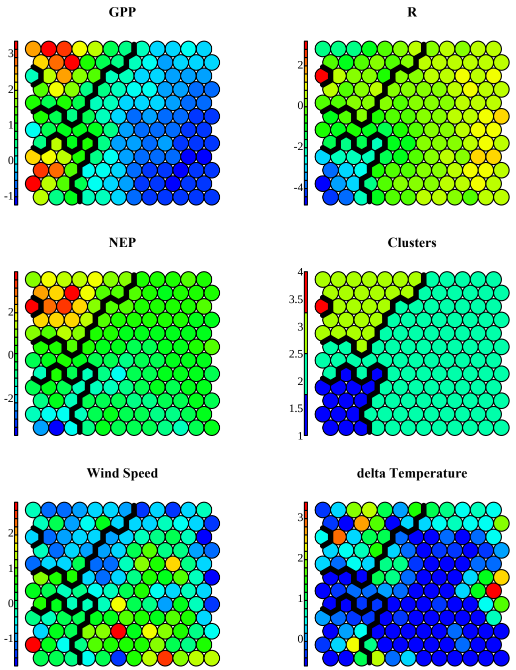

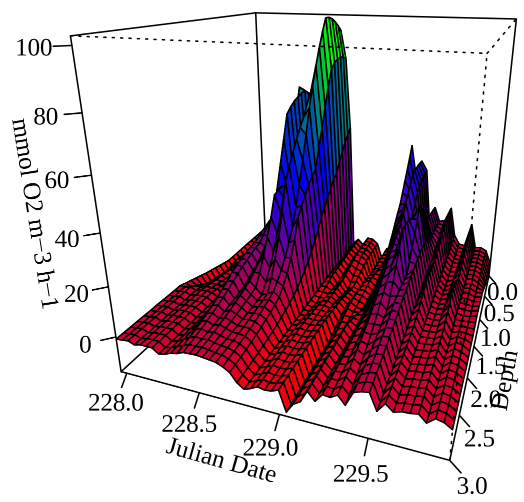

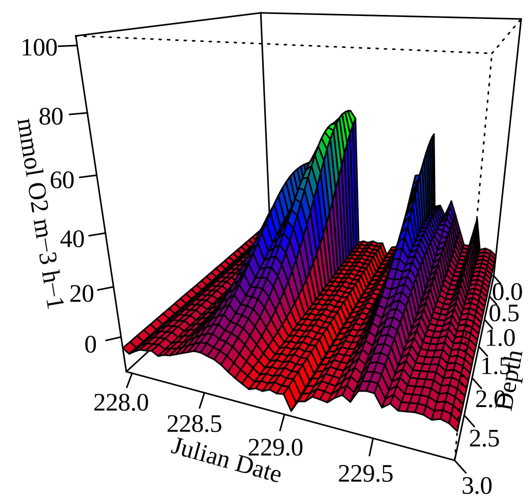

What can we do with it?

- Climate drivers are difficult to control, but their effects must be taken into account when planning water quality management.
- Increasing temperature is likely to make it more difficult to reach water quality targets by affecting internal nutrient cycling.
- Nutrient loading targets may be more effective if we focus on specific nutrient fractions (e.g., dissolved and reactive P).

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