Understanding Lake Recovery from Historical Acidification: The Important Role of Browning

Black River Watershed Conference June 2-3, 2025

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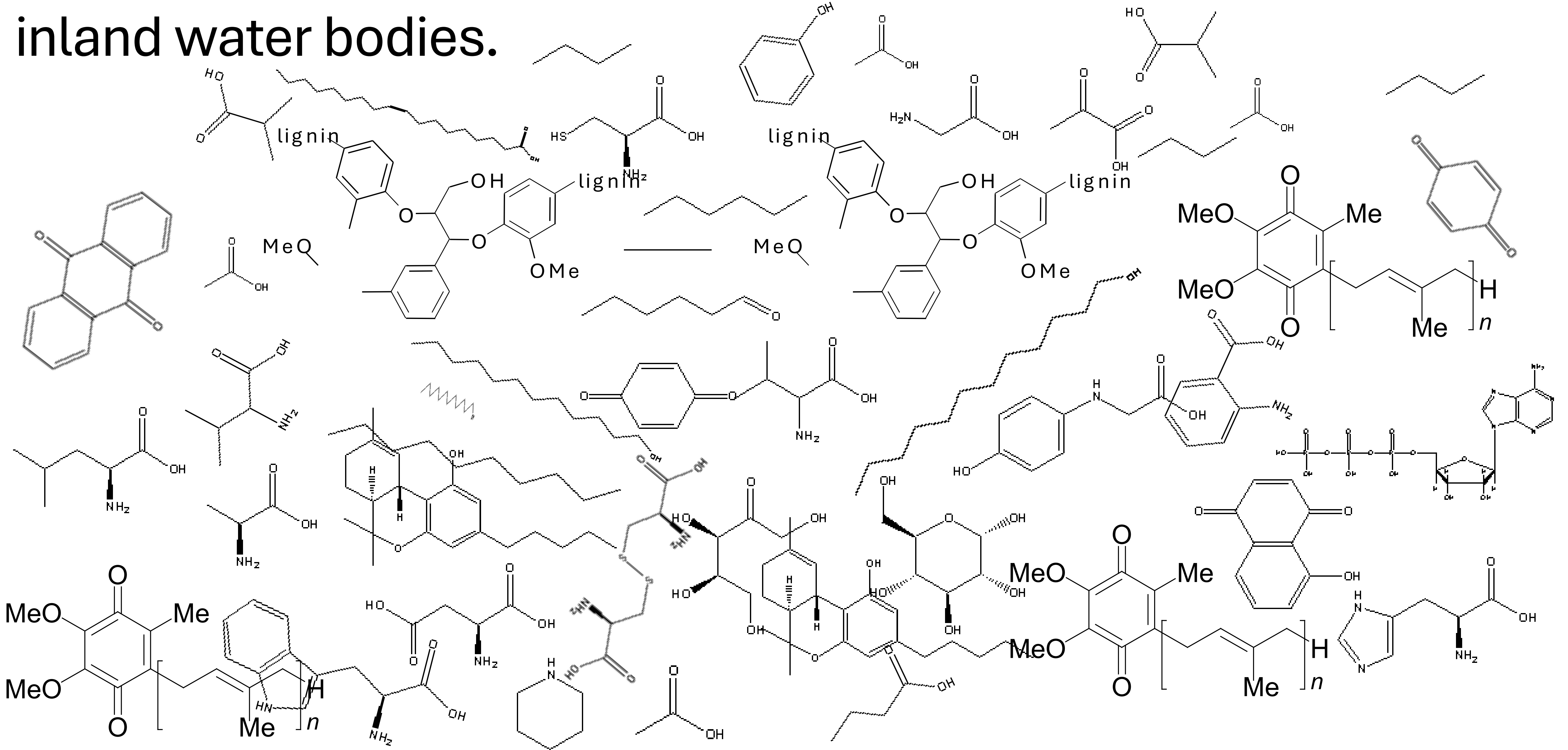
What is lake browning?

The process of increasing dissolved organic matter (DOM) in lakes and other waterbodies, including throughout upstate New York.

OK, but what is dissolved organic matter?

Dissolved organic matter is a heterogeneous pool of carbon-based molecules. DOM is often the largest pool of carbon in inland water bodies.



Dissolved Organic Matter (DOM)

Operationally-defined as the material from living (or previously living) things which passes through a filter

Size: mm

µm

nm

Particulate OM

DOM

colloidal

truly dissolved

zooplankton

phytoplankton

bacteria

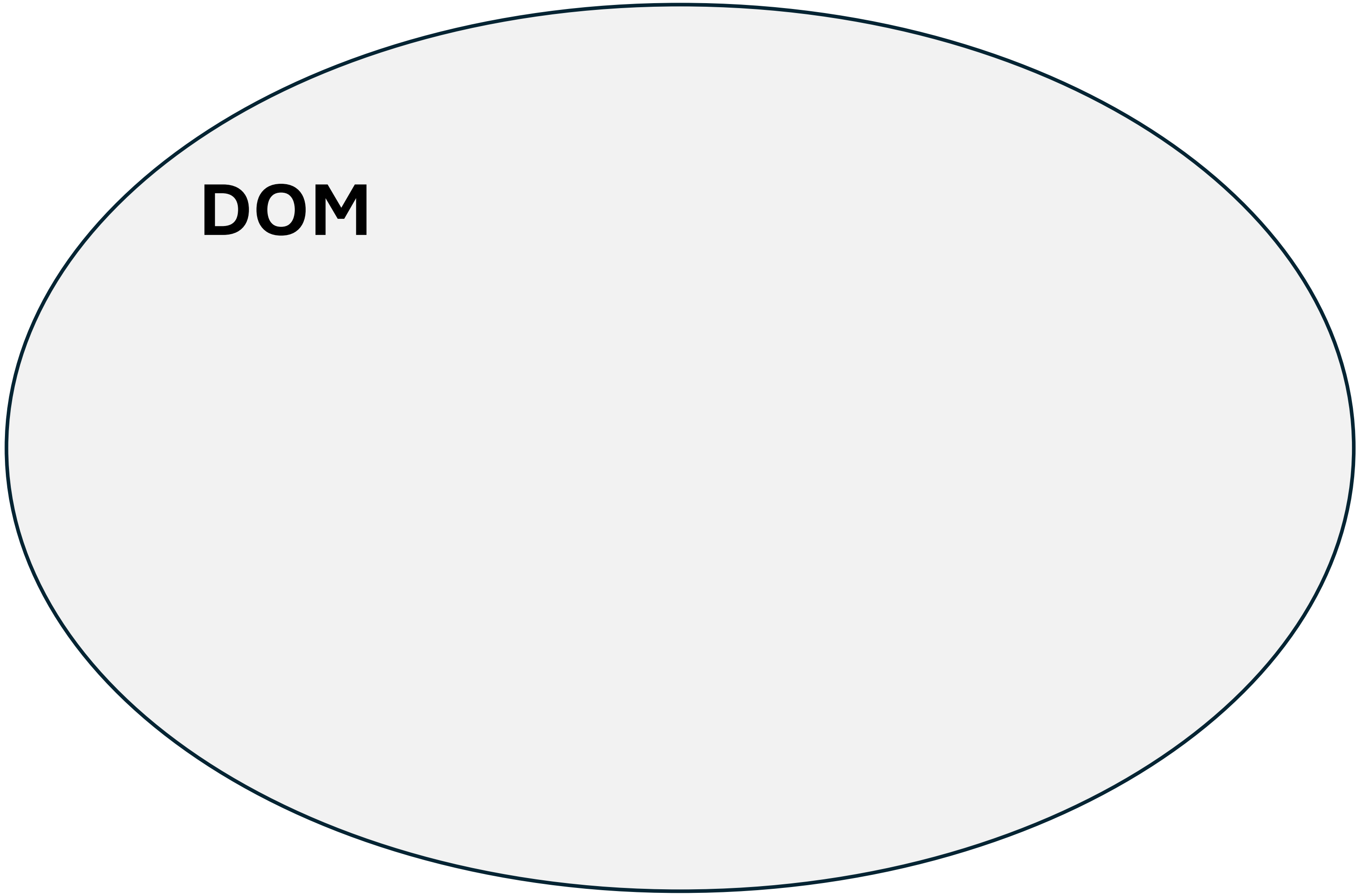
viruses

macromolecules

Adapted from Azam and Malfatti (2007) Nat. Rev. Microbiol.

So many acronyms…

- DOM = dissolved organic matter

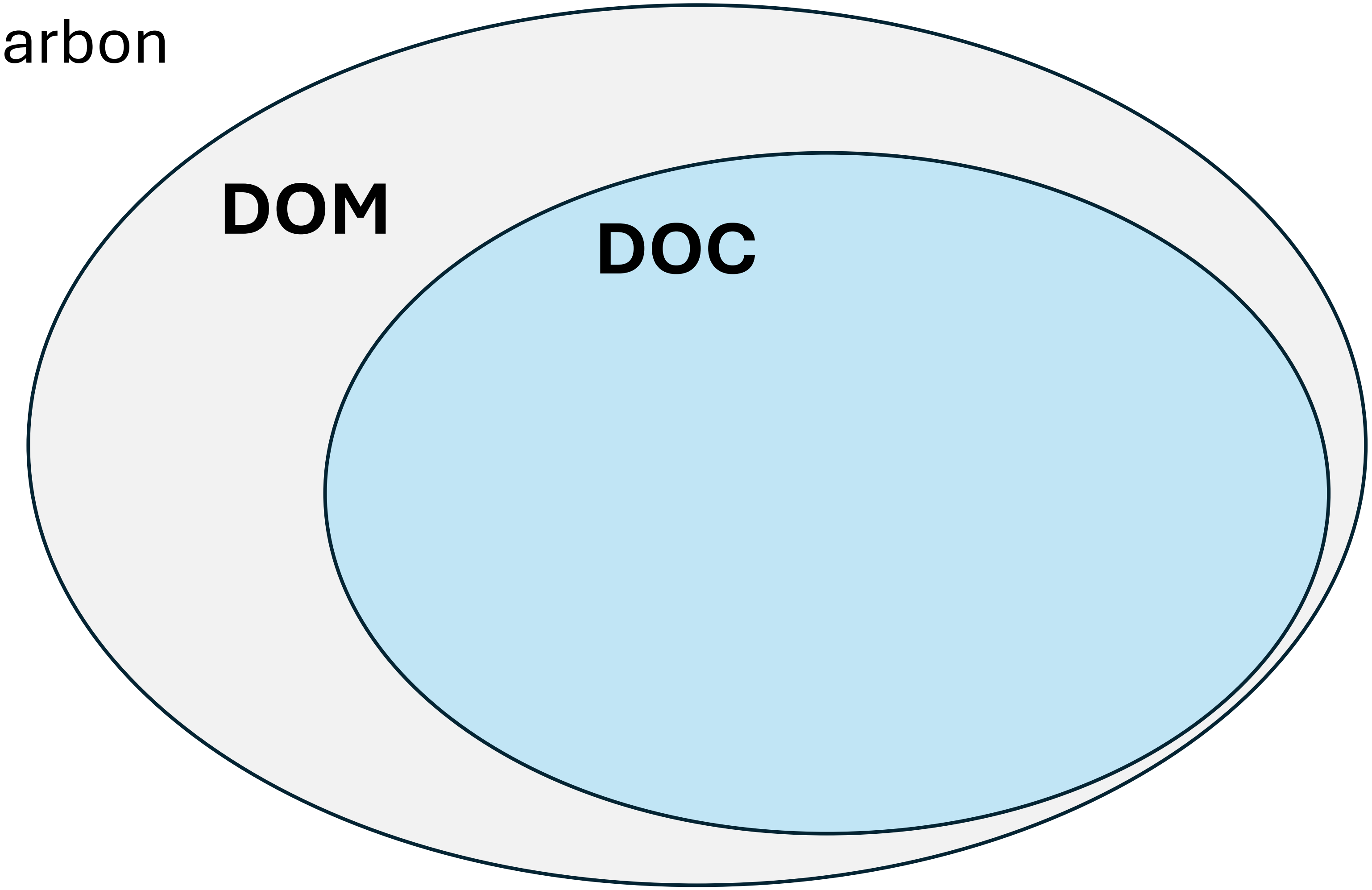


DOM is often the largest pool of organic matter in inland waters.

Inland waters play a key role in global carbon cycling because of DOM.

So many acronyms…

- DOM = dissolved organic matter
- DOC = dissolved organic carbon

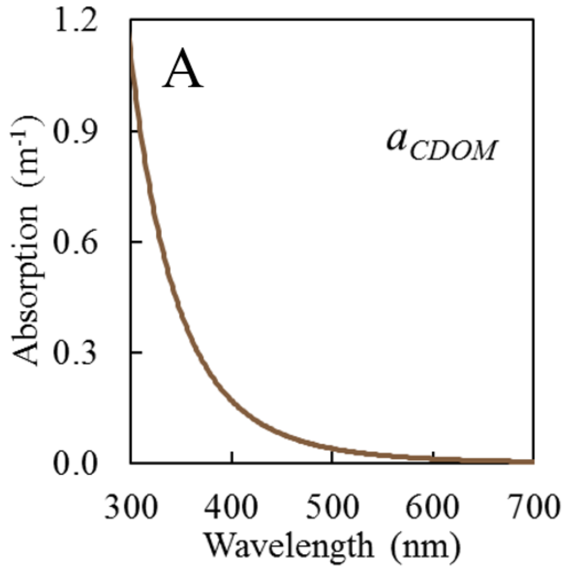


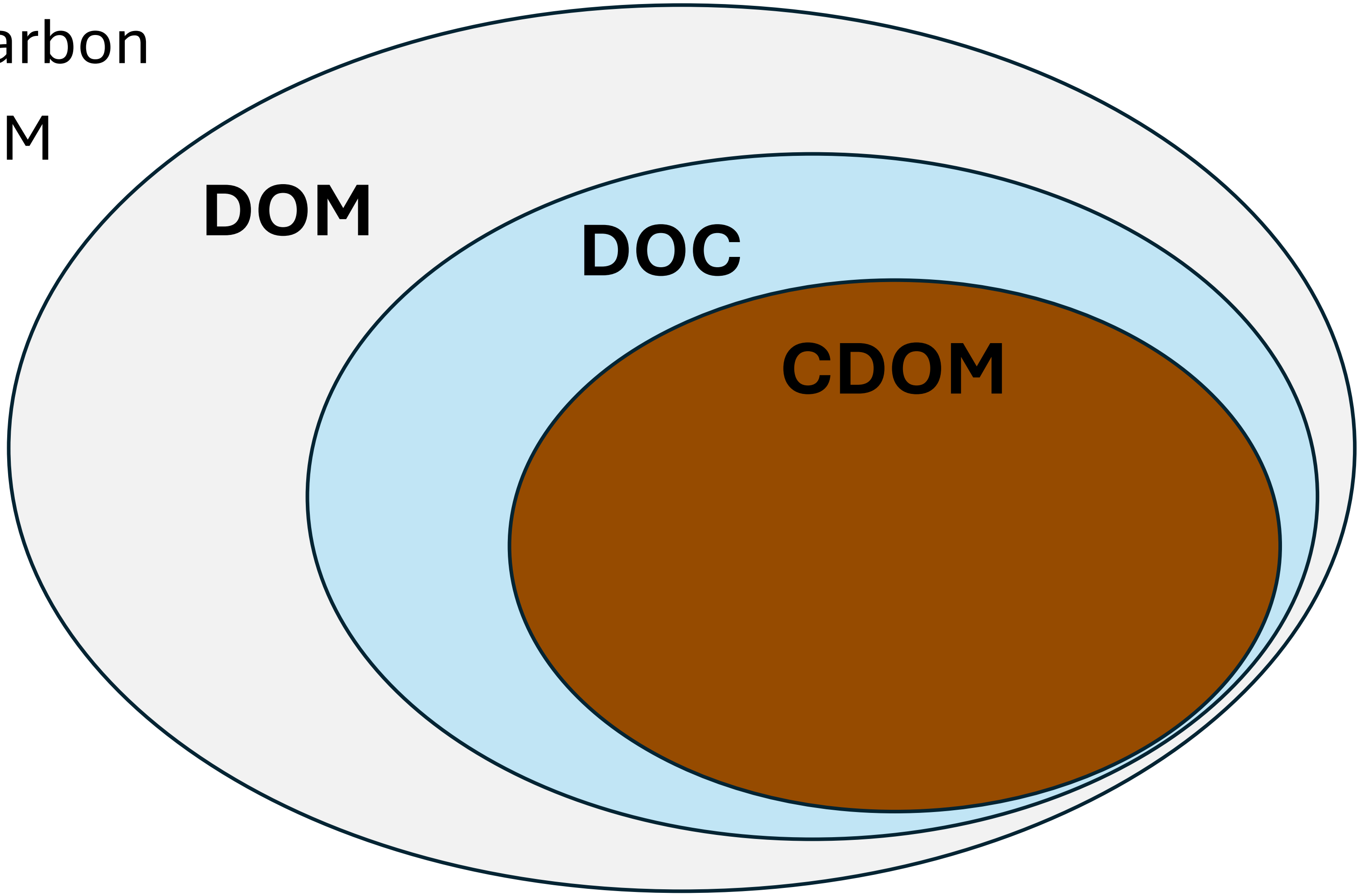
DOC is often how DOM is measured.

So many acronyms...

- DOM = dissolved organic matter
- DOC = dissolved organic carbon
- CDOM = chromophoric DOM

CDOM is what we see. It absorbs light (and heat).

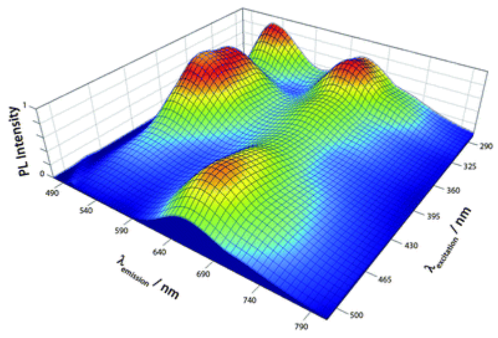


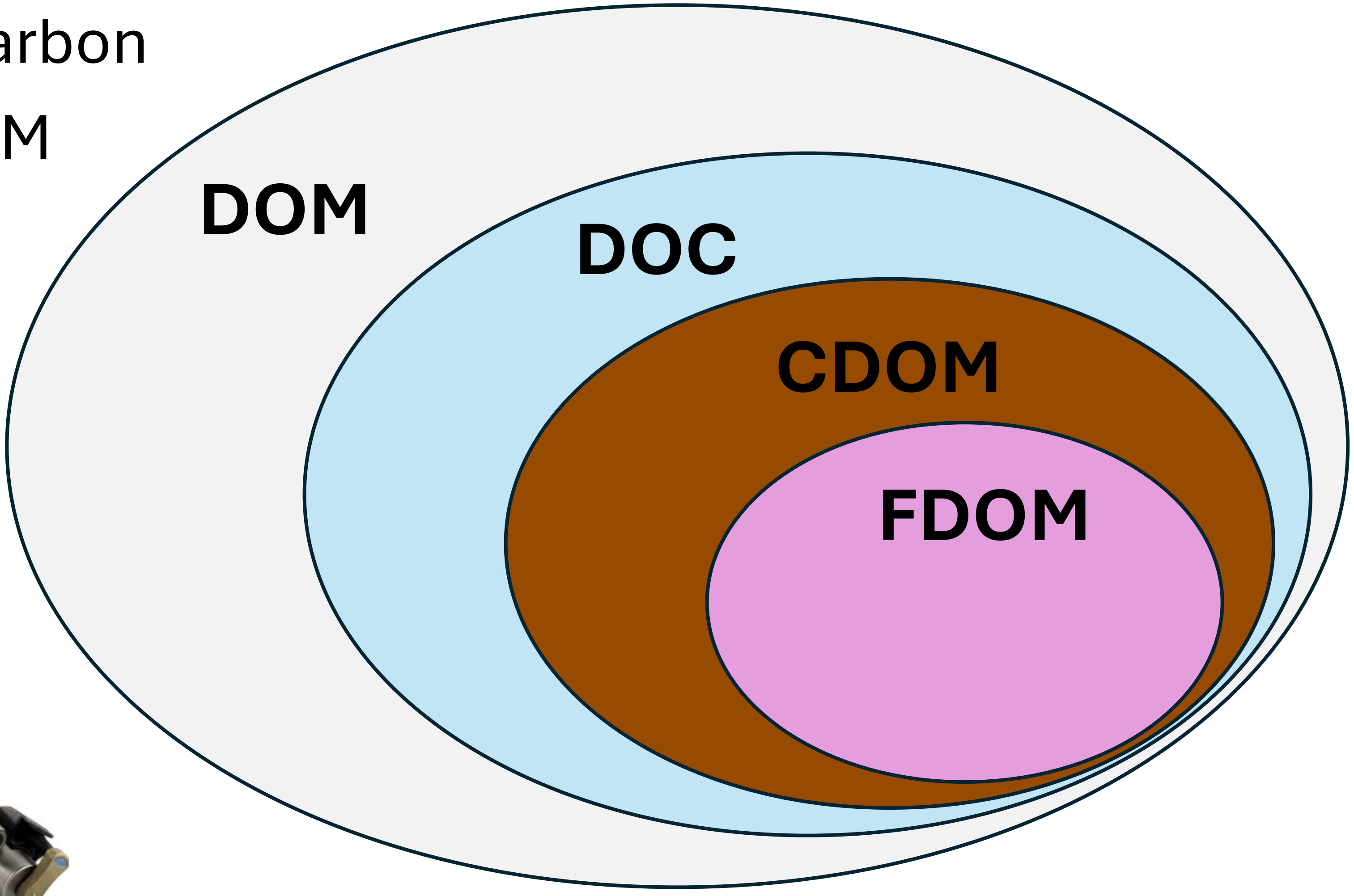


So many acronyms…

- DOM = dissolved organic matter
- DOC = dissolved organic carbon
- CDOM = chromophoric DOM
- FDOM = fluorescent DOM

FDOM is what in situ sensors can measure.





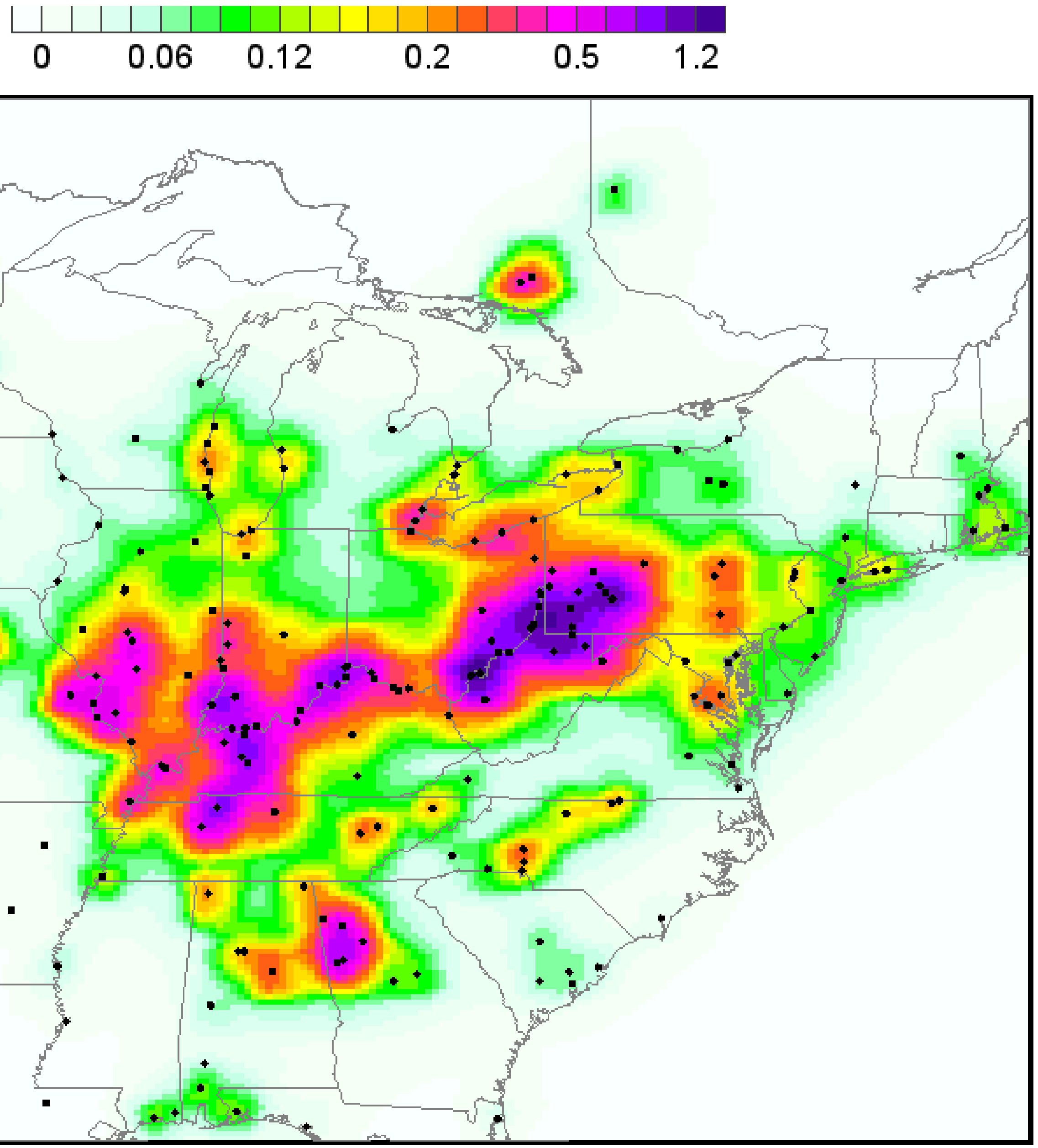
DOM source affects its characteristics and how it interacts with other substances.

- **Terrestrial plants**
- **Microbes (bacteria, algae)**
- Man-made (organic pollutants)

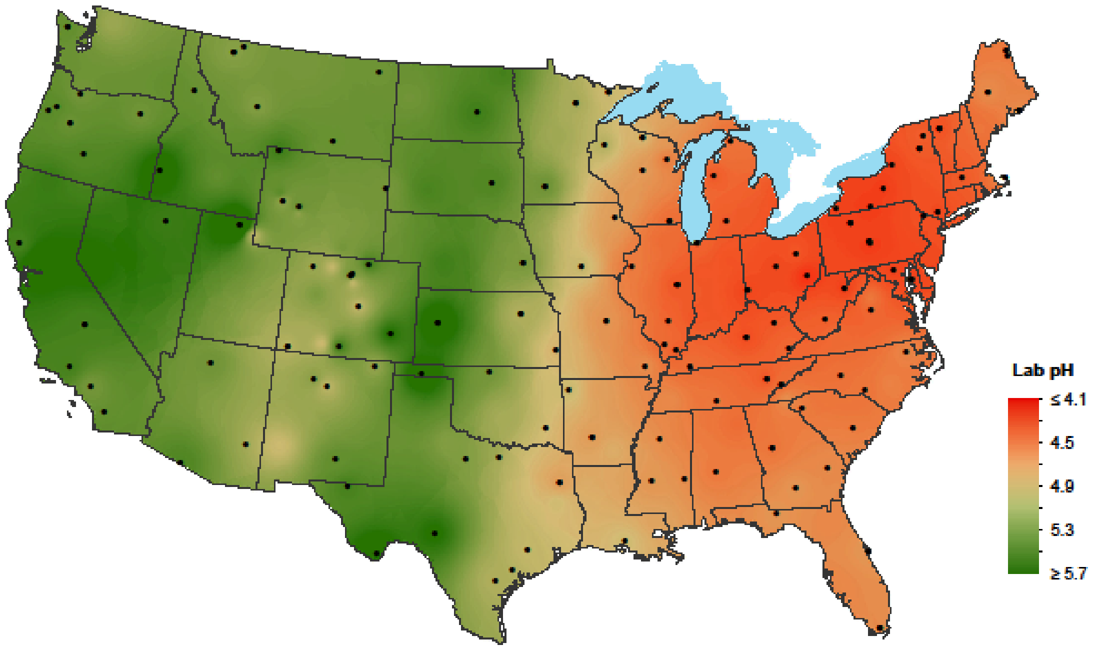
Why is lake browning occurring?
What is causing it and what are its effects?

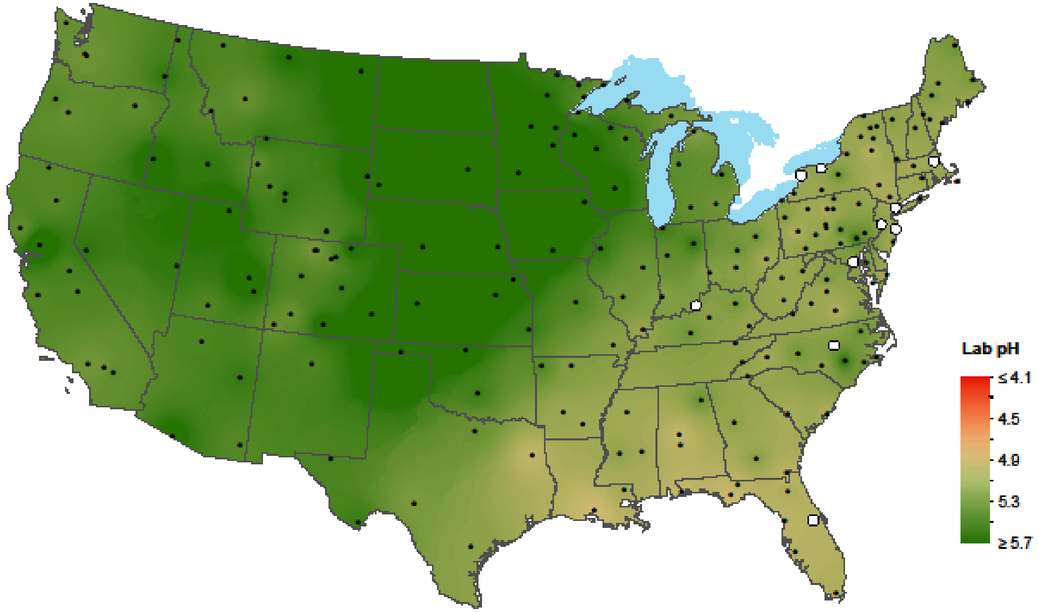
Sulfur Dioxide concentration

1980



Precipitation pH, 1985 vs 2016





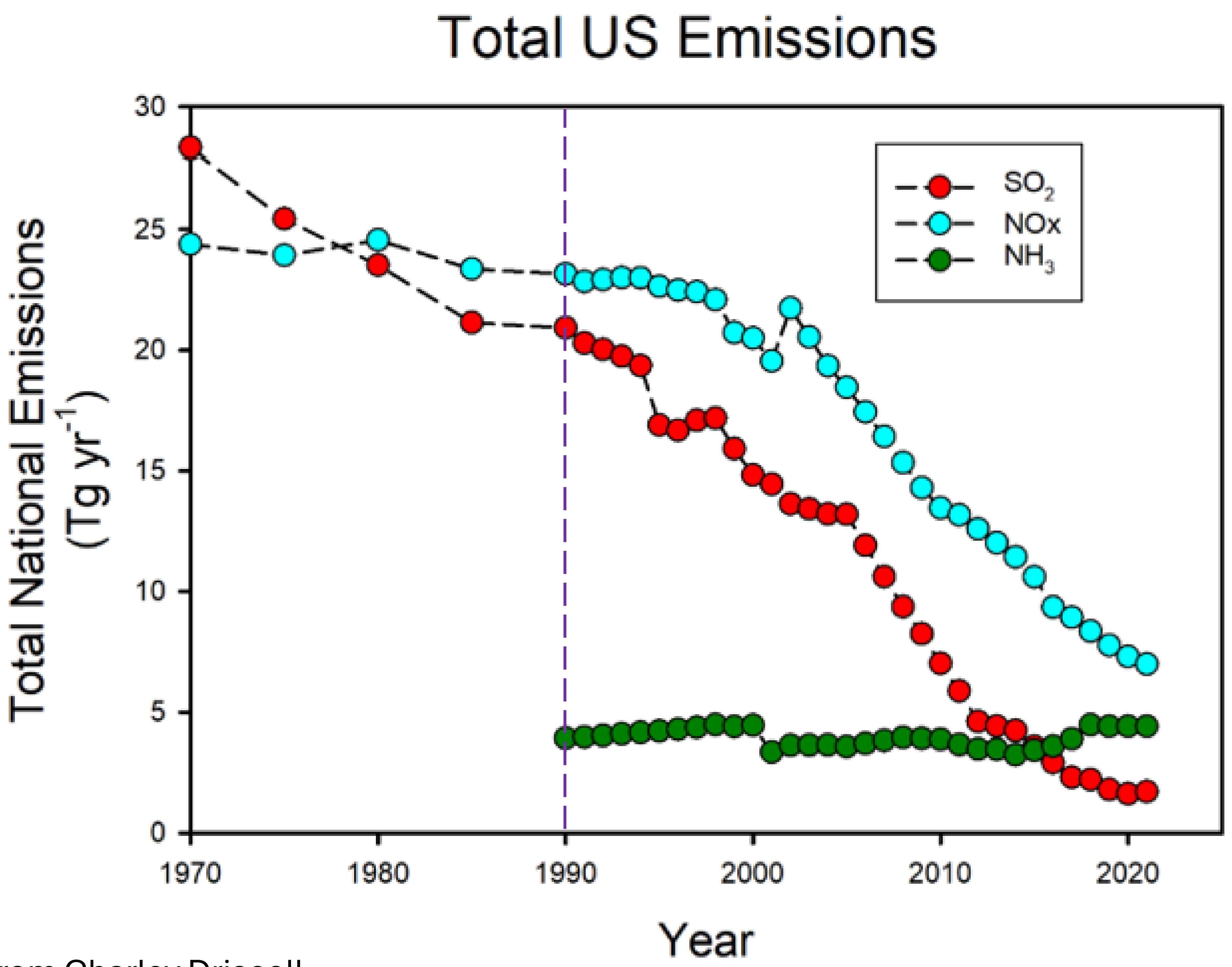
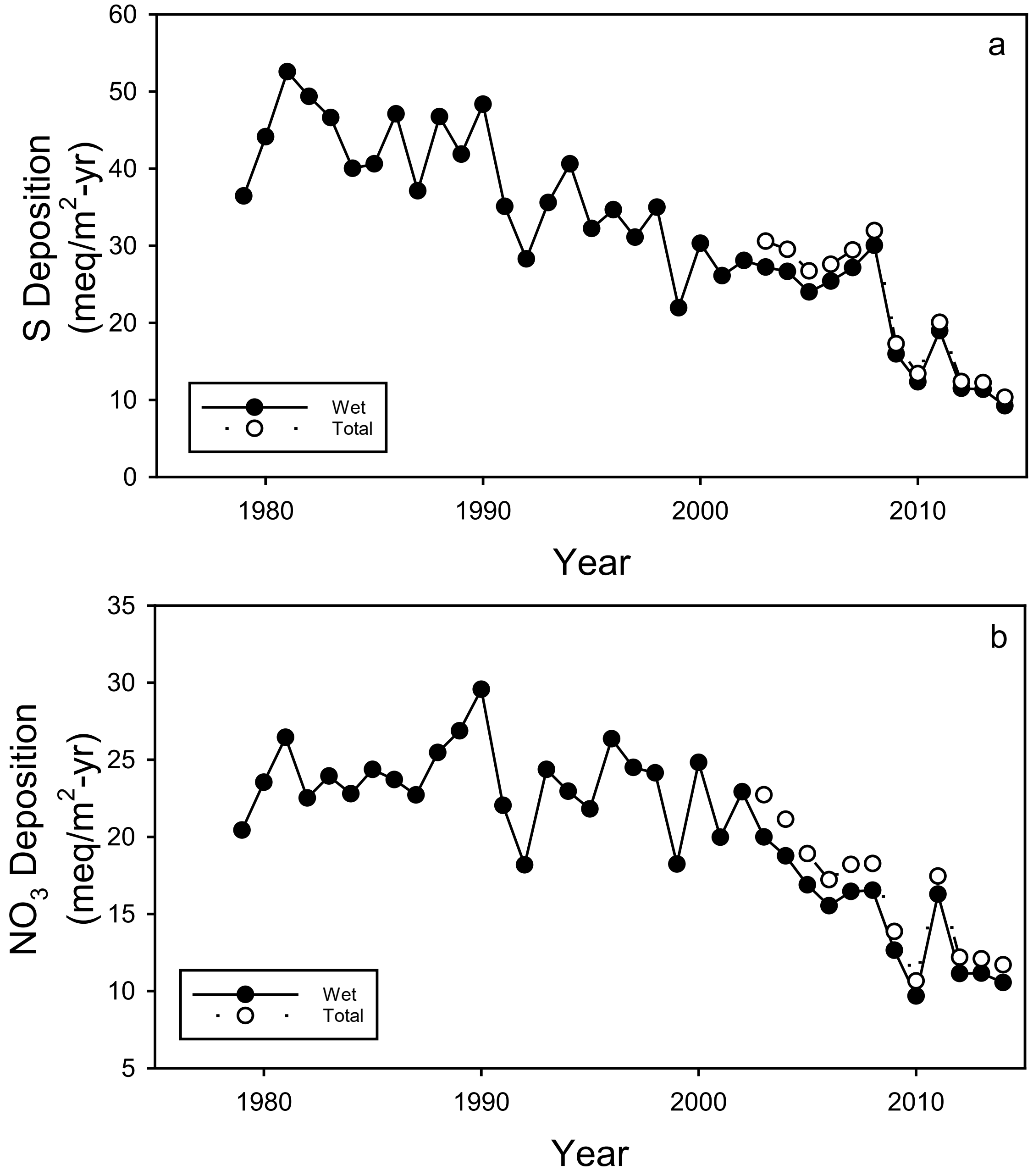
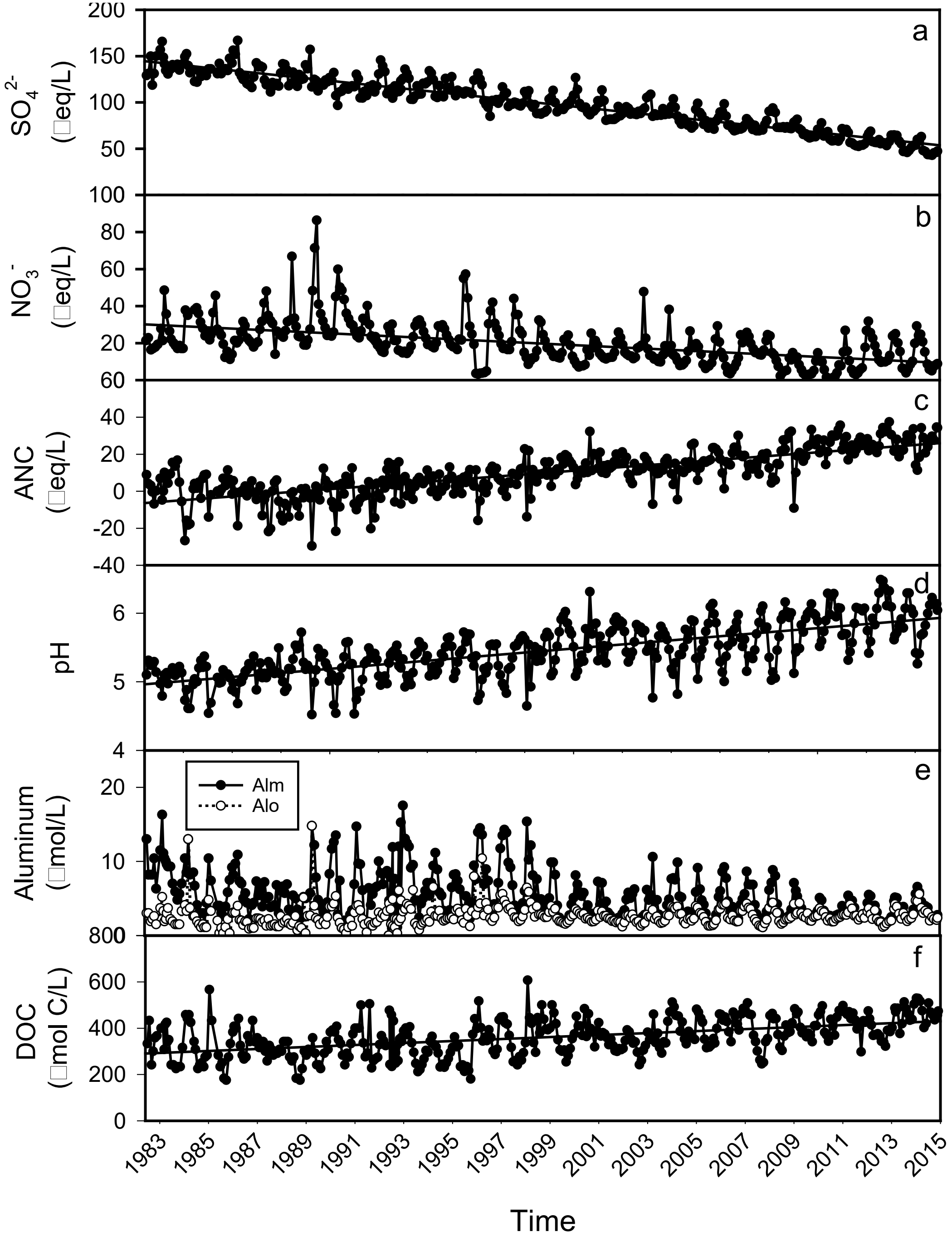


Figure modified from Charley Driscoll

Trends in the Adirondacks



Water chemistry trends in Big Moose Lake, NY



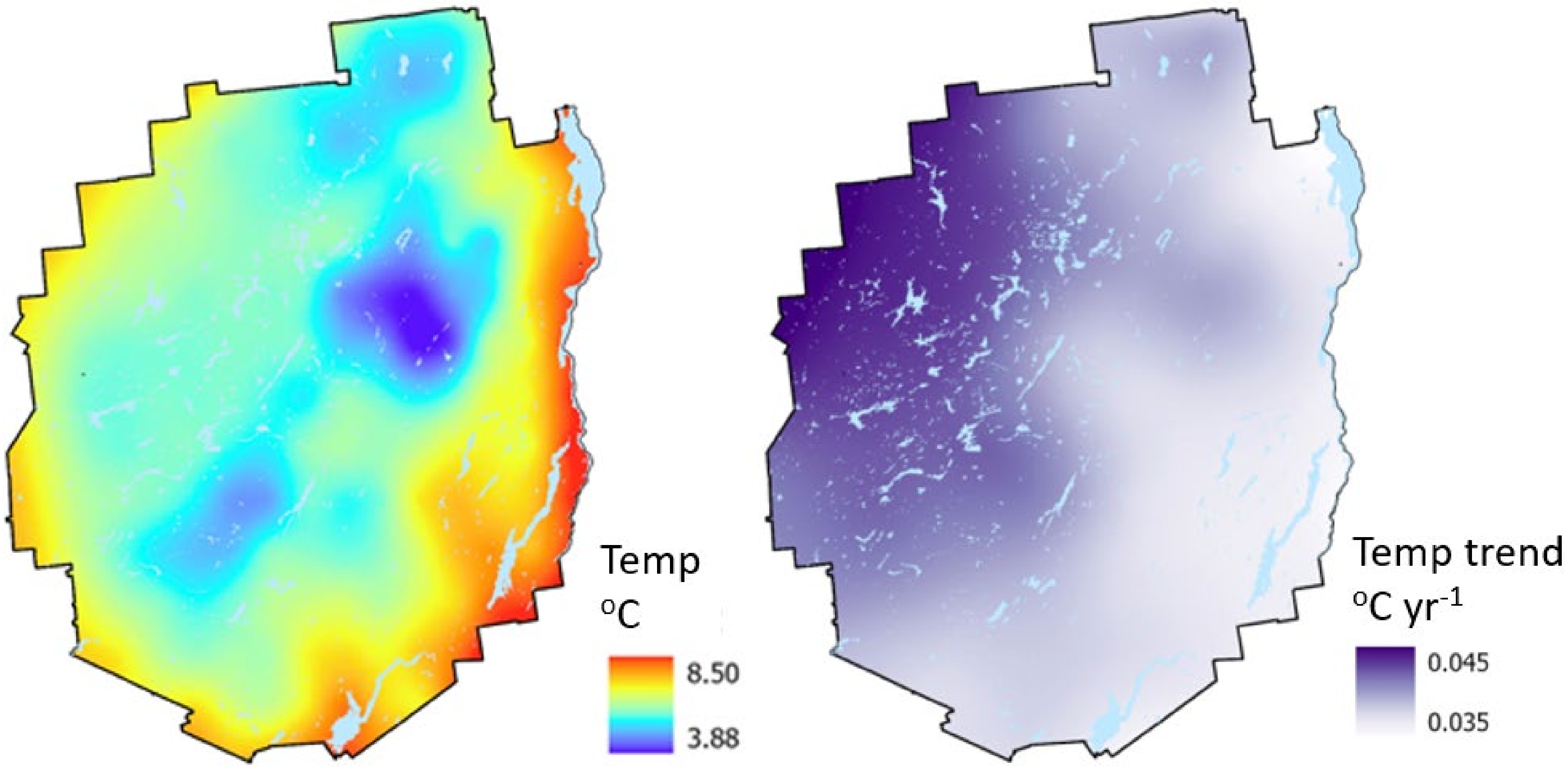
Lake browning is associated with recovery from acid deposition.

A line through the observations shows a statistically significant trend ($p < 0.05$).

Acid-neutralizing capacity (ANC) is a measure of the buffering capacity against acidification of a solution, e.g. surface water or soil water.

ANC is defined as the difference between cations of strong bases and anions of strong acids (see below), or dynamically as the amount of acid needed to change the pH value from the sample's value to a chosen different value.

Climate change may be amplifying lake browning

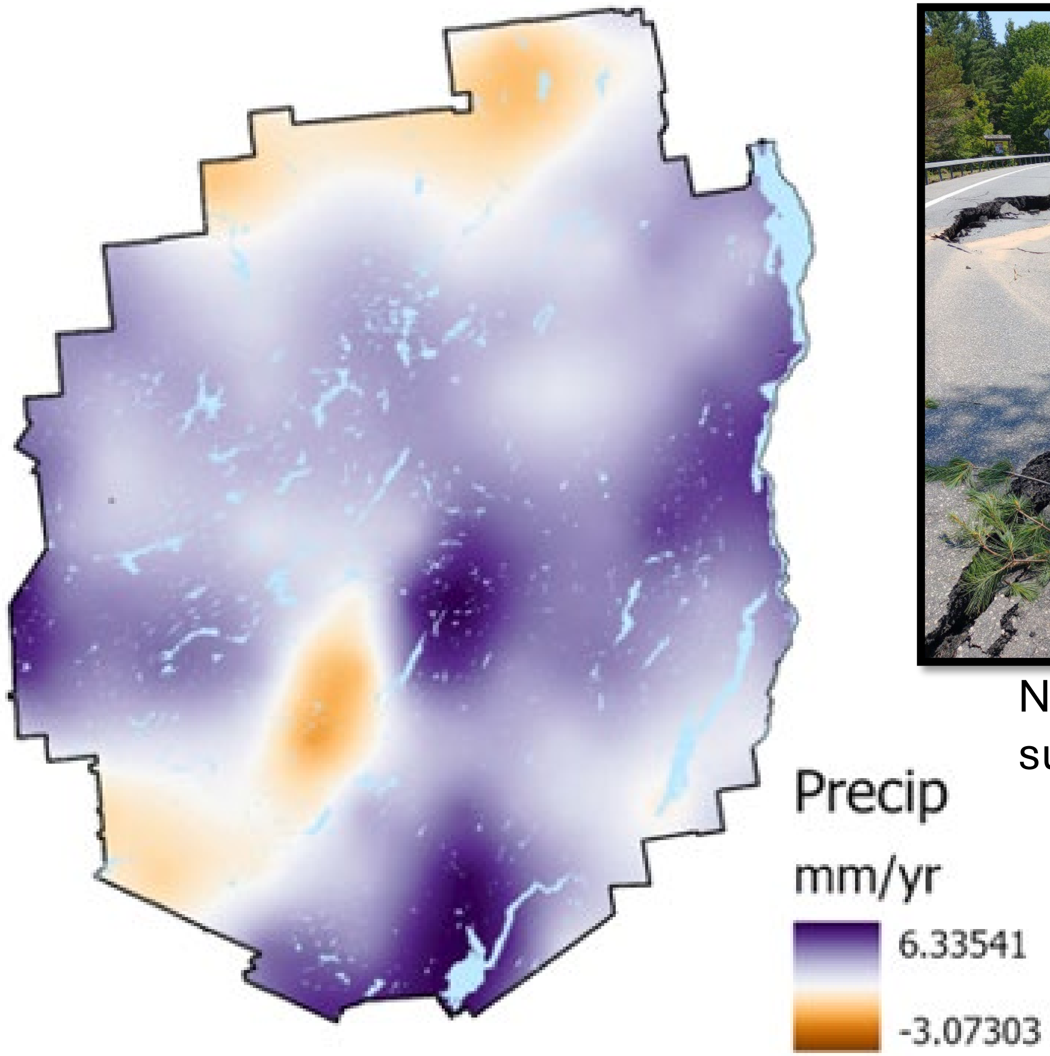


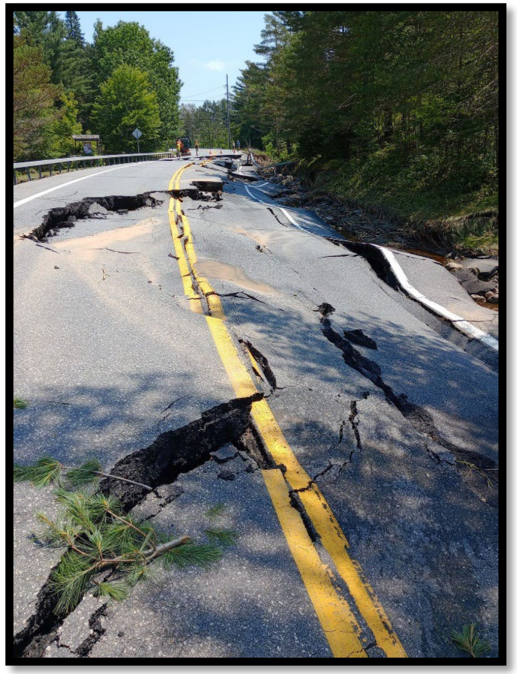
Longer growing seasons

More precipitation

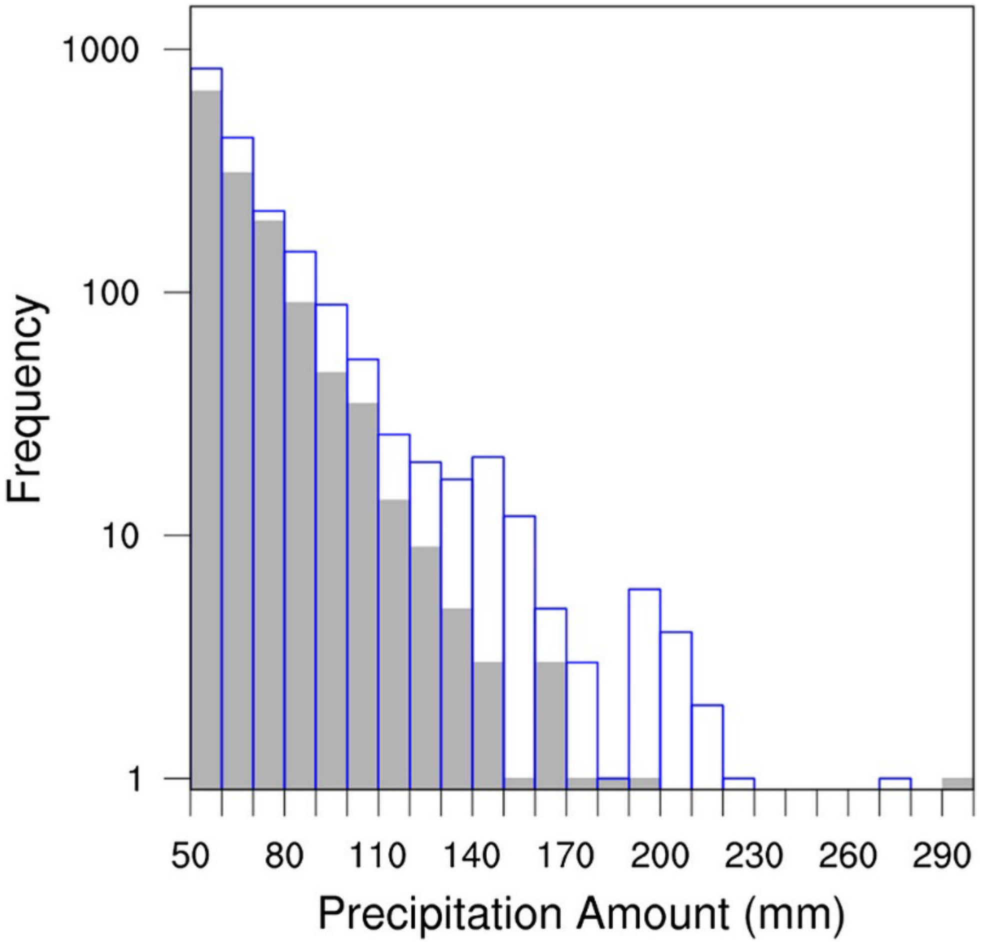
More extreme storms

Precipitation is increasing, especially extreme storms





Newcomb, NY
summer 2023



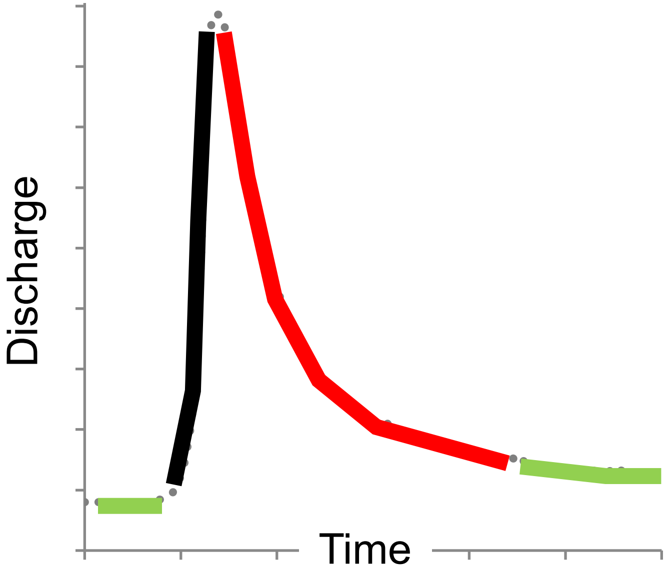
The frequency of precipitation events ≥ 50 mm for 1979–96 (**gray**) and 1997–2014 (**blue**).

Howarth et al. 2019, J. Hydrometeorology

Storms can be a major source of DOM

Photos by Kevin Ryan and Jamie Shanley

Baseflow



Rising limb

Falling limb

Lake browning reduces water clarity

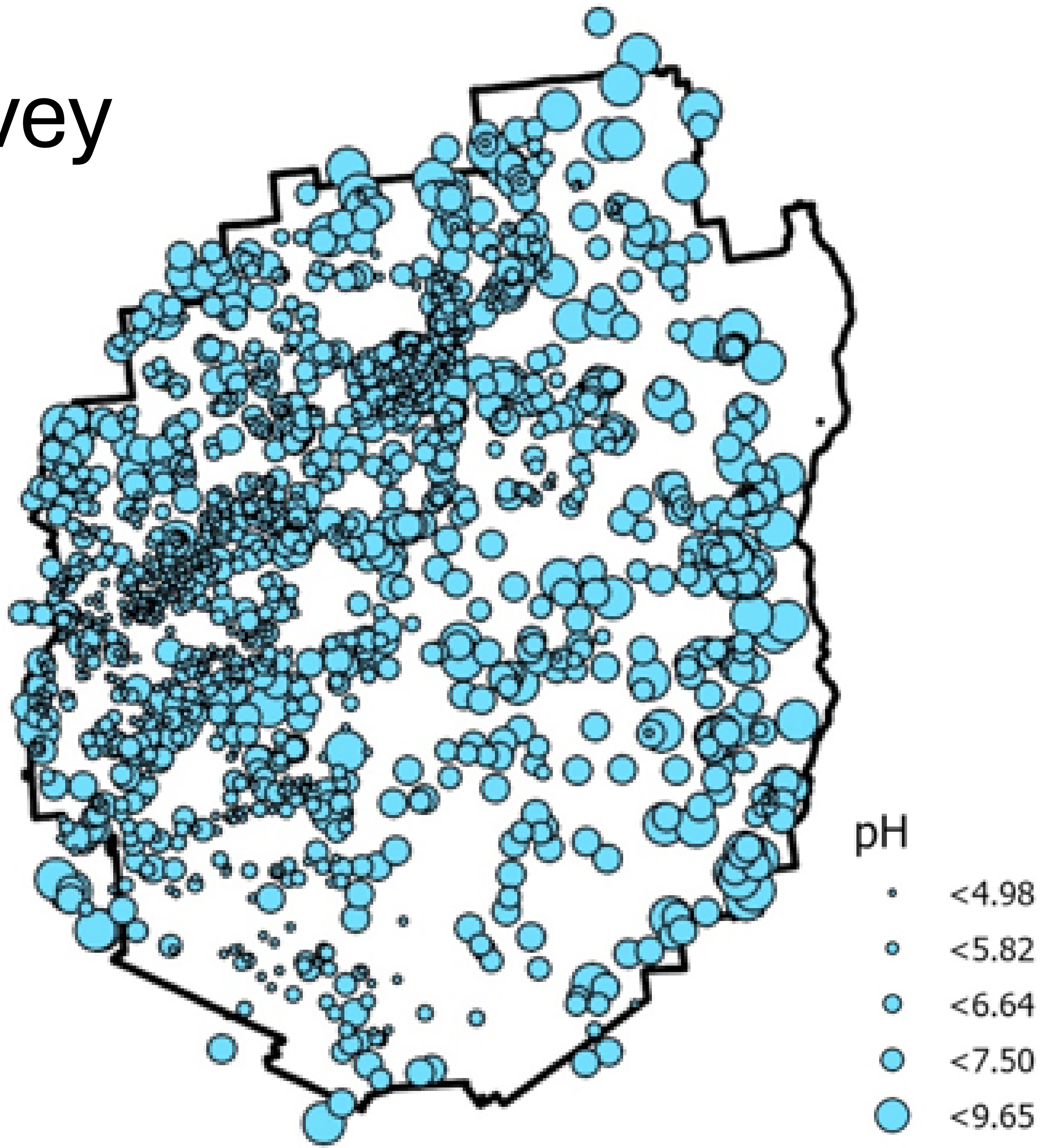
Blue water, oligotrophic (low Chl, low DOM)

Green water, eutrophic (high Chl)

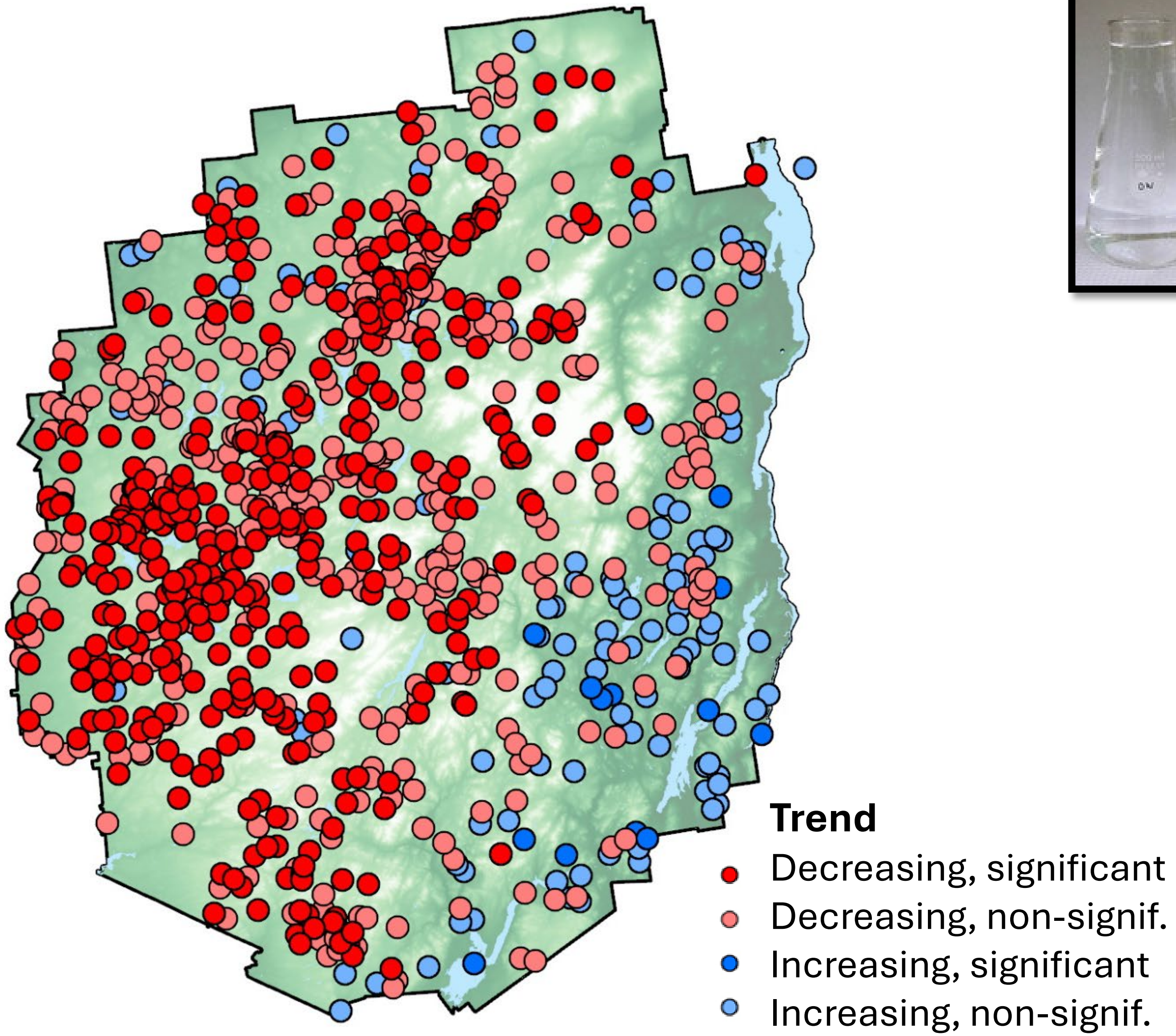
Brown water, dystrophic (high DOM)

Adirondack Lake Survey

- 1984-1987
- Objectives included classifying Adirondack lakes based on sensitivity to acid deposition
- Sampled chemistry of nearly 1,500 lakes
- Provided important baseline assessment of acidification impacts

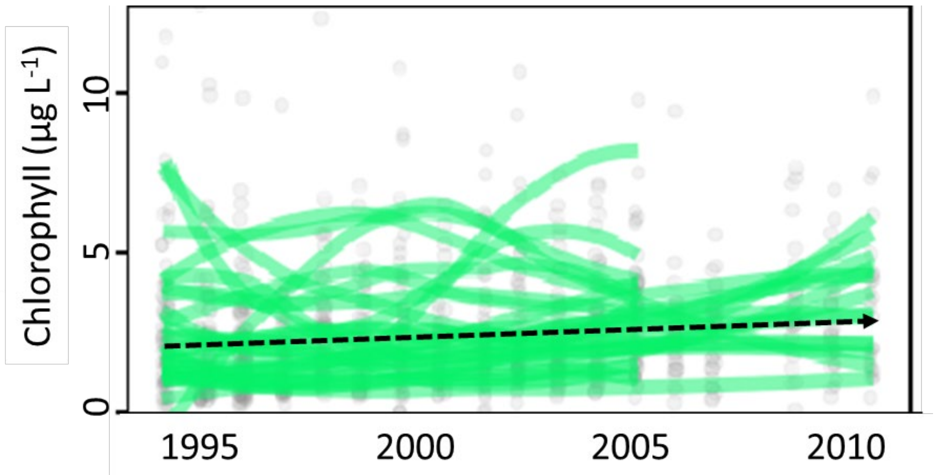


Remote sensing indicates widespread water clarity losses



Browning

Greening: 27% algal increase



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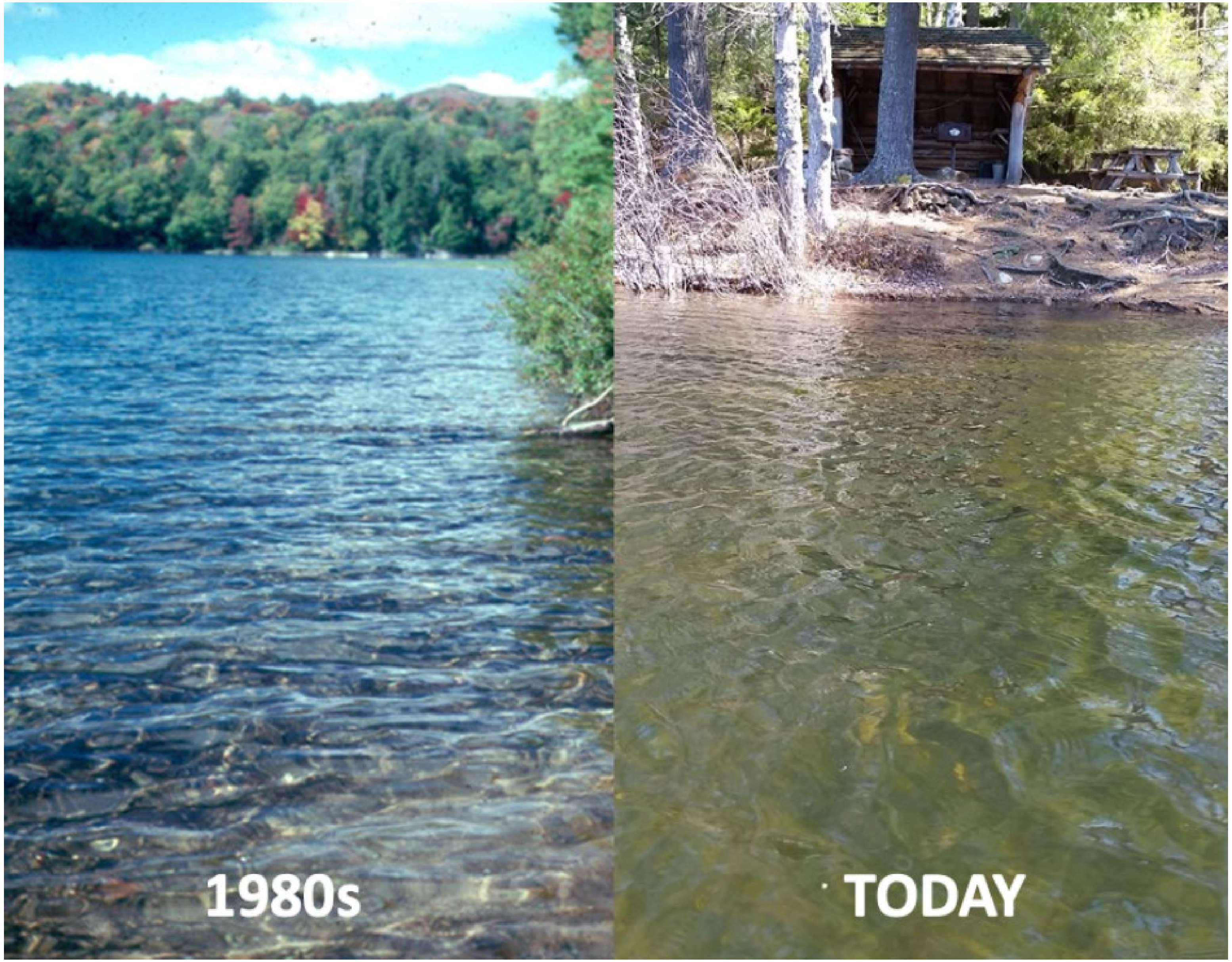
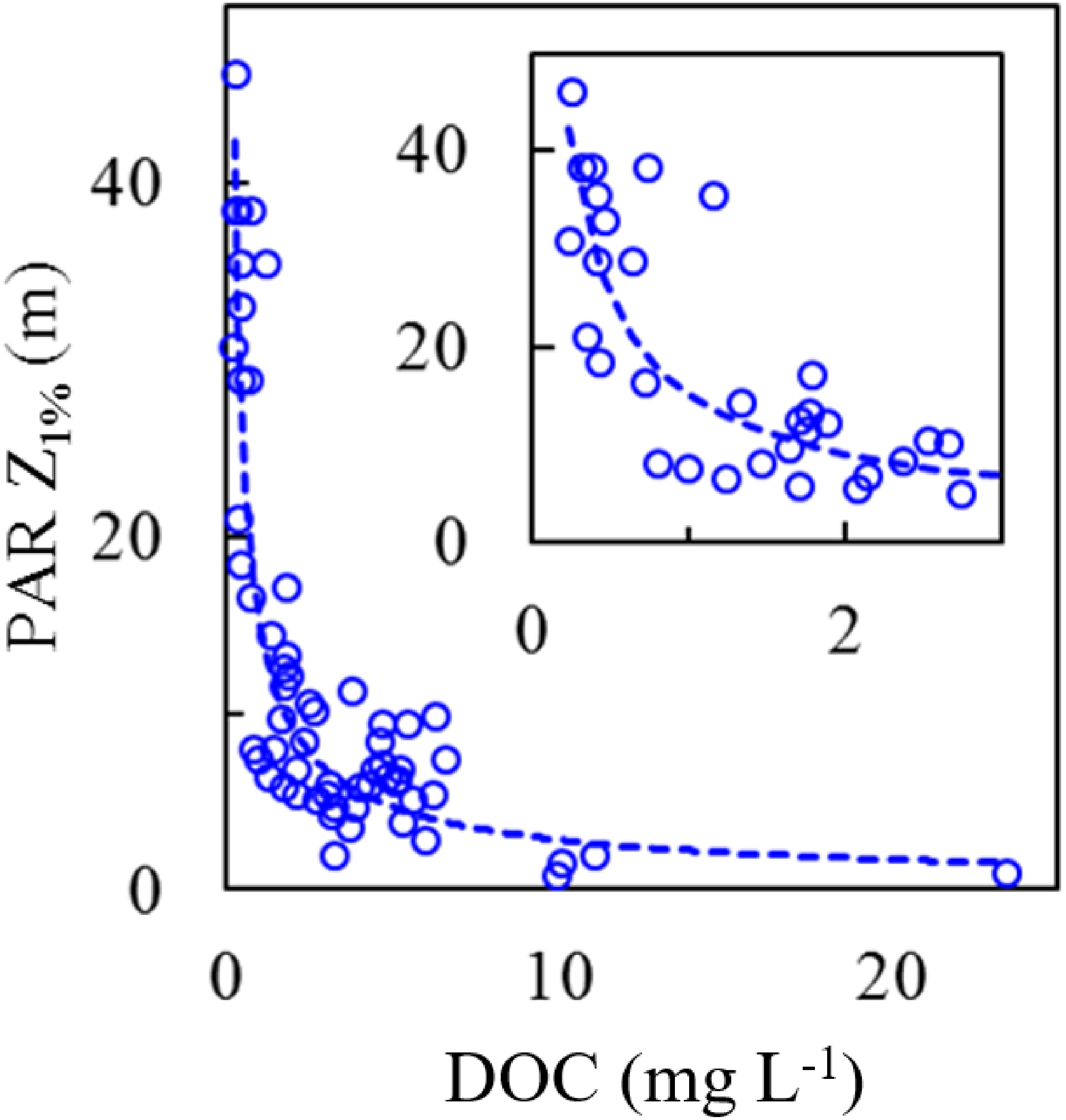


Bear Pond, Adirondacks

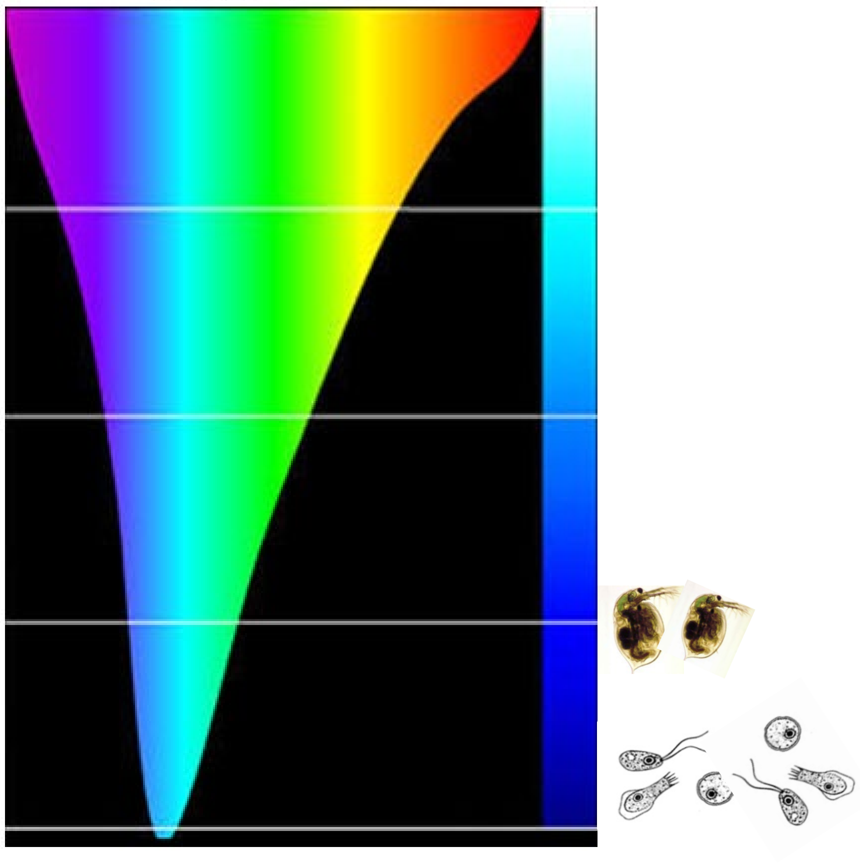
Courtesy Curt Stager, Paul Smith's College

Browning reduces light availability underwater

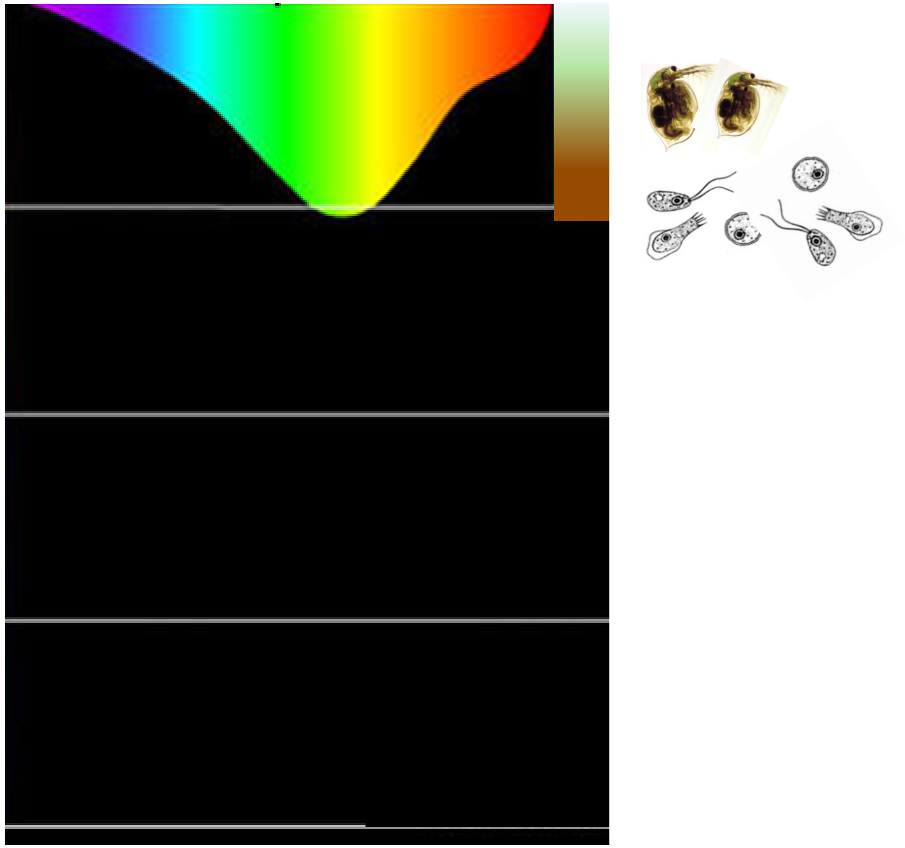


Browning alters the vertical distribution of light – and by altering light it impacts many other attributes

Low DOM lake 

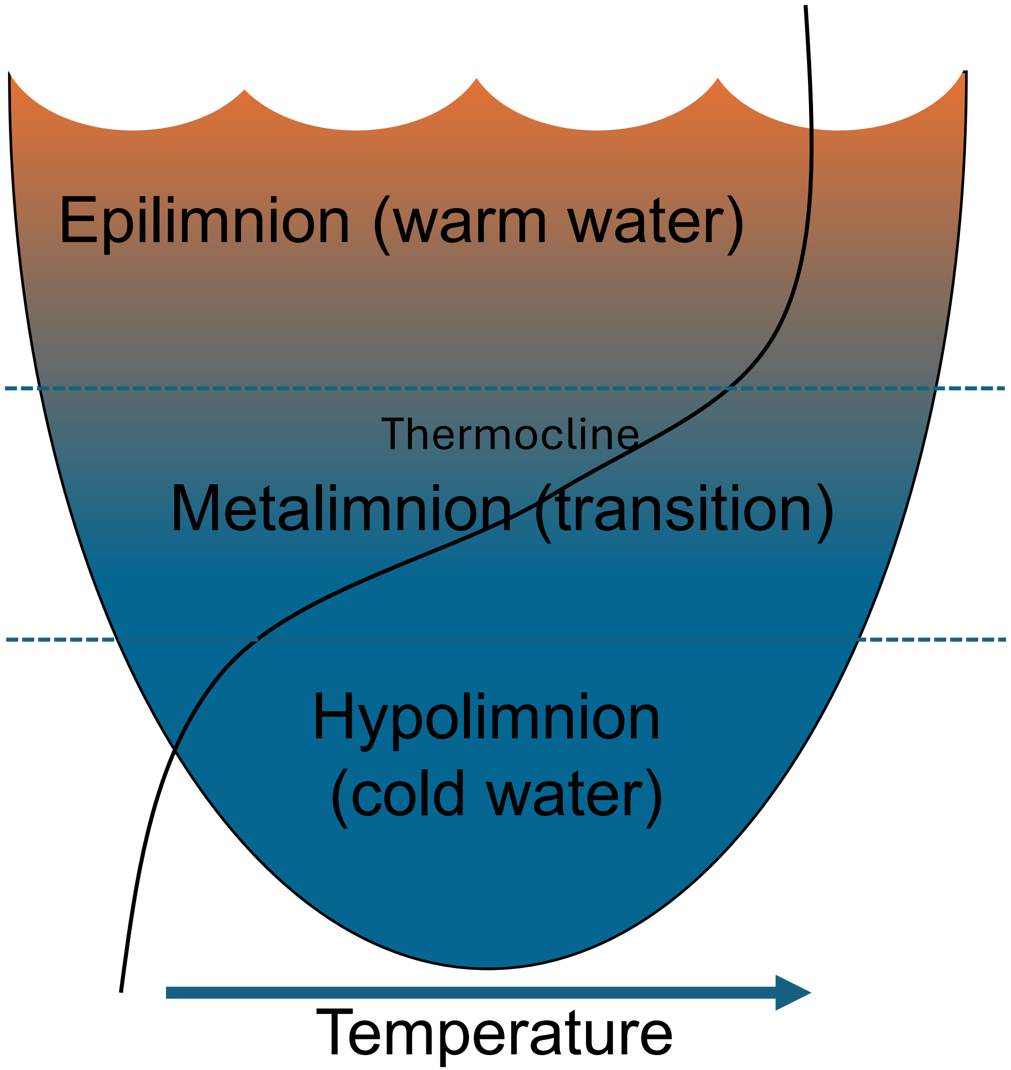


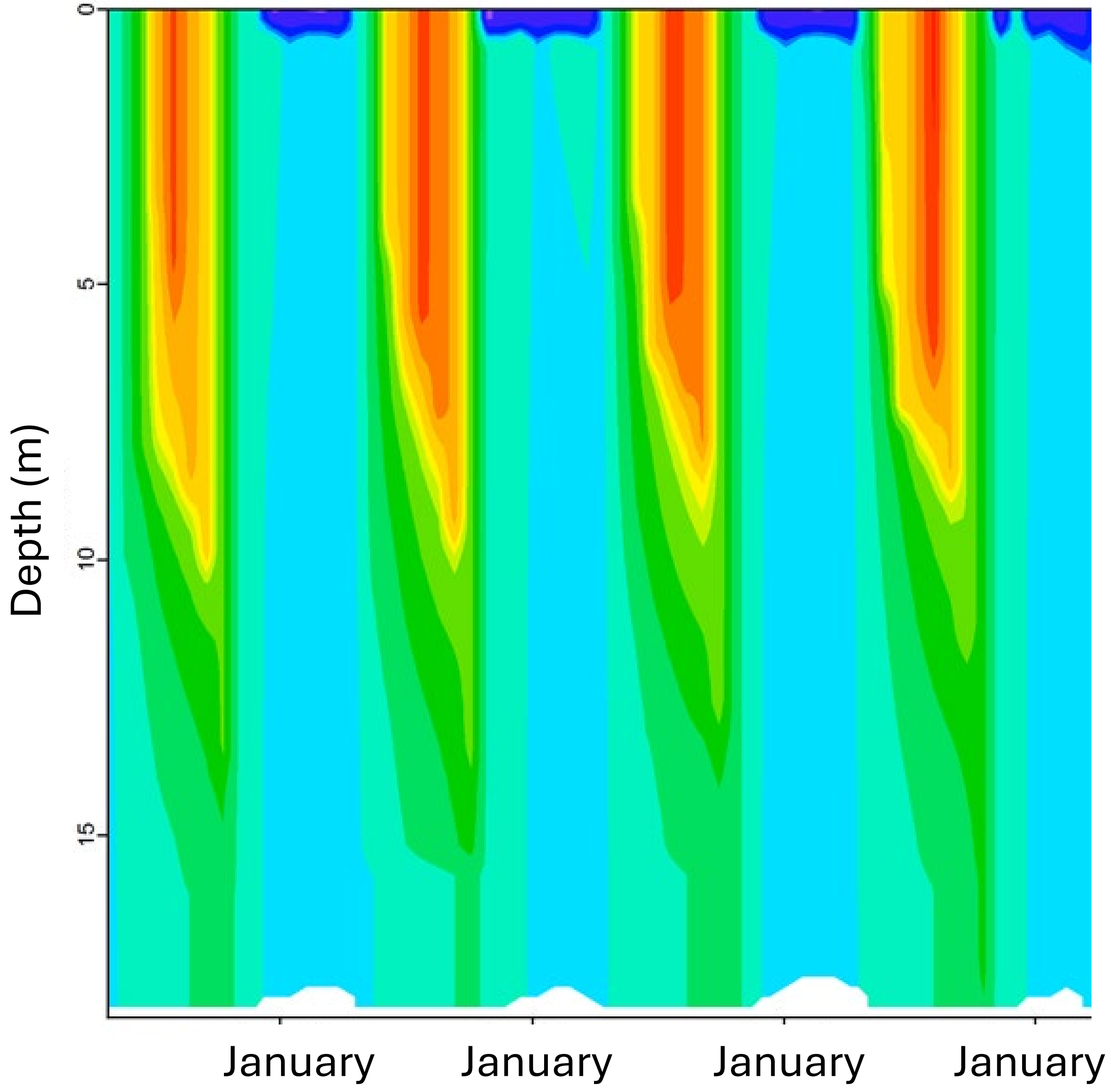
High DOM lake 



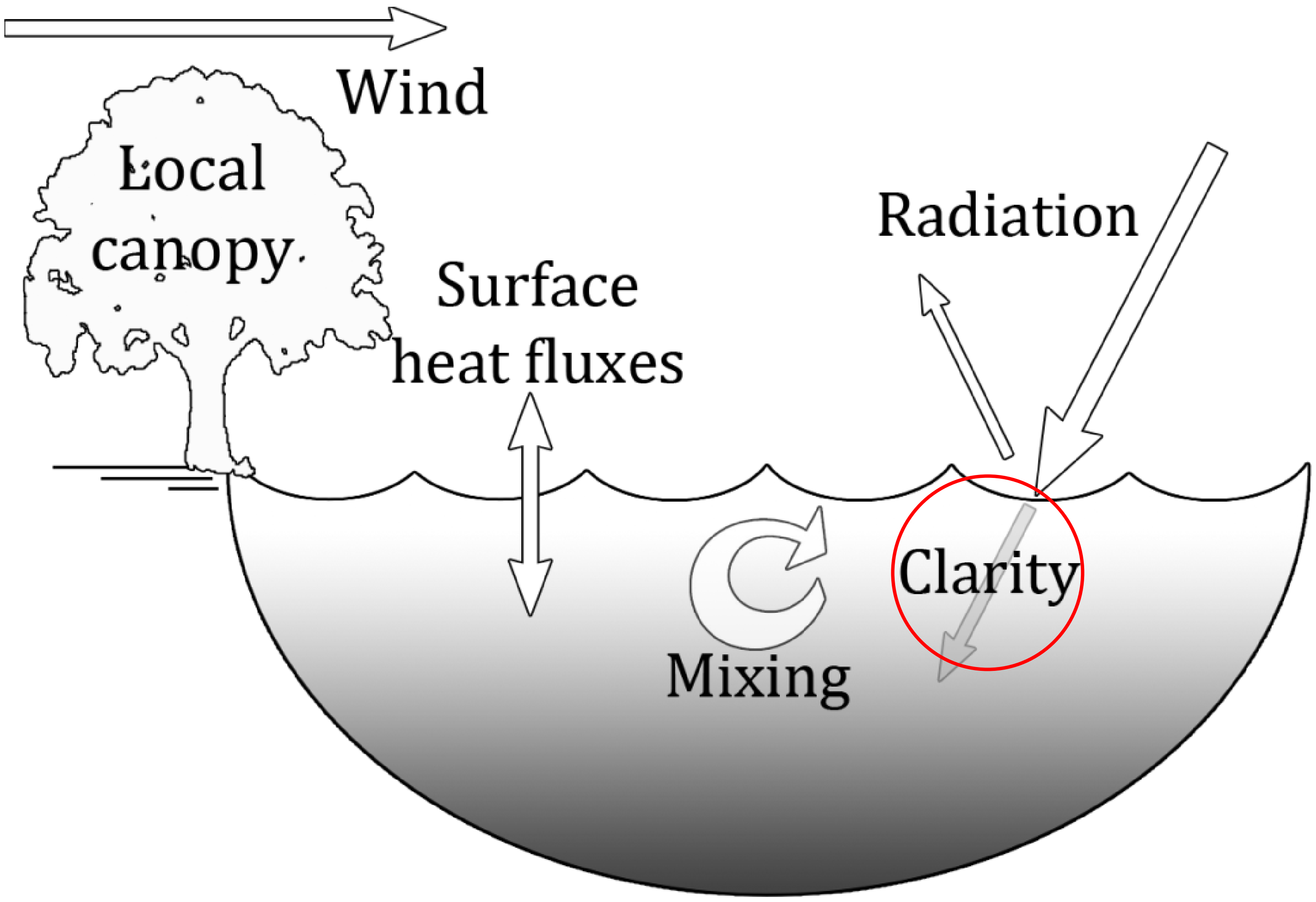
Rose et al. 2009a PPS, Rose et al. 2009b JGR Biogeosci, Rose et al. 2012 L&O

Browning alters lake temperature and thermal (density) stratification

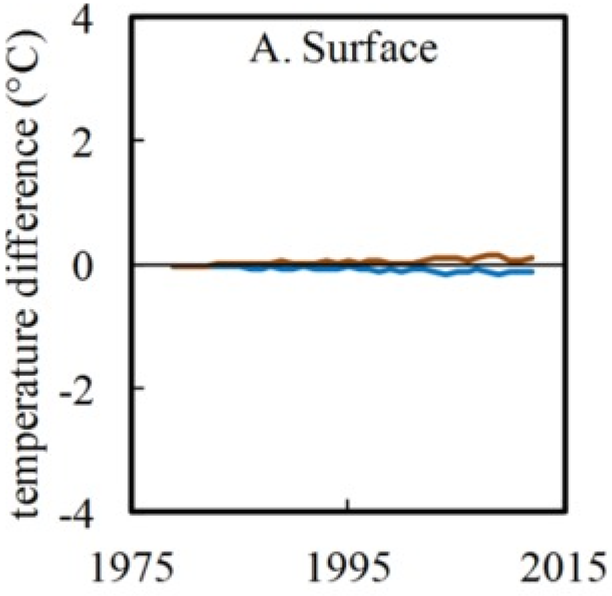




How does lake browning alter lake temperatures and stratification?



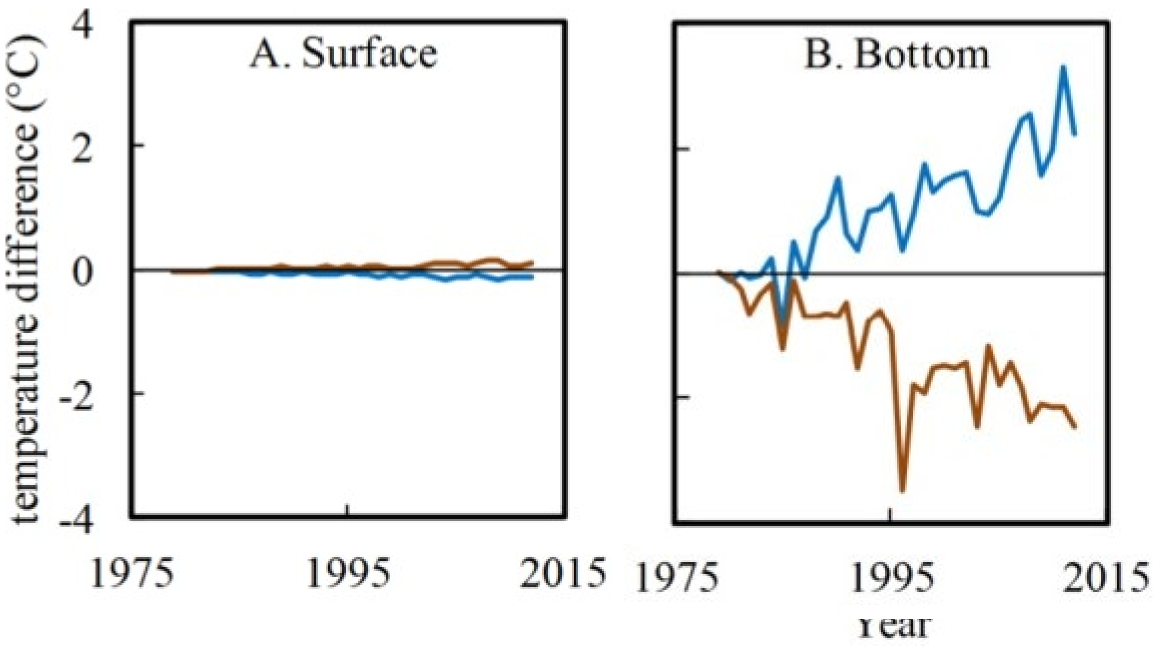
Changing water clarity can amplify or suppress climate-induced warming.



Browning slightly amplifies surface temperatures

Rose et al. 2016, L&O Letters

Changing water clarity can amplify or suppress climate-induced warming.

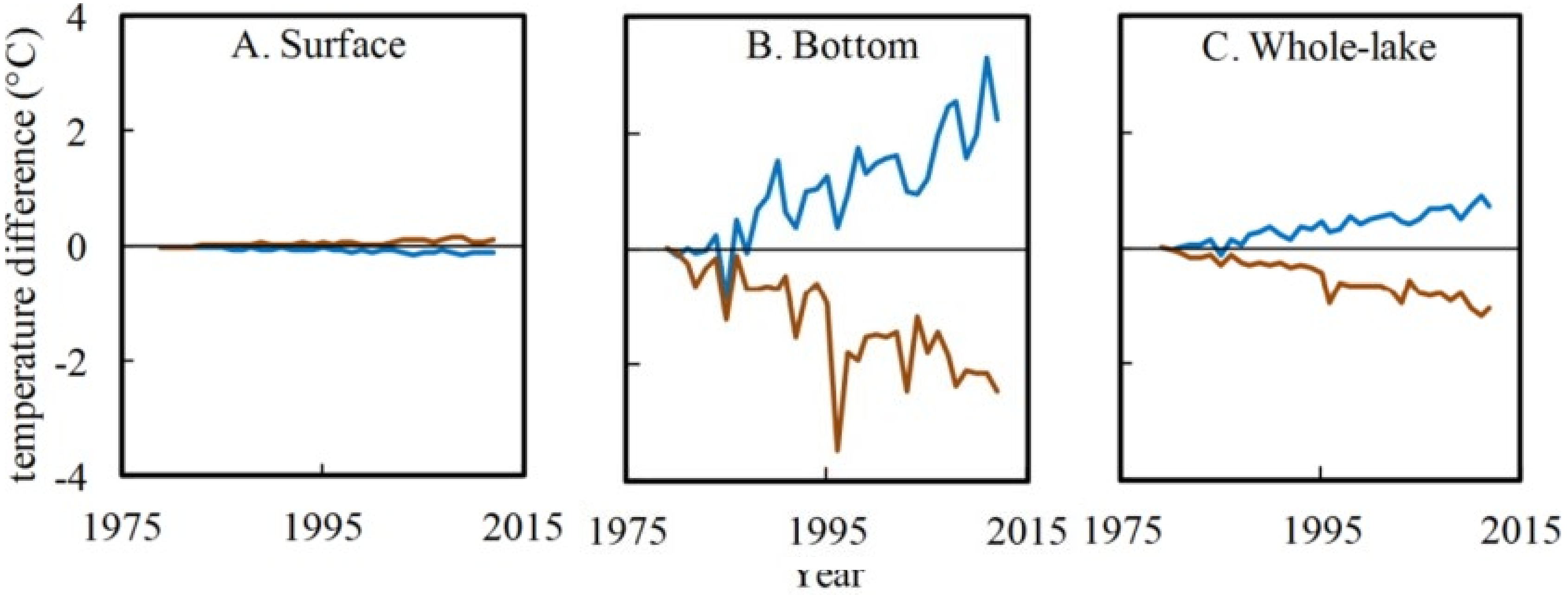


Browning slightly amplifies surface temperatures

Browning suppresses deep temperatures

Rose et al. 2016, L&O Letters

Changing water clarity can amplify or suppress climate-induced warming.



Browning slightly amplifies surface temperatures

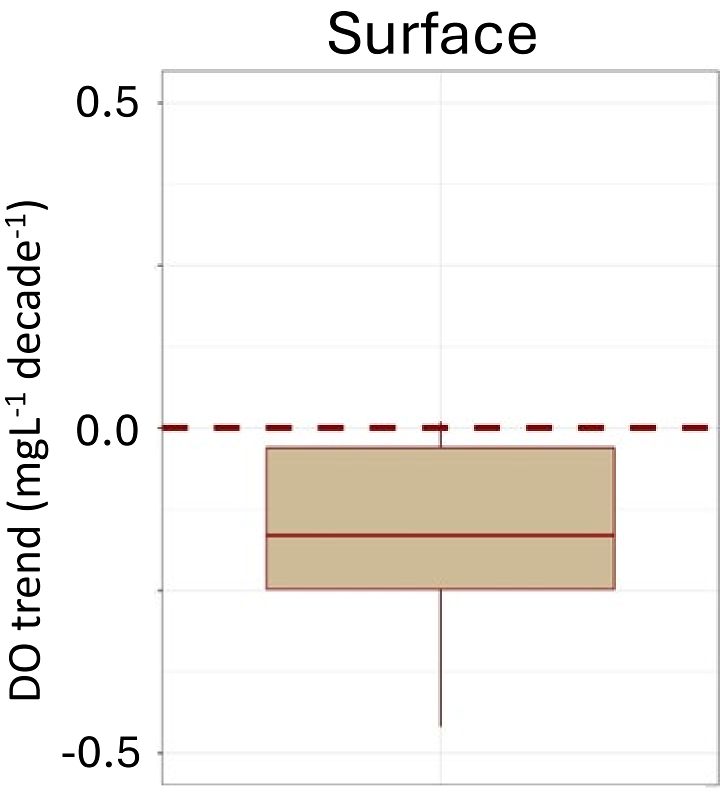
Browning suppresses deep temperatures

Browning suppresses whole-lake temperatures

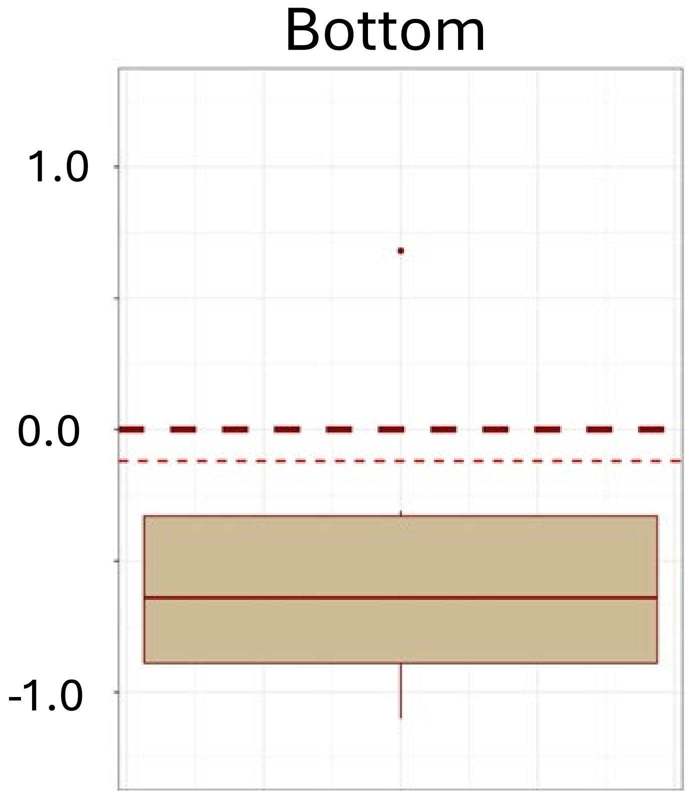
By amplifying surface temperatures while suppressing deep temperatures, browning creates a greater temperature difference through the water column (i.e., stronger stratification)

Rose et al. 2016, L&O Letters

Browning contributes to dissolved oxygen losses, reducing oxy-thermal habitat available for cold water fishes

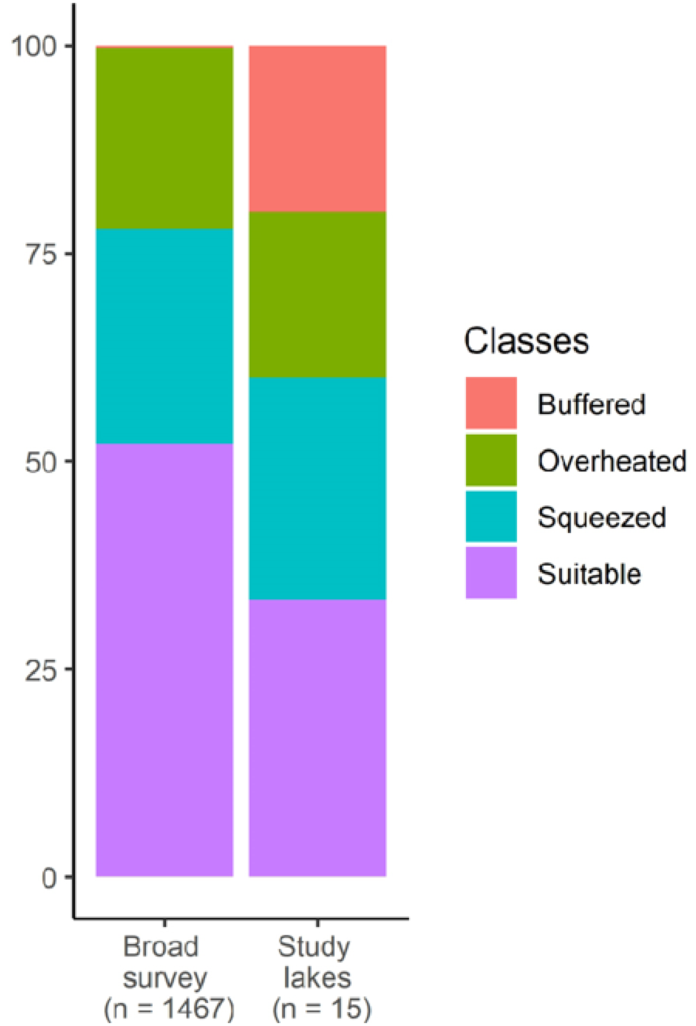


Median DO trend:
-0.16 mgL^{-1} $decade^{-1}$



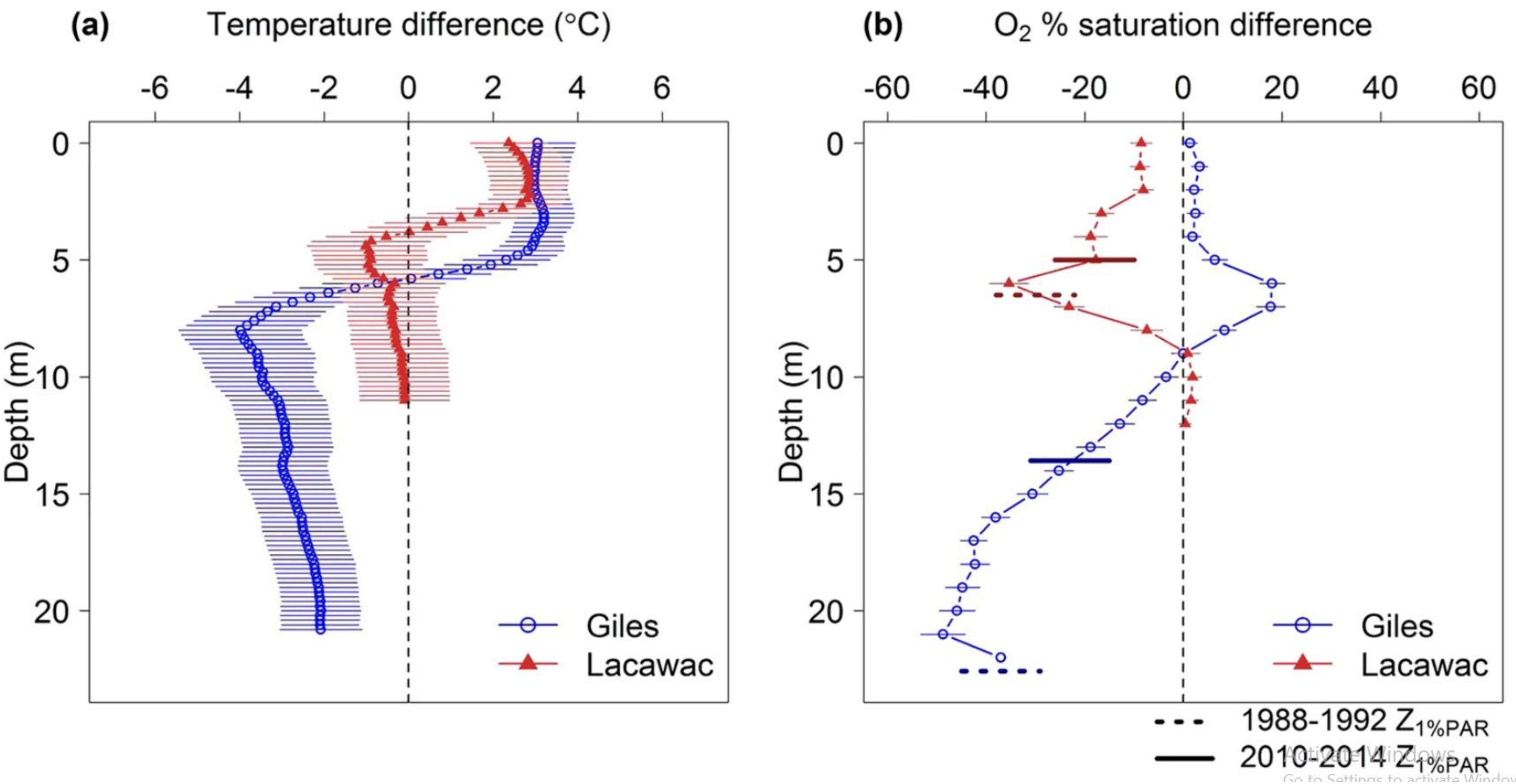
Median DO:
-0.64 mg L^{-1} $decade^{-1}$

Loss of trout habitat



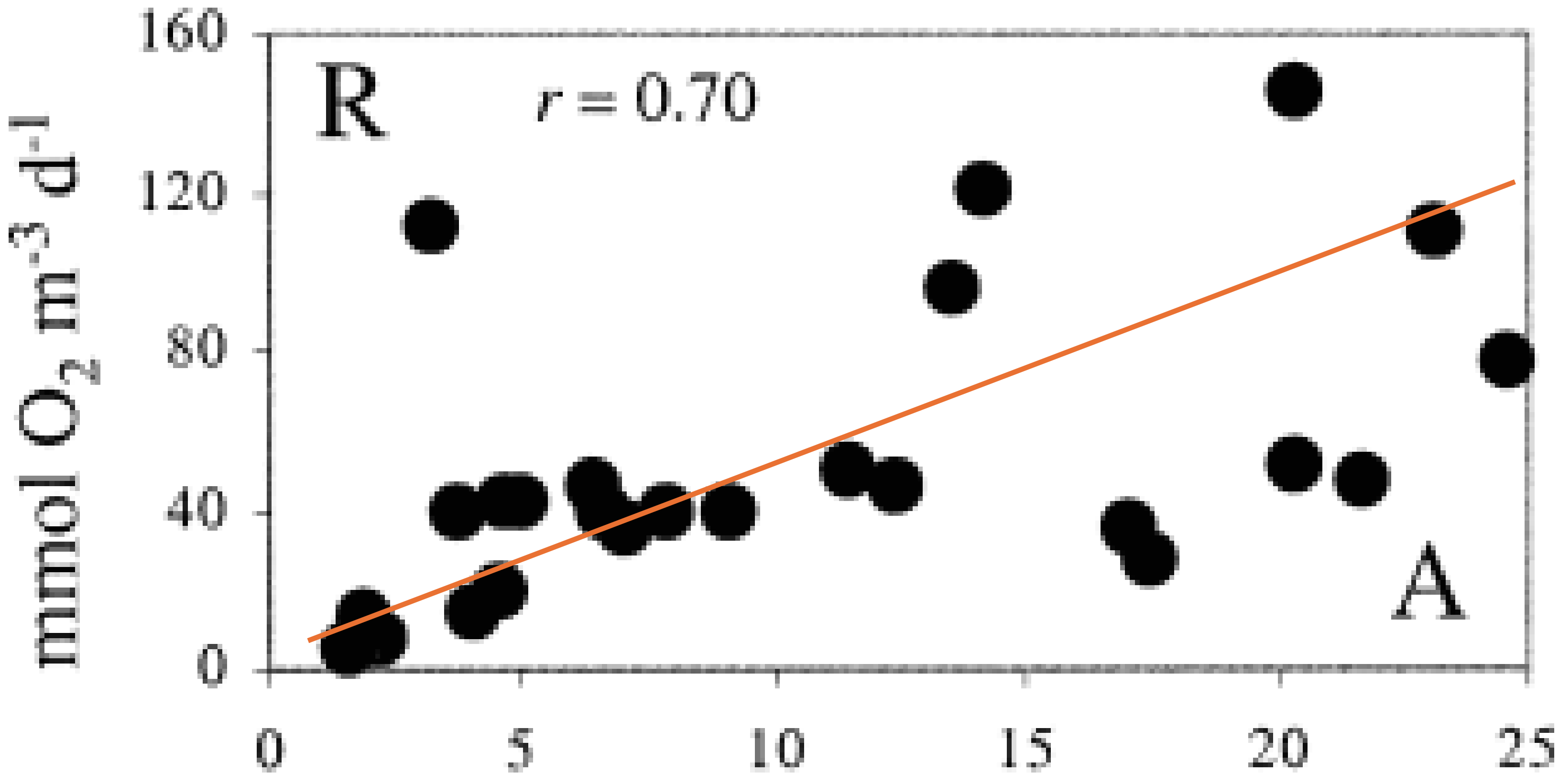
Based on AEAP data (n=28)

Jane et al. 2024 PNAS

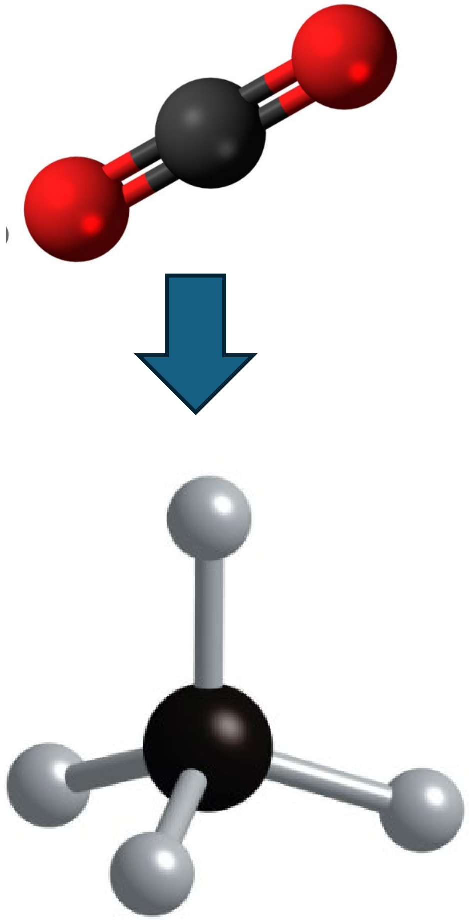


Williamson et al. 2015

Higher DOM is associated with more respiration (more oxygen consumption & more CO_2 emissions)

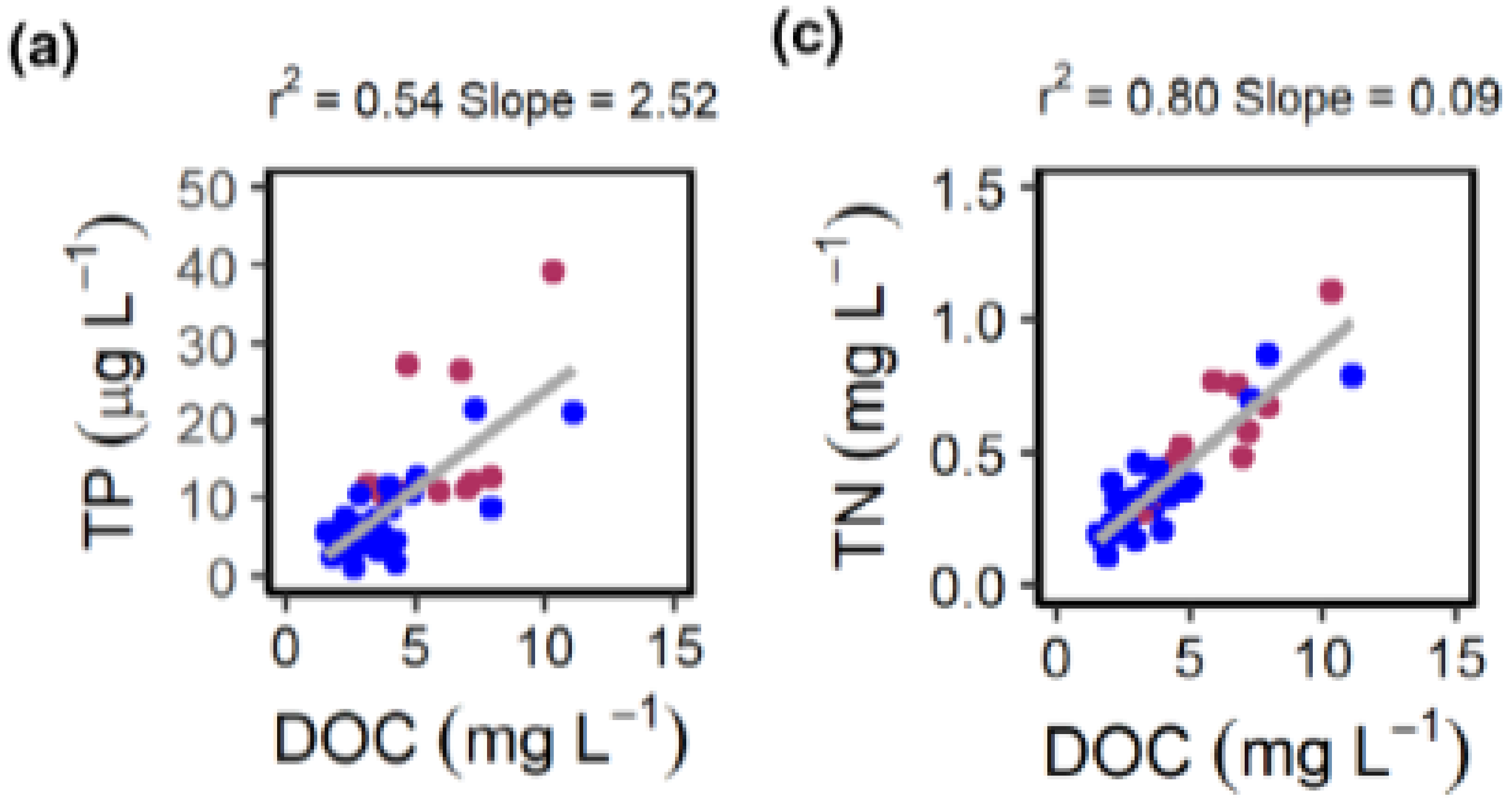


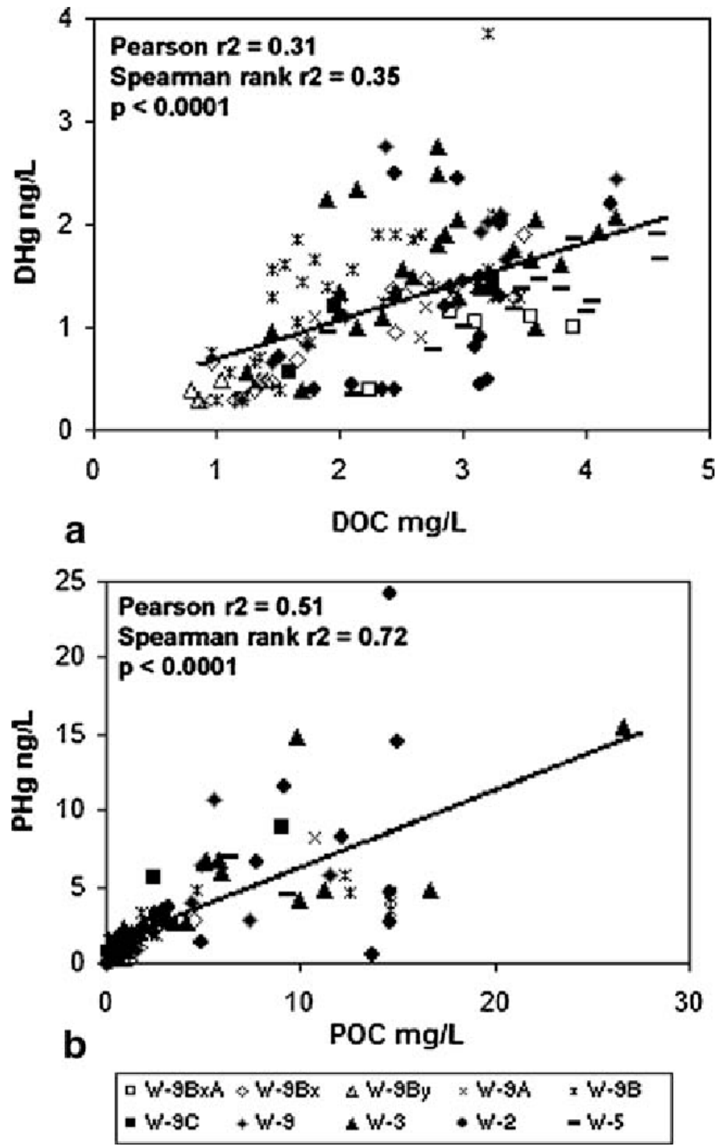
DOC concentration (mg/L)



Hanson et al. 2003

Dissolved organic matter can be a source of nutrients and metals





Stetler et al. 2021

Schuster et al. 2007

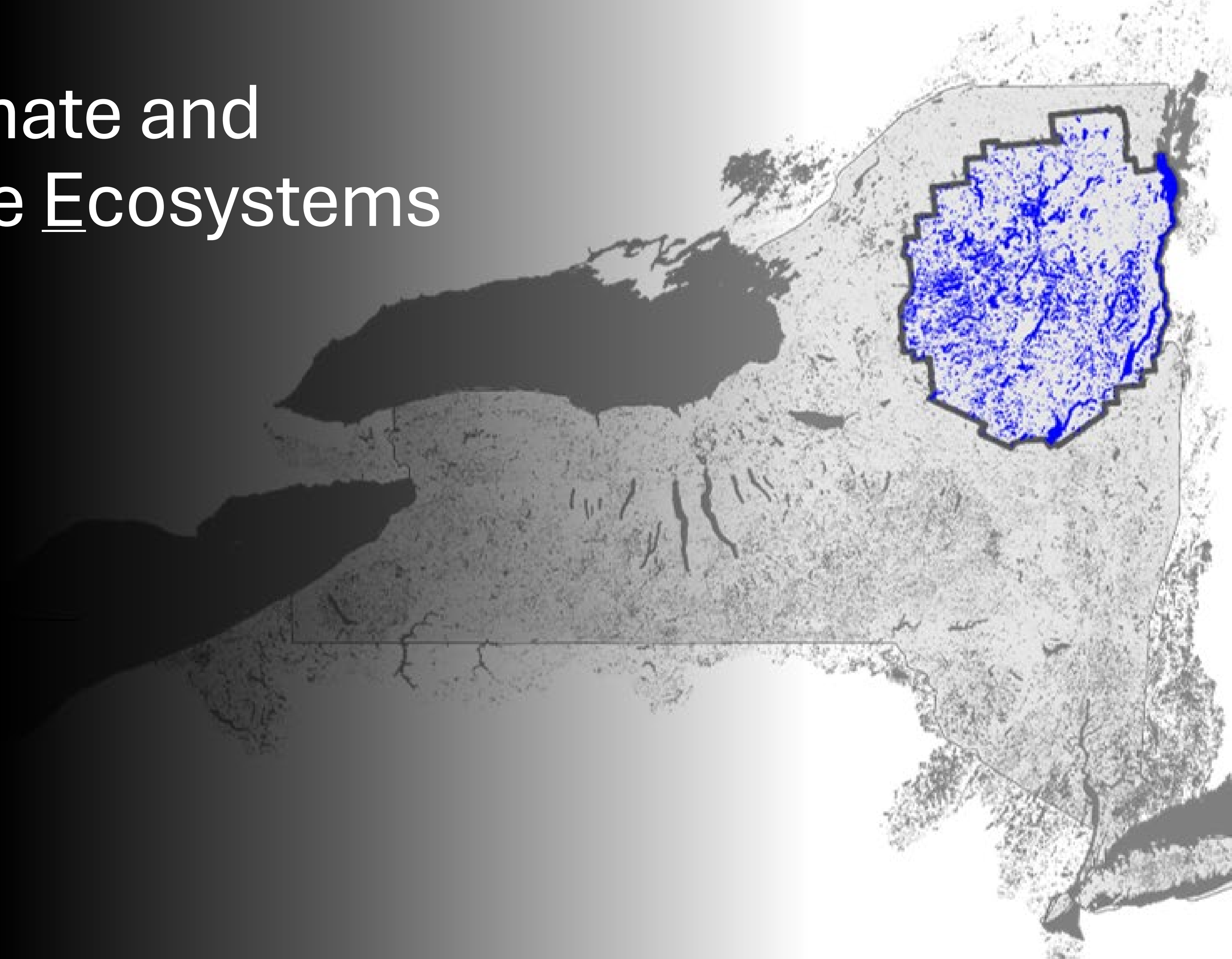
Why is lake browning important?

- DOM is often largest source of organic carbon in aquatic ecosystems
- Major regulator of water clarity; regulates UV and visible light
- Regulates how heat is absorbed (temperature & stratification)
- Influences oxygen availability and oxy-thermal habitat – impacts fisheries habitat & food webs
- Can contribute to greater CO_2 and CH_4 emissions
- Can be a source of nutrients (e.g., N & P) and have bound Hg (influences speciation, fate, and transport of metals)

Other aspects not discussed…

- Can produce toxic disinfection byproducts during drinking water treatment
- Can "sensitize" the photochemical breakdown of pollutants
- Can regulate pH
- Hydrophobic organic pollutants can partition into it
- Electron acceptor and donator; antioxidant and oxidant

SCALE:
A Survey of Climate and Adirondack Lake Ecosystems



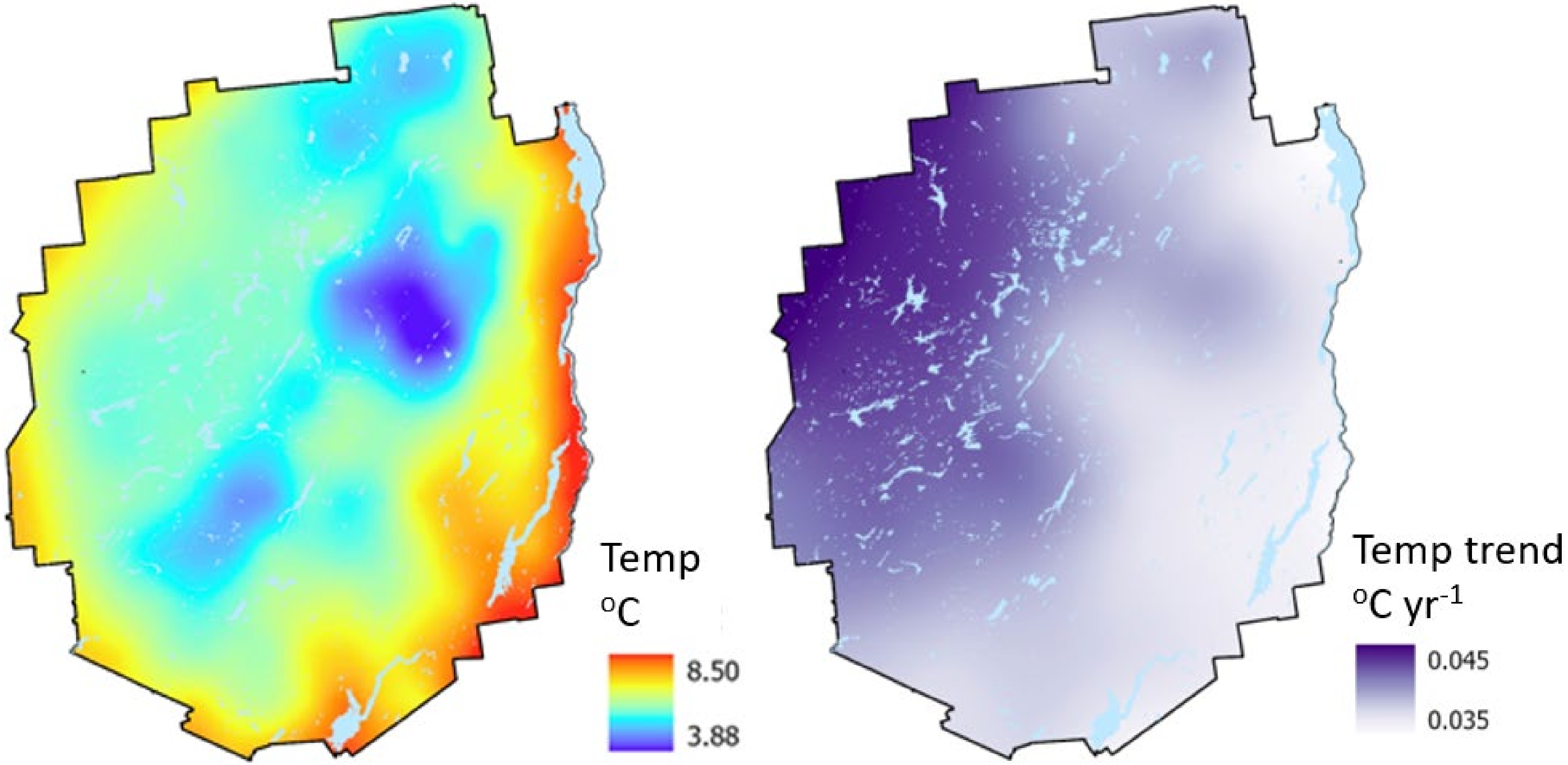
Climate change

- Warming temperatures
- Ice cover loss & longer stratification
- Dissolved oxygen loss
- Precipitation increases
- Cold-water species extirpation

Interacting stressors

- *Browning*
- Mercury loading
- Land use/land cover change
- Invasive species
- Harmful algal blooms
- Salinization

Today, Adirondack waterbodies are recovering from historical acidification, but also challenged by climate change & interactions with other stressors

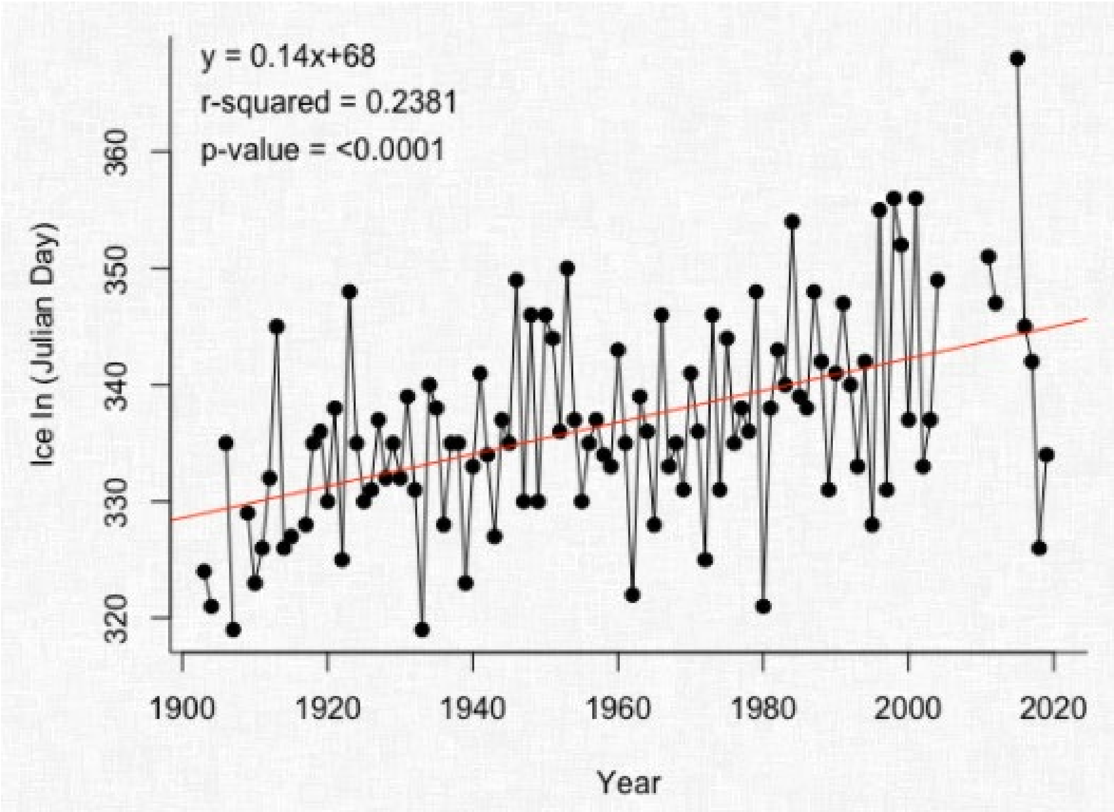


A new series of threats necessitates a new survey – far beyond just chemistry

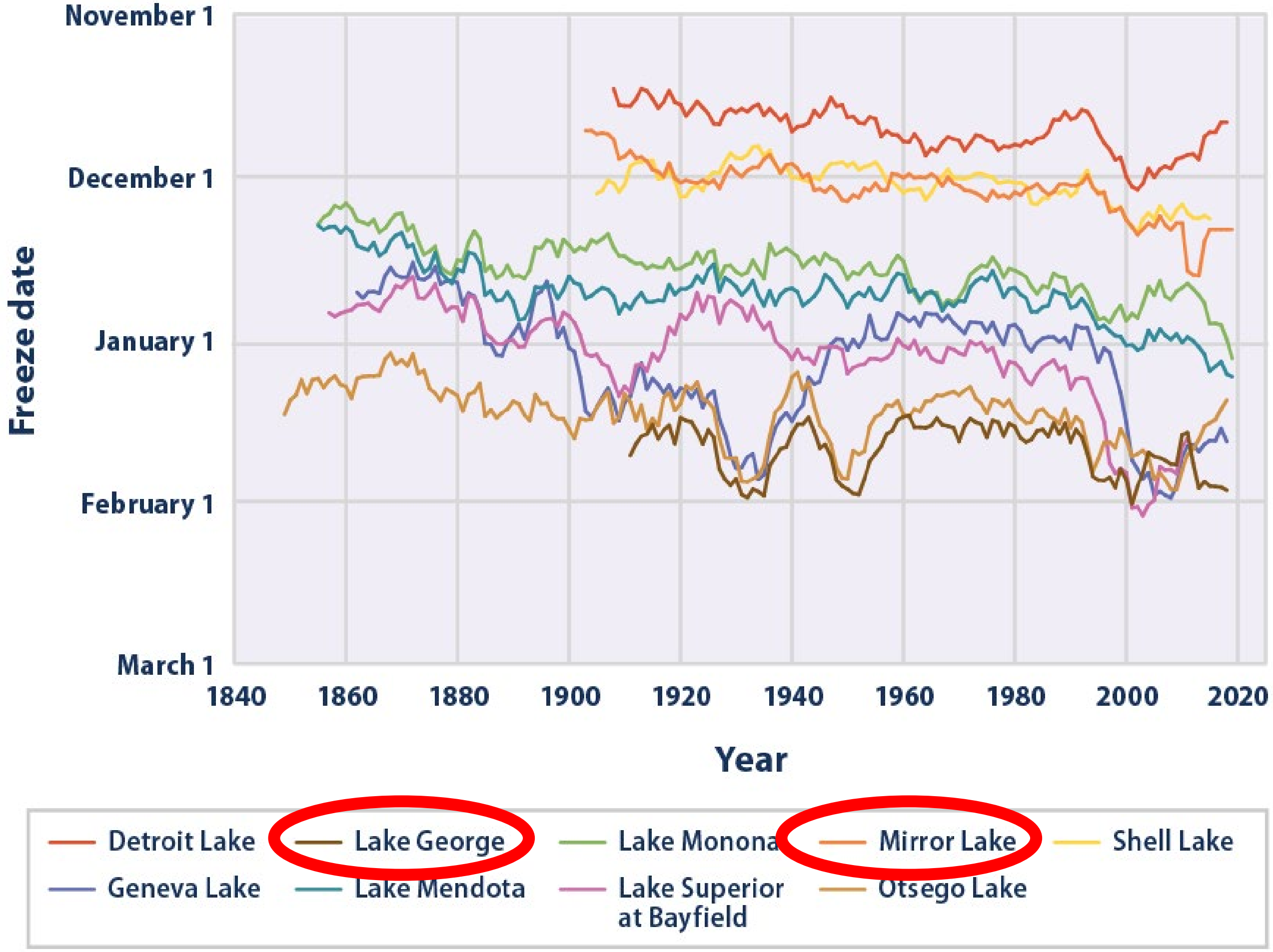
Seasonal lake ice is declining & the summer is lengthening

Ice-on dates for Mirror Lake

(from Ausable Freshwater Center)

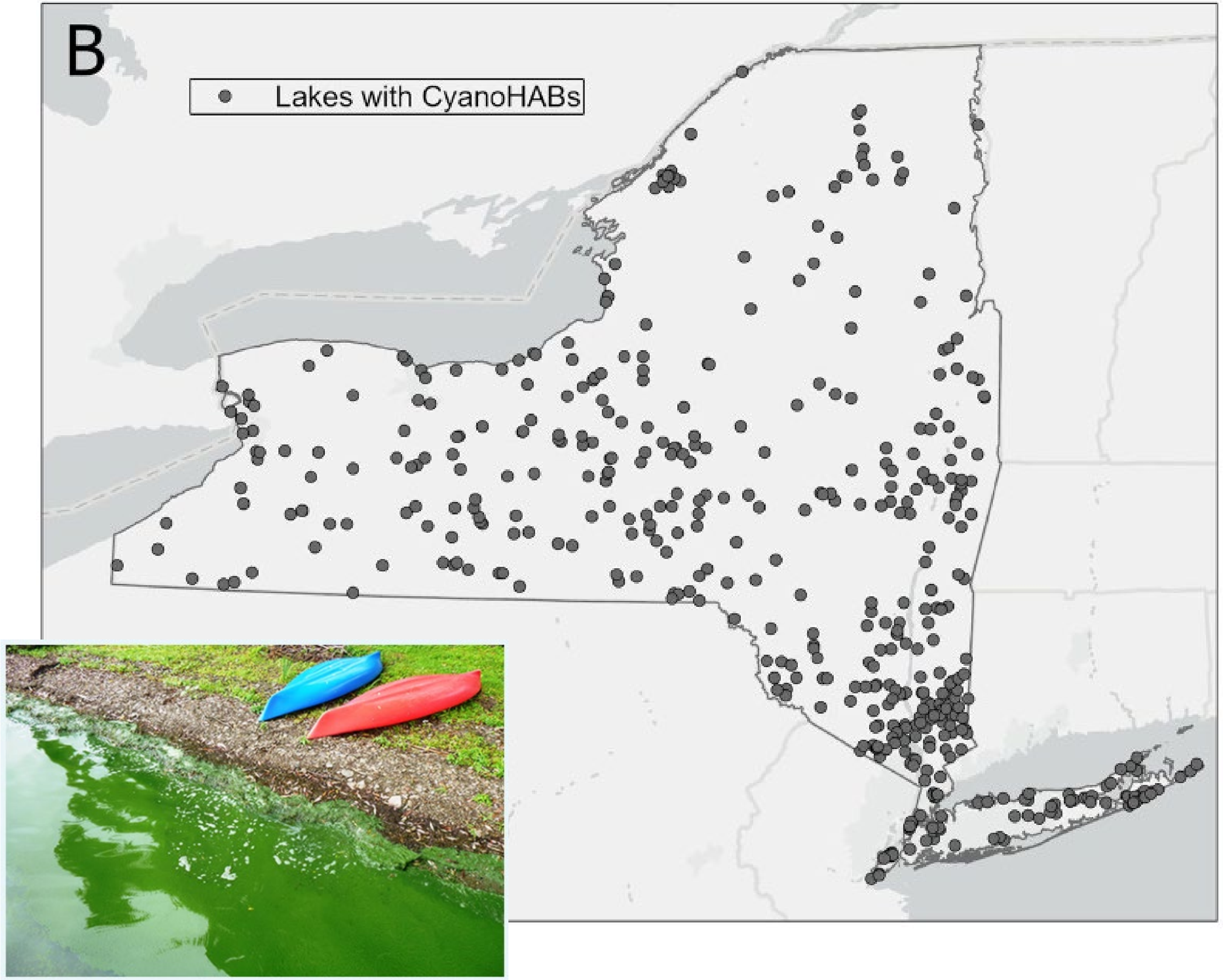


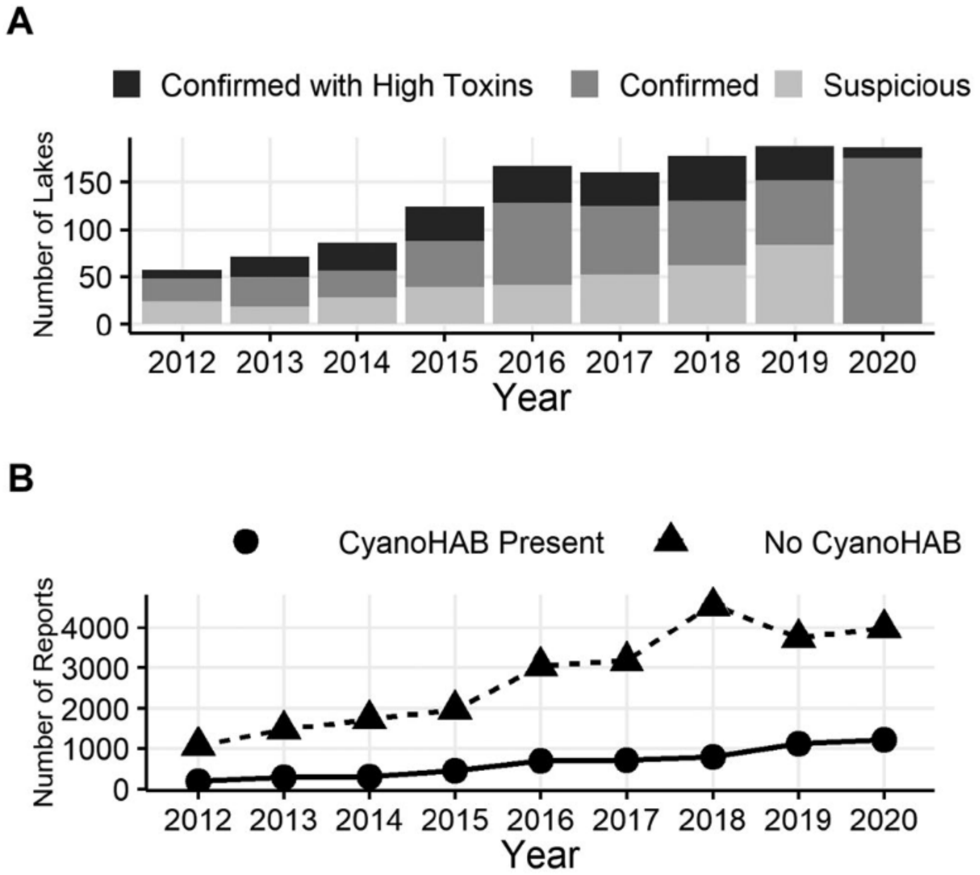
EPA Climate Change Indicators



Lake ice is a defining feature of northern lakes. Loss impacts both ecology & human uses.

Algal blooms are widespread in NY and increasing over time.

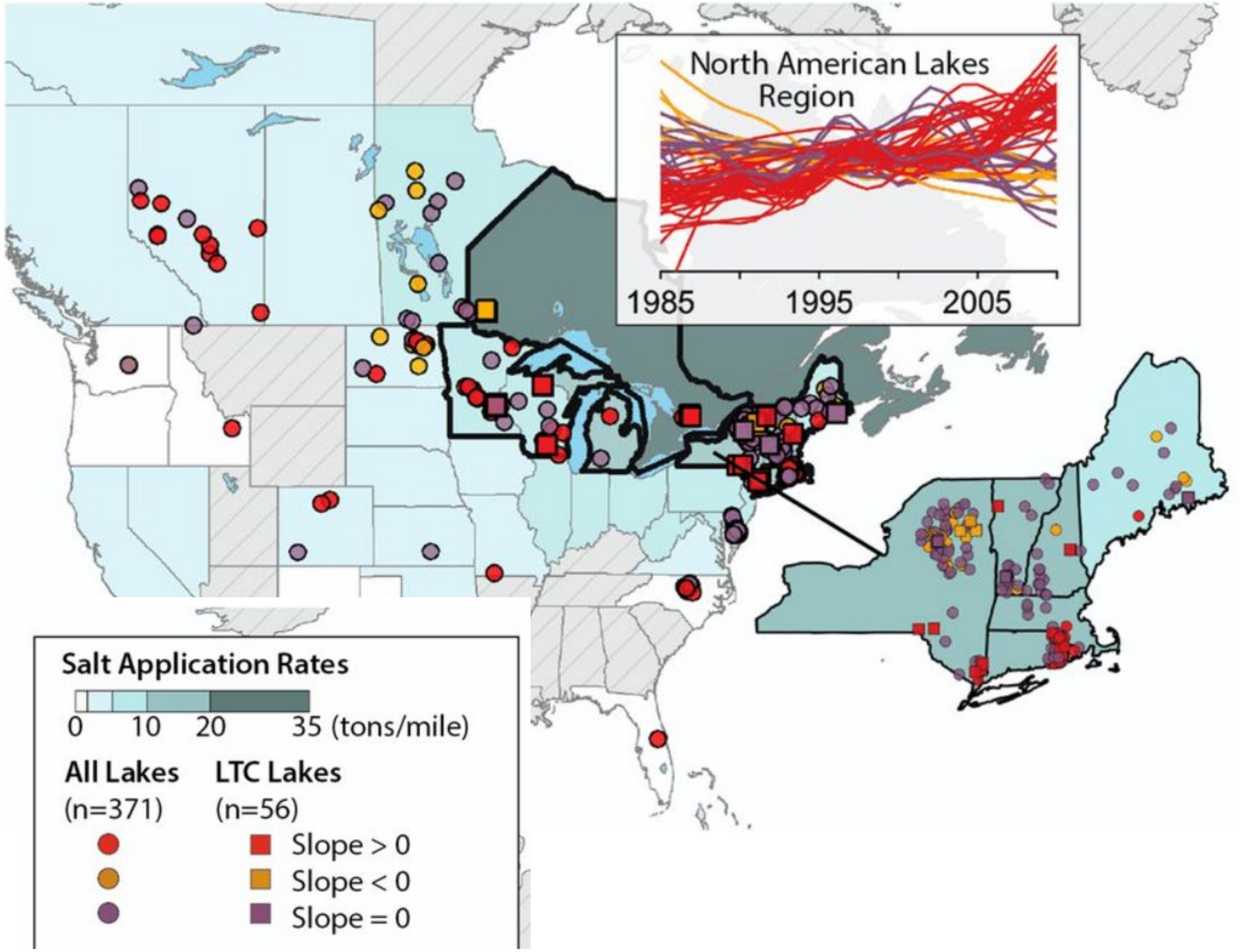




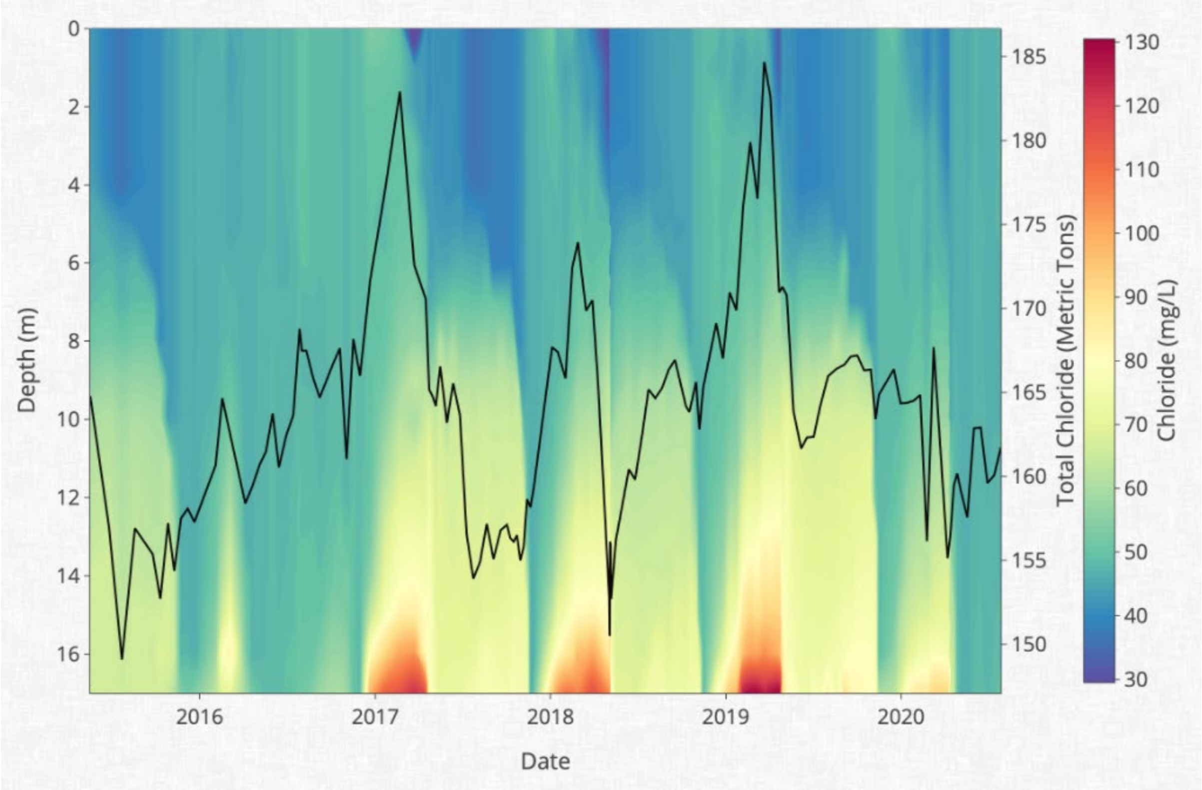
Gorney et al., 2023

Salinization

National salinization



Mirror Lake, NY



Salt is toxic and can inhibit lake mixing, leading to anoxia in deep waters

Dugan et al. 2017

Wiltse et al. 2019

The widespread and substantial changes in the Adirondacks is a call to conduct a new lake survey

- Leverage the wealth of historical datasets to select waterbodies and assess trends
- Leverage recent technological innovations, from high-frequency sensors to eDNA
- Assess nearly all aspects of these ecosystems, from physics to fish

Planning workshop: July 2021

Funding provided by NEW YORK STATE OF OPPORTUNITY. | NYSERDA

A consortium approach

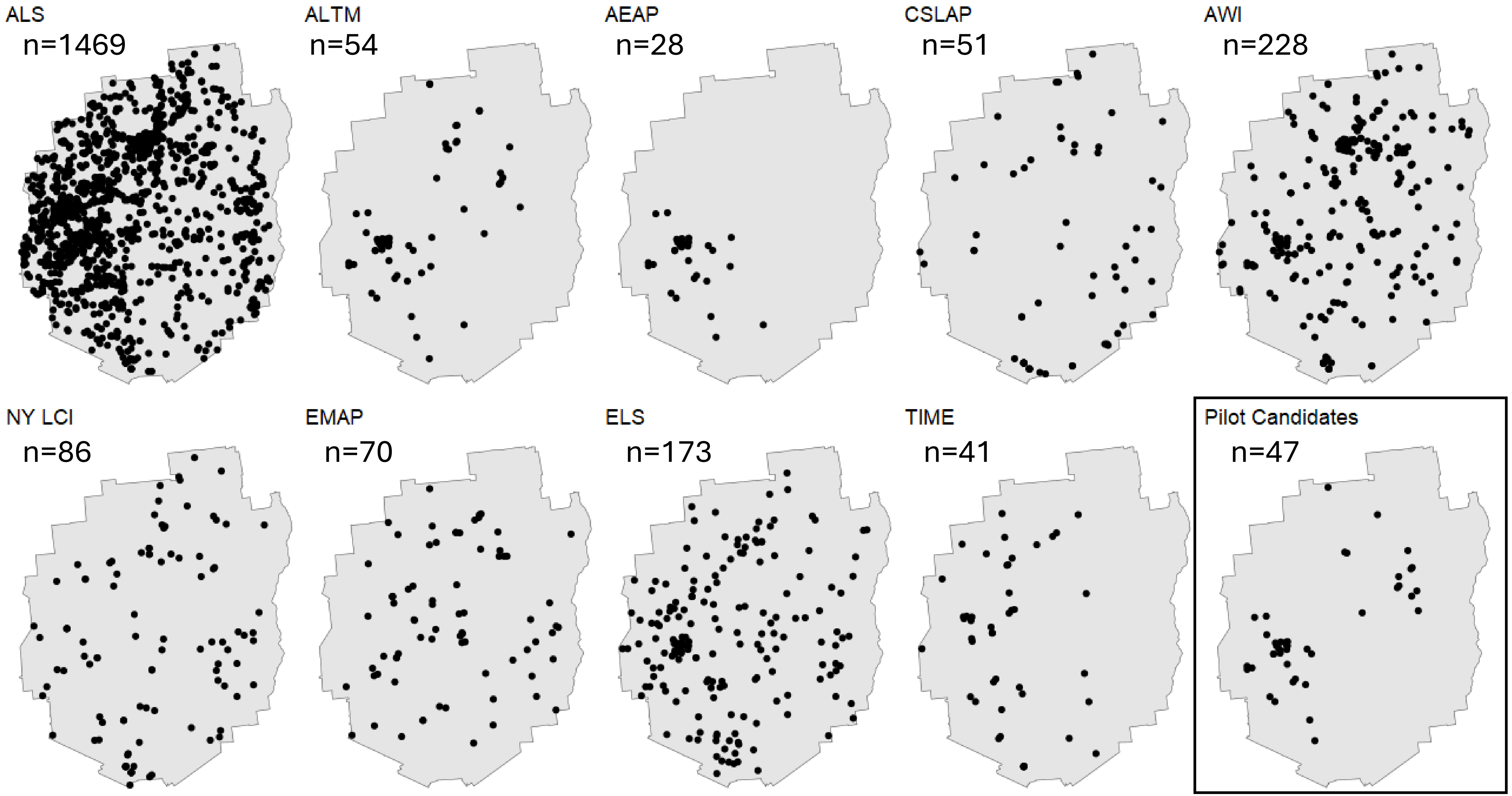
(in no particular order)

- USGS science for a changing world
- Paul Smith's College
- Adirondack Lakes Survey Corporation www.adirondacklakessurvey.org
- NYS Museum New York State Museum
- New York City College of Technology City Tech
- New York State Department of Environmental Conservation
- Syracuse University
- ESF State University of New York College of Environmental Science and Forestry
- The Nature Conservancy
- New York State Office of the Attorney General
- Cornell University
- Rensselaer
- Ausable River Association
- Adirondack Council Preserving Water, Air and Wildlands
- New York State of Opportunity. | NYSERDA
- EPA United States Environmental Protection Agency

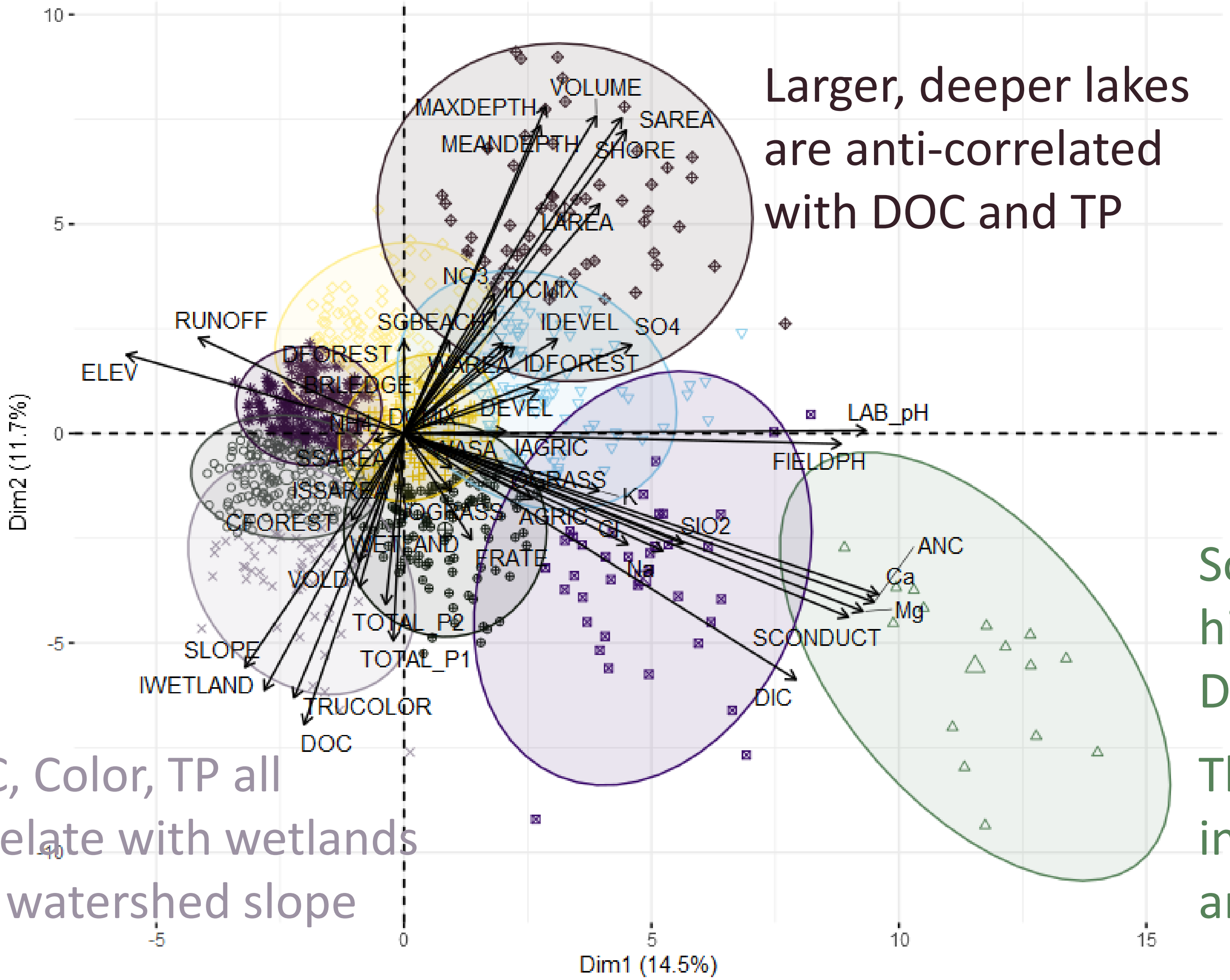
Four motivating themes

- How has the warming climate and increasing severe storms affected baseline conditions of water temperature, oxygen, and nutrients in Adirondack lakes?
- How is climate change affecting the biota of Adirondack lakes?
- How is climate change affecting carbon cycling, including the role of lake browning in carbon cycling?
- Are harmful algal blooms (HABs) becoming more prevalent under climate change?

Data mining of historical Adirondack lake sampling programs



Clustering the 1980s Adirondack Lake Survey



Larger, deeper lakes are anti-correlated with DOC and TP

Some lakes have very high conductivity, ANC, DIC, Ca

These are somewhat independent of DOC and TP

DOC, Color, TP all correlate with wetlands and watershed slope

SCALE Sampling Design

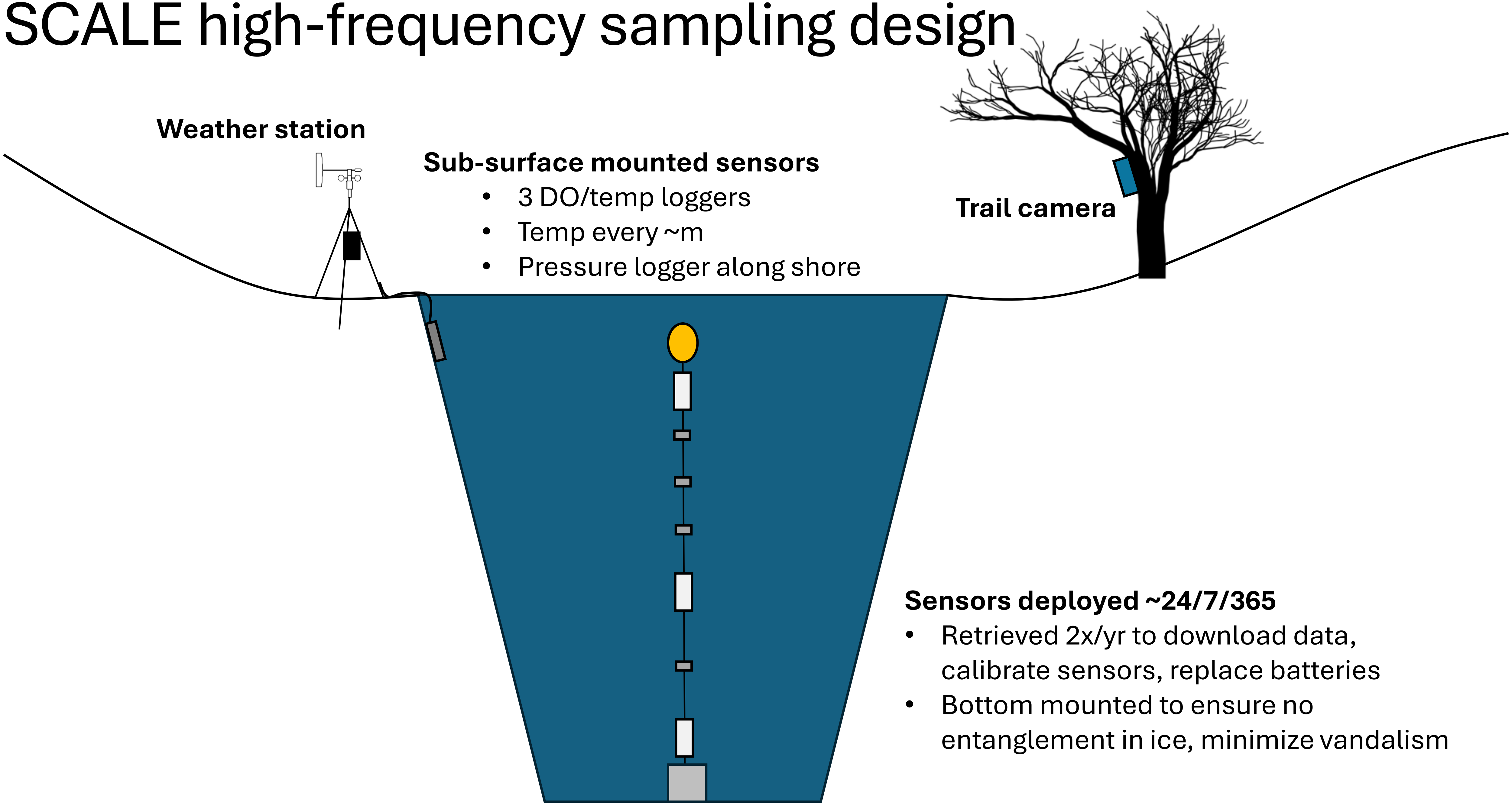
A NESTED APPROACH FOR SURVEYING OVER 300 ADIRONDACK LAKES AND PONDS

CLASS 1: HIGH INTENSITY
Ten lakes will undergo the greatest sampling efforts. These lakes will be monitored continuously via high frequency sensors over the three-year study period. In addition, they will receive up to six visits per season to perform the full suite of field sampling and analysis.

CLASS 2: MODERATE INTENSITY
Moderate Intensity: 30 additional lakes will receive the high intensity treatment, but for a one-year duration. Groups of 10 lakes will rotate annually over the three-year study period.

CLASS 3: LOW INTENSITY
Low Intensity: Up to 260 of these candidate lakes will be sampled on a one-time basis over three years. These lakes will be sampled to establish baseline conditions.

SCALE high-frequency sampling design



Sub-surface mounted sensors
- 3 DO/temp loggers
- Temp every ~m
- Pressure logger along shore

Sensors deployed ~24/7/365
- Retrieved 2x/yr to download data, calibrate sensors, replace batteries
- Bottom mounted to ensure no entanglement in ice, minimize vandalism

Analyte list

Chemical & Biological attributes

- Al (total, organic, inorganic)
- Hg, MeHg
- Ca, Cl, Fe, Mg, Na, Zn, Se
- ANC, DIC
- N & P species (TN, TP, TDN, NH4, SRP)
- TSS, NVSS
- SiO2
- SO4
- Color, dissolved absorbance, DOC, EEMs
- Chlorophyll a
- Phytoplankton community
- Zooplankton community
- eDNA for mollusks, fish, AIS
- Stable isotopes: C, N, H
- Cyanobacteria toxins

Field measurements (water column profile)

- Light attenuation, Secchi disk
- Sonde profile
    - Temperature
    - pH/ORP
    - Conductivity,
    - Dissolved oxygen
    - Turbidity
    - fDOM
    - Chlorophyll
    - Phycoerythrin fluorescence
- Phytoplankton taxonomic groups (BBE fluoroprobe)
    - Green algae
    - Blue-green algae/cyanobacteria
    - Diatoms/dinoflagellates
    - Cryptophytes
- Greenhouse gases
    - CO_2, CH_4, N_2O

SCALE timeline

- 2023-2024: SCALE Pilot effort (Complete)
  - Data mining, modeling, and remote sensing work
  - Methods development (eDNA, stable isotopes, C characterization)
- 2025-2027: Field operations
  - Winter 2025-2026: Community meeting
- 2028 and beyond: Data analysis, visualization, assessments, and reporting

Thank you!

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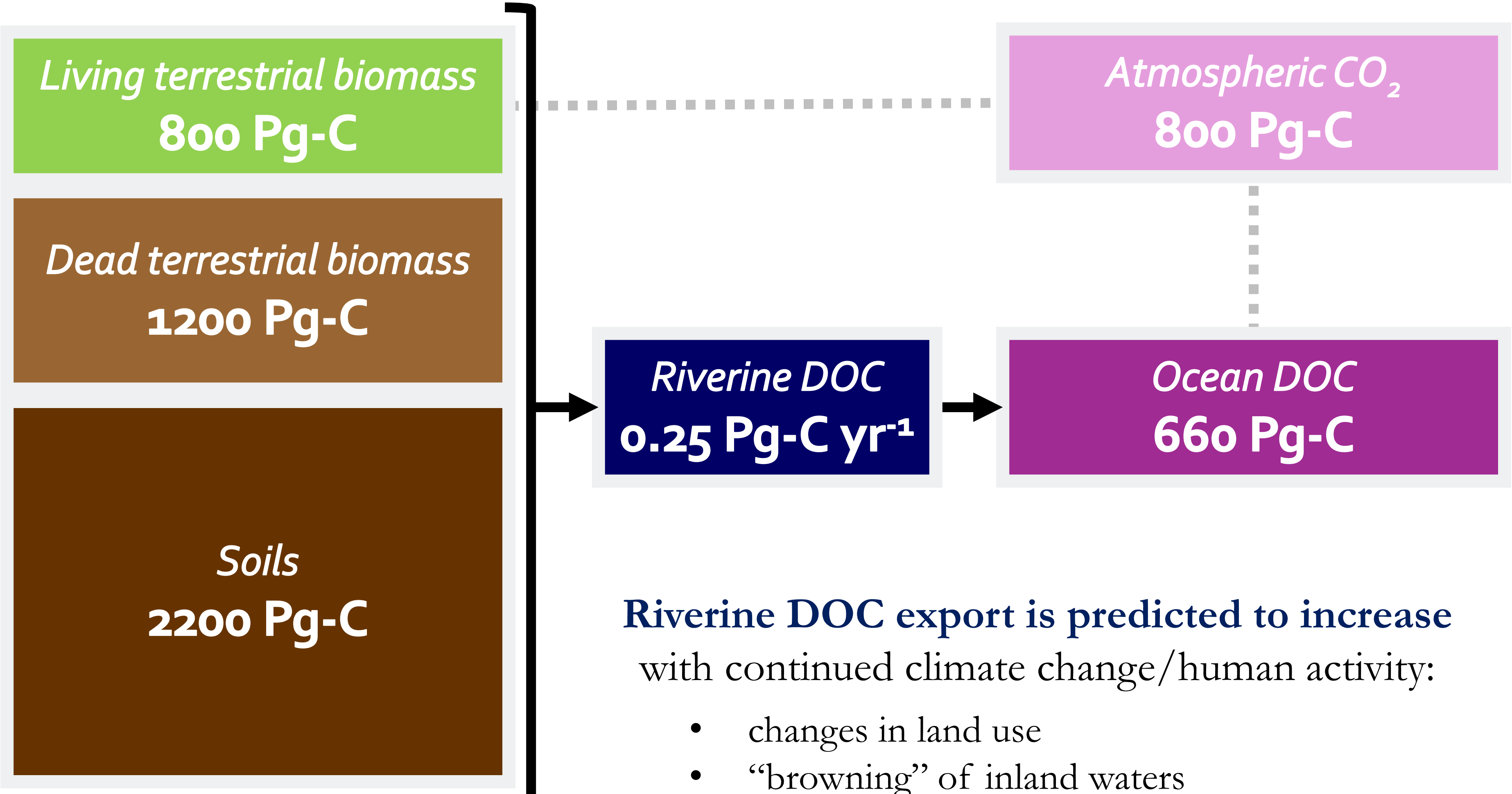
Support from:

Thank you!

Role of dissolved organic carbon (DOC) in global cycles

on land | *inland waters* | *open ocean*



$1\ Pg = 10^{15}\ g$

Riverine DOC export is predicted to increase with continued climate change/human activity:

- changes in land use
- "browning" of inland waters
- enhanced severity/frequency of storm events

Hedges et al. (1997) Organic Geochemistry

Early research in the 1960s highlighted the potential of air pollution to reduce the pH in precipitation.

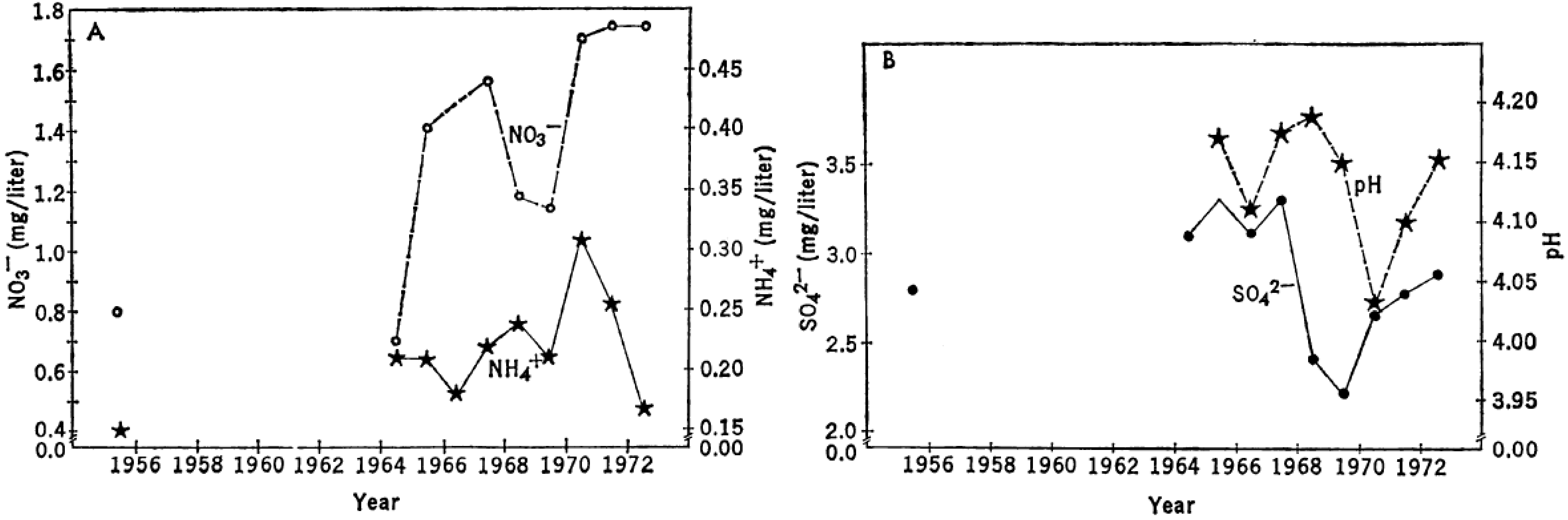


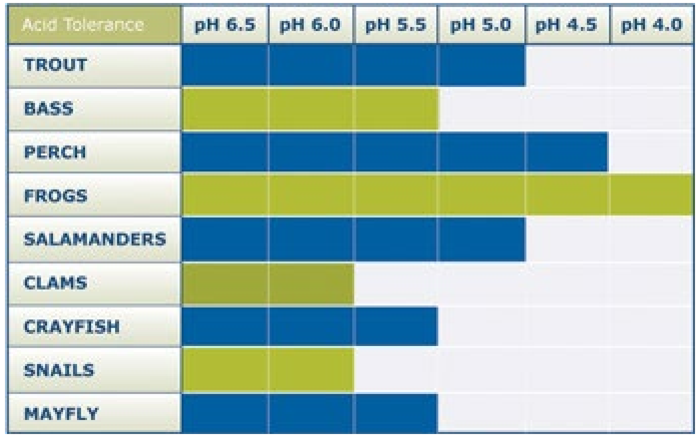
Fig. 1. Weighted annual concentrations of NO_3^- and NH_4^+ (A) and SO_4^{2-} and the *p*H (B) of precipitation at the Hubbard Brook Experimental Forest in New Hampshire. Values for 1955–1956 were estimated from Junge and Werby (*35*) and Junge (*36*).

Gene Likens, Cary Institute for Ecosystem Studies discovered acid rain (Likens and Bormann 1974, Science).

Chromophoric Dissolved Organic Matter (CDOM)

- Source of carbon and nutrients
- Derived from both terrestrial and aquatic sources
- Indicator of terrestrial vegetation
- Changing; e.g., recovery from acidification
  - “Ozone of the underwater world”

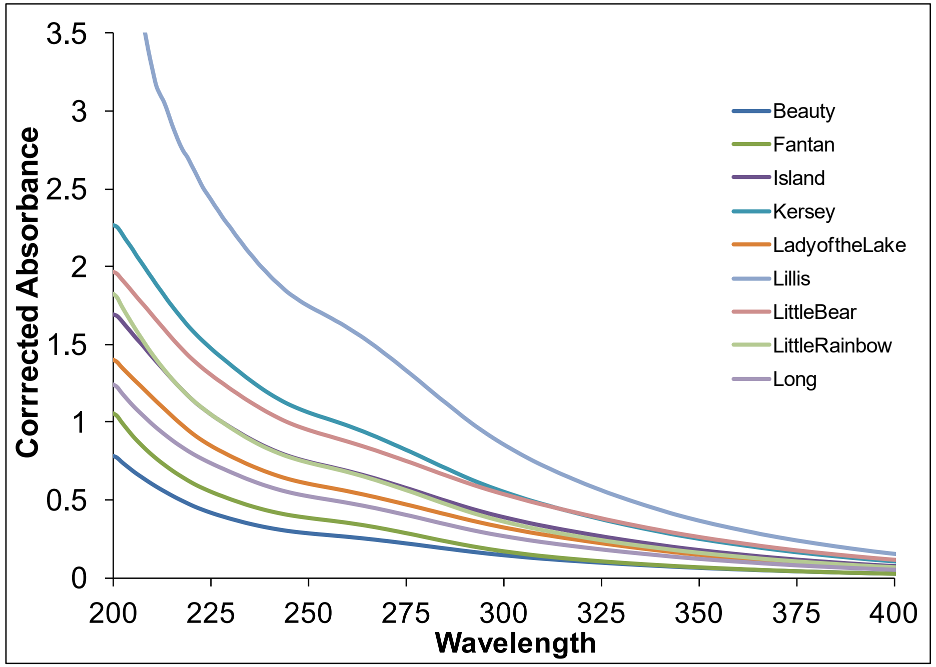
What are the ecological effects of acidification?

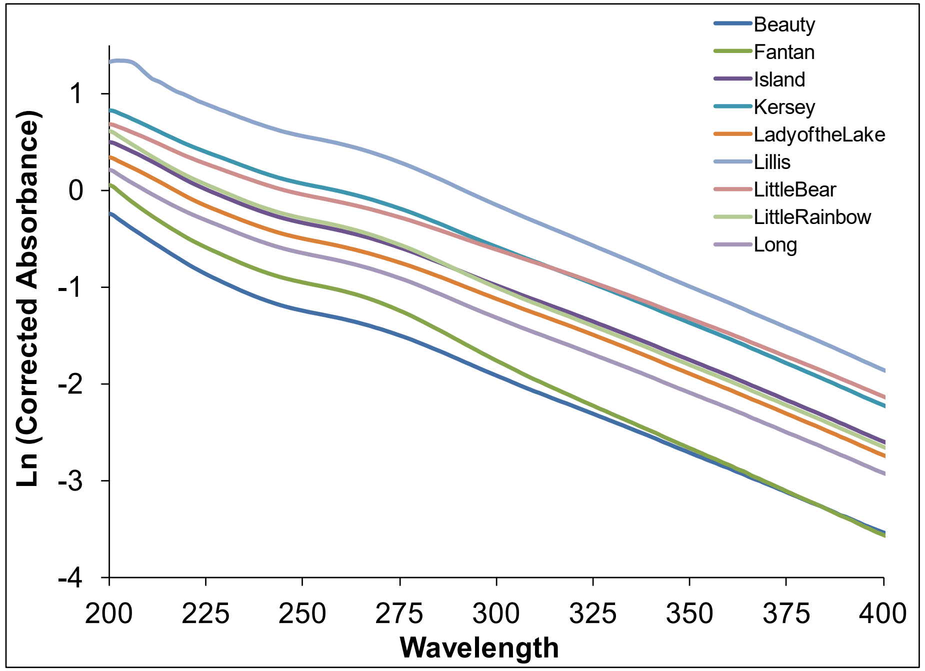


- Decrease in pH
  - Weathering rates increased
  - Degrades built and natural structures
- Decrease in primary production
  - Terrestrial: dying forests, reduced GPP
  - Aquatic: “Clean” clear water – because algae can’t grow & DOM not soluble!
- Increase in aluminum mobilization to aquatic ecosystems
  - Al highly toxic to fish (it reduces gill function, leading to asphyxiation)
- Decrease solubility in dissolved organic matter (DOM)
  - Increases water clarity, reduced CO_2 emissions
- Impedes nutrient cycles
  - Calcium, Magnesium, Potassium
  - Ca cannot be pulled back seasonally, leading to Ca deficiency over time.
  - Decline in economically important vegetation (e.g., Sugar Maples)

CDOM often measured using absorbance scans.

Absorbance at any wavelength can be estimated given a slope and absorbance at one wavelength



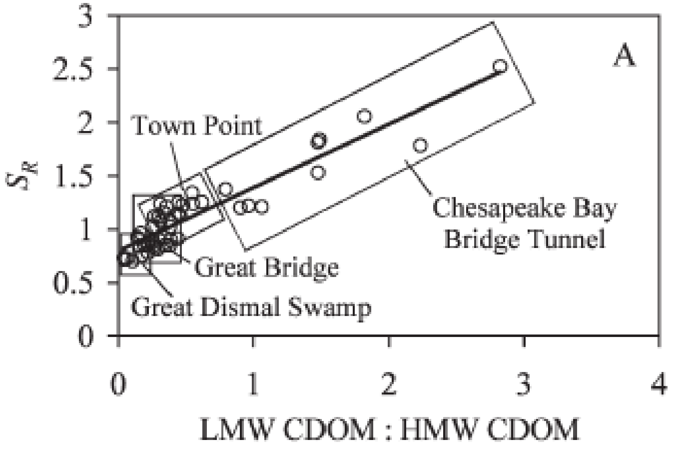


Important DOM optical properties

$S_{275\text{-}295}$

$S_{350\text{-}400}$

S_R ($S_{275\text{-}275}$: $S_{350\text{-}400}$)

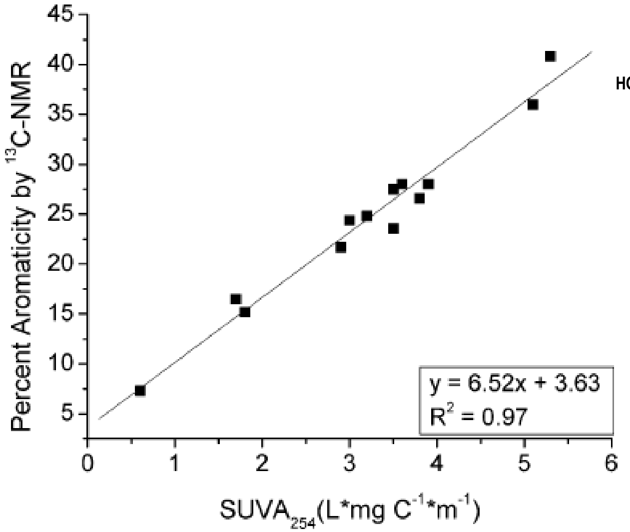


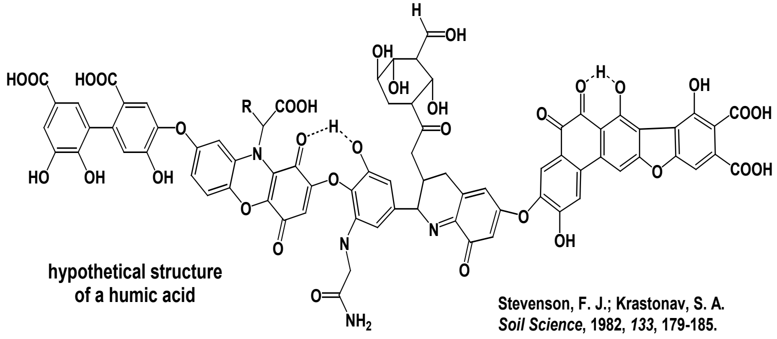
a_{440}

a_{254}

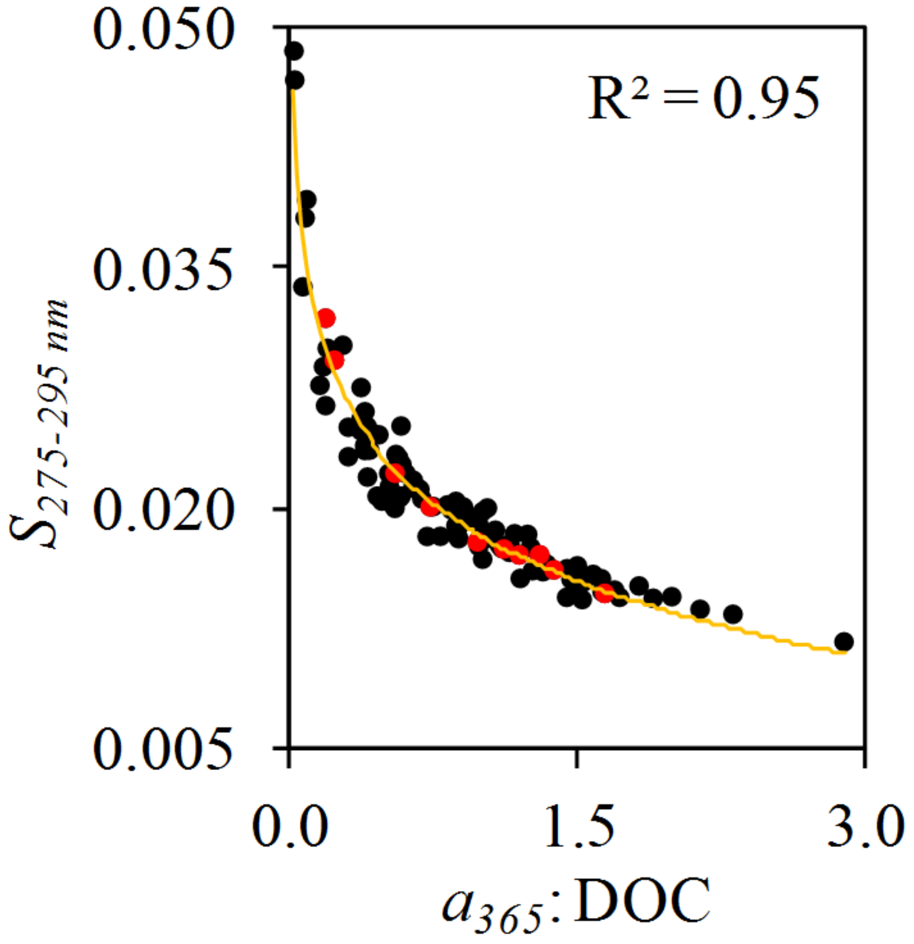
a_{254}: DOC

a_{250}: a_{365}





DOC specific absorbance is closely related to spectral slope.



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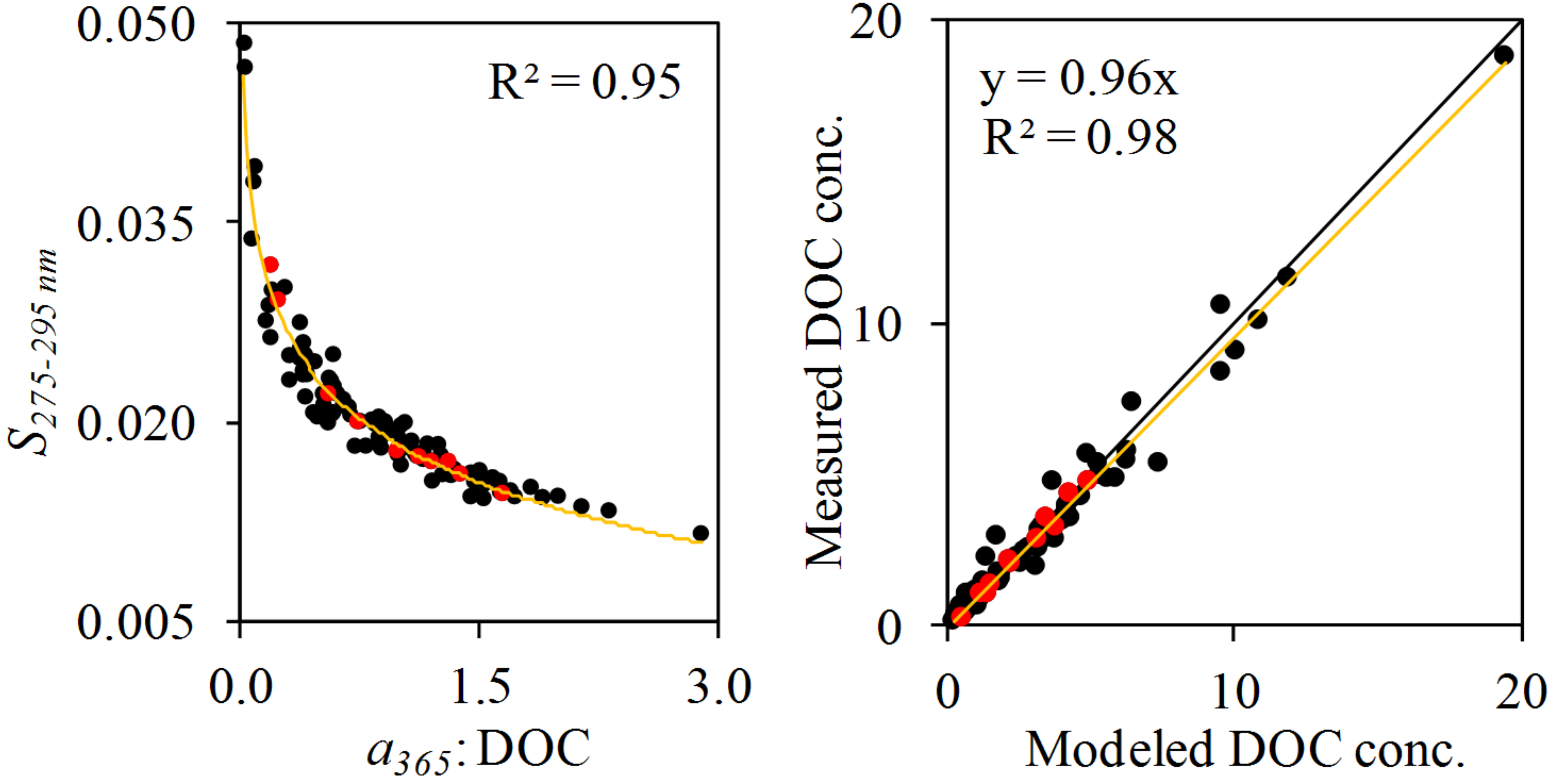
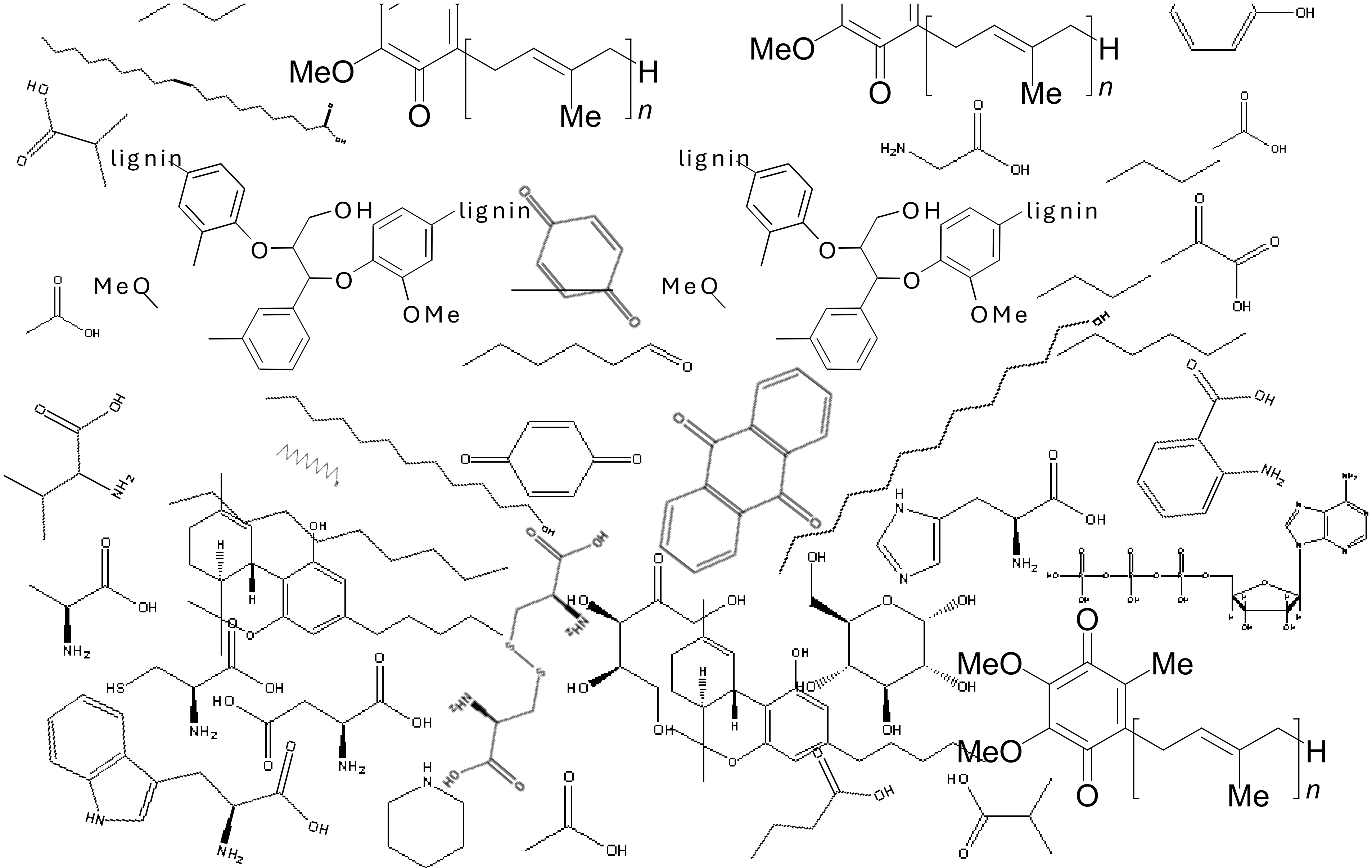


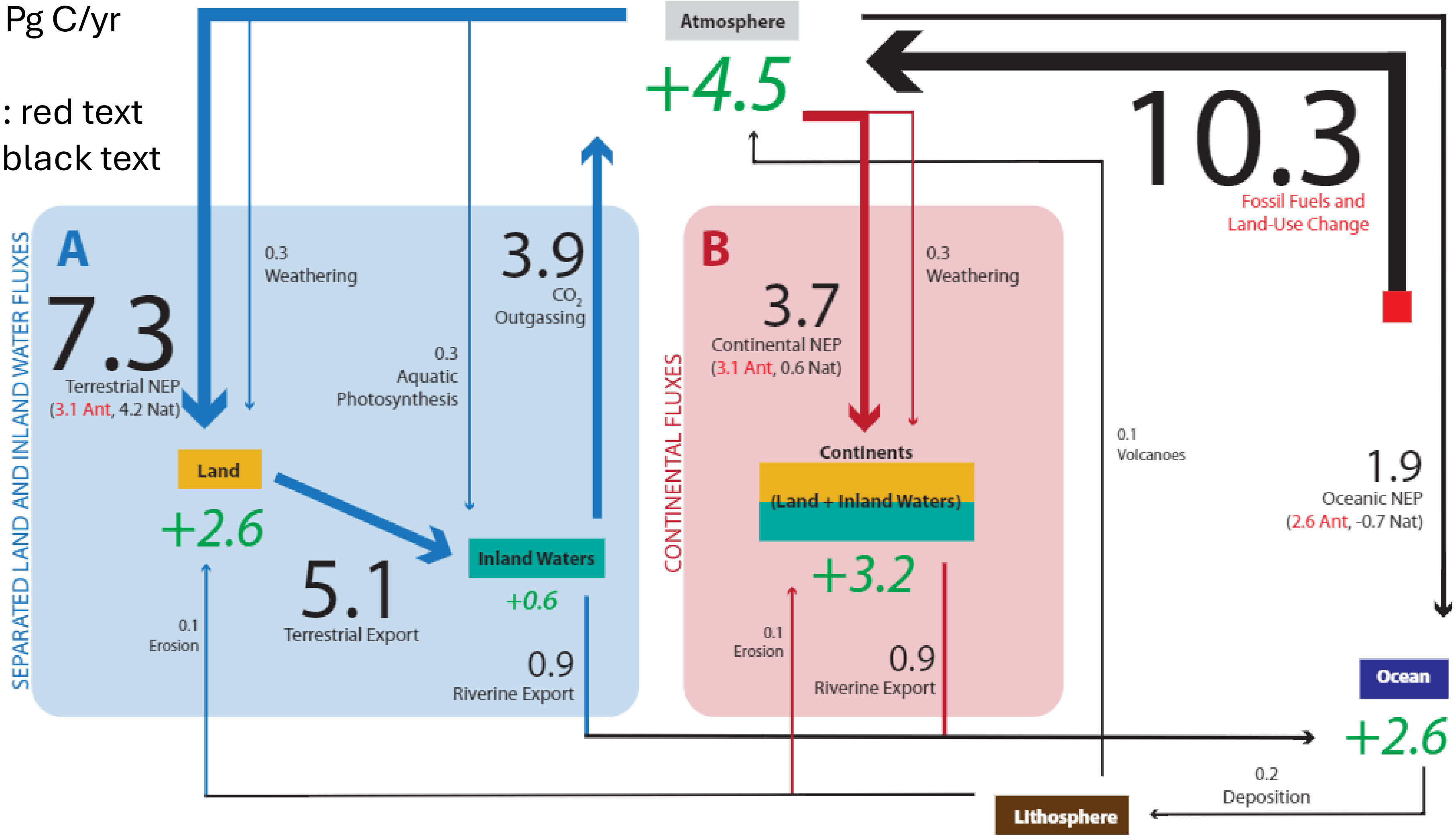
Can we estimate DOC if we can measure absorbance and spectral slope in situ?



Lake play an important role in the global carbon cycle.

Net C fluxes in Pg C/yr

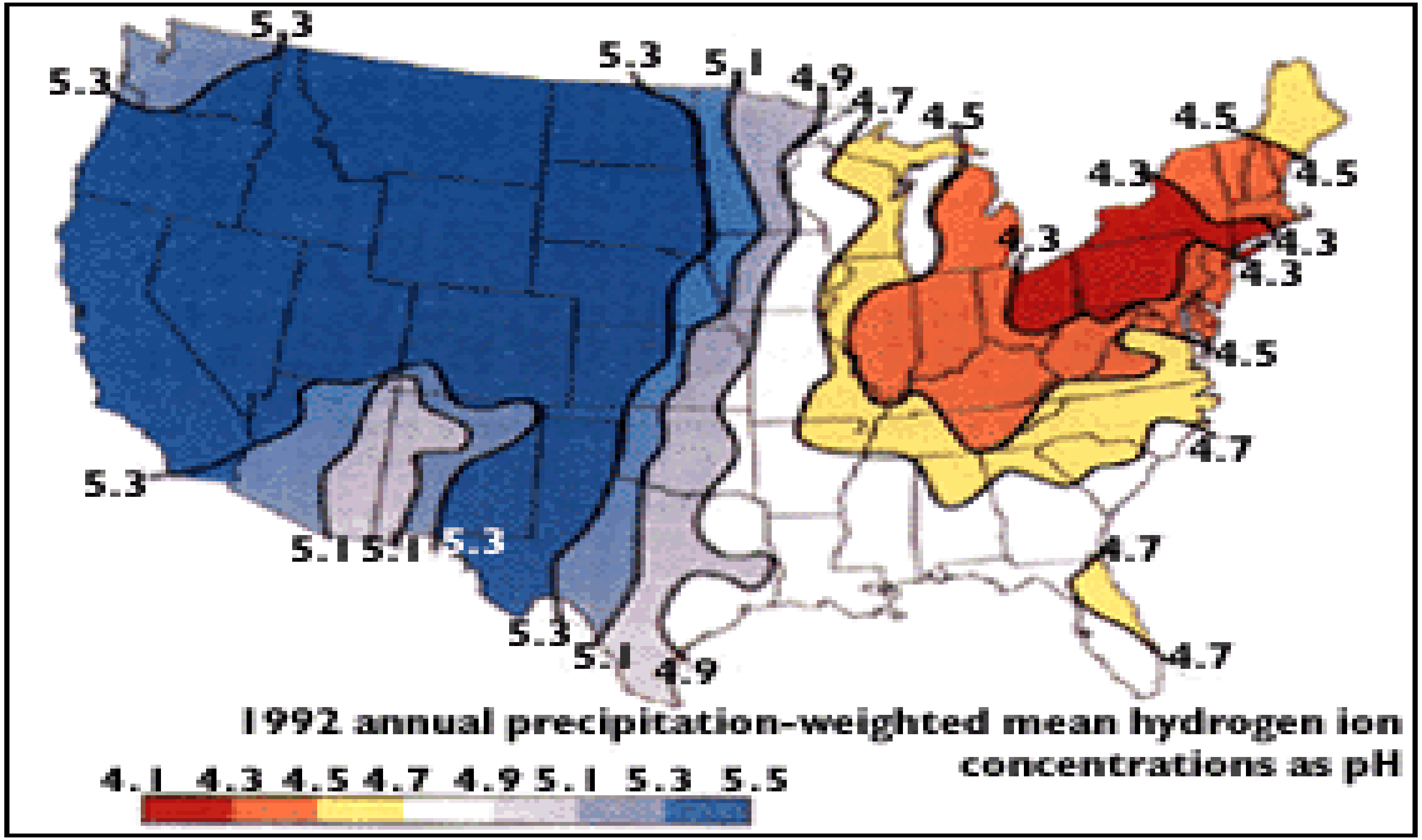
Anthropogenic: red text
Pre-industrial: black text



Blue panel and arrows (A) show fluxes between partitioned land and inland waters components.
Red panel and arrows (B) show alternate conception of the fluxes through a “continental” boundary, where land and aquatic fluxes are merged.

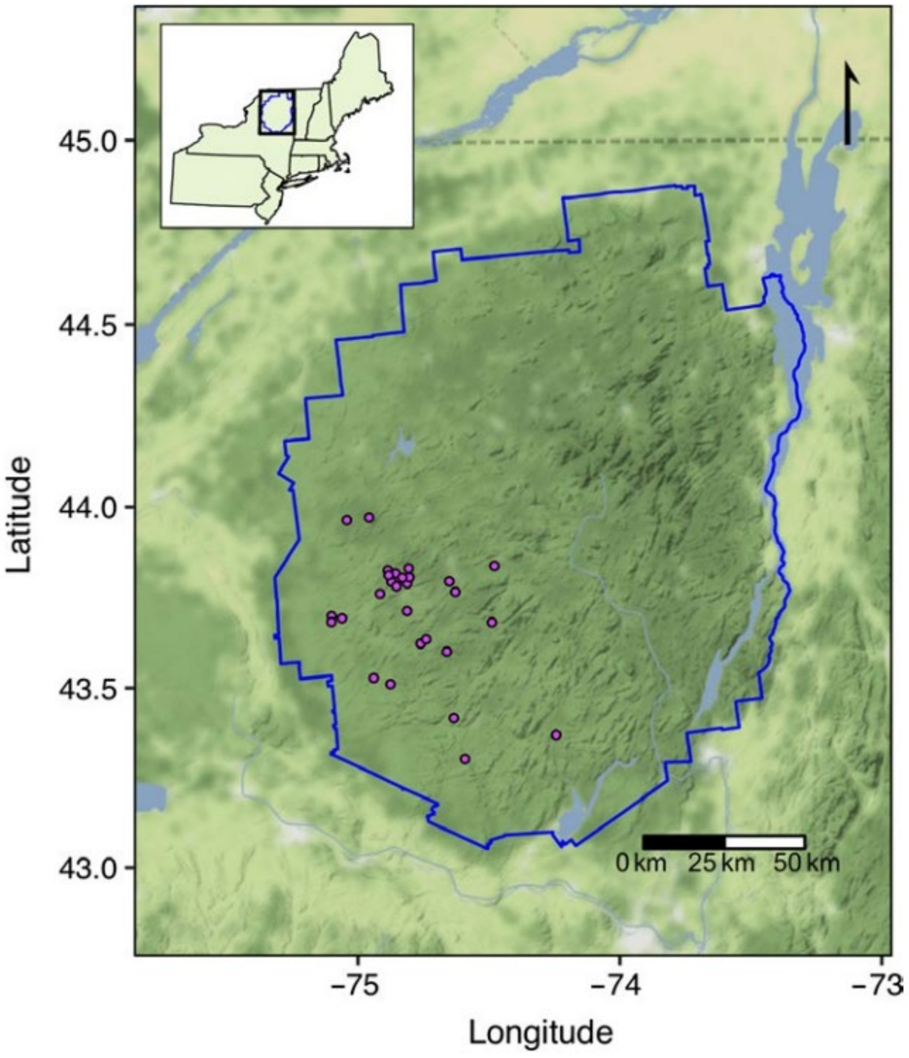
Drake et al. 2017

At peak SO_2 emissions, precipitation was highly acidic.

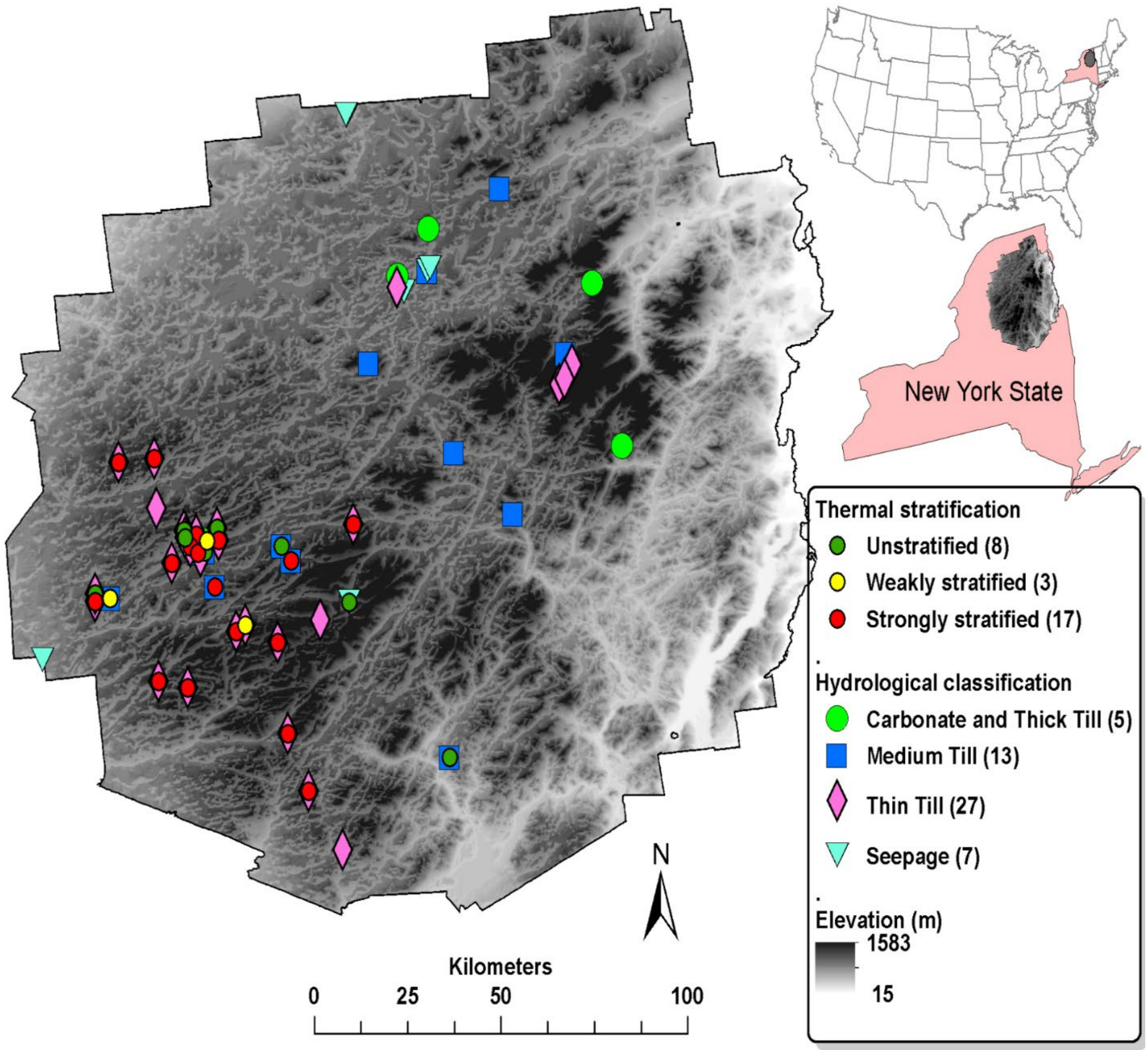


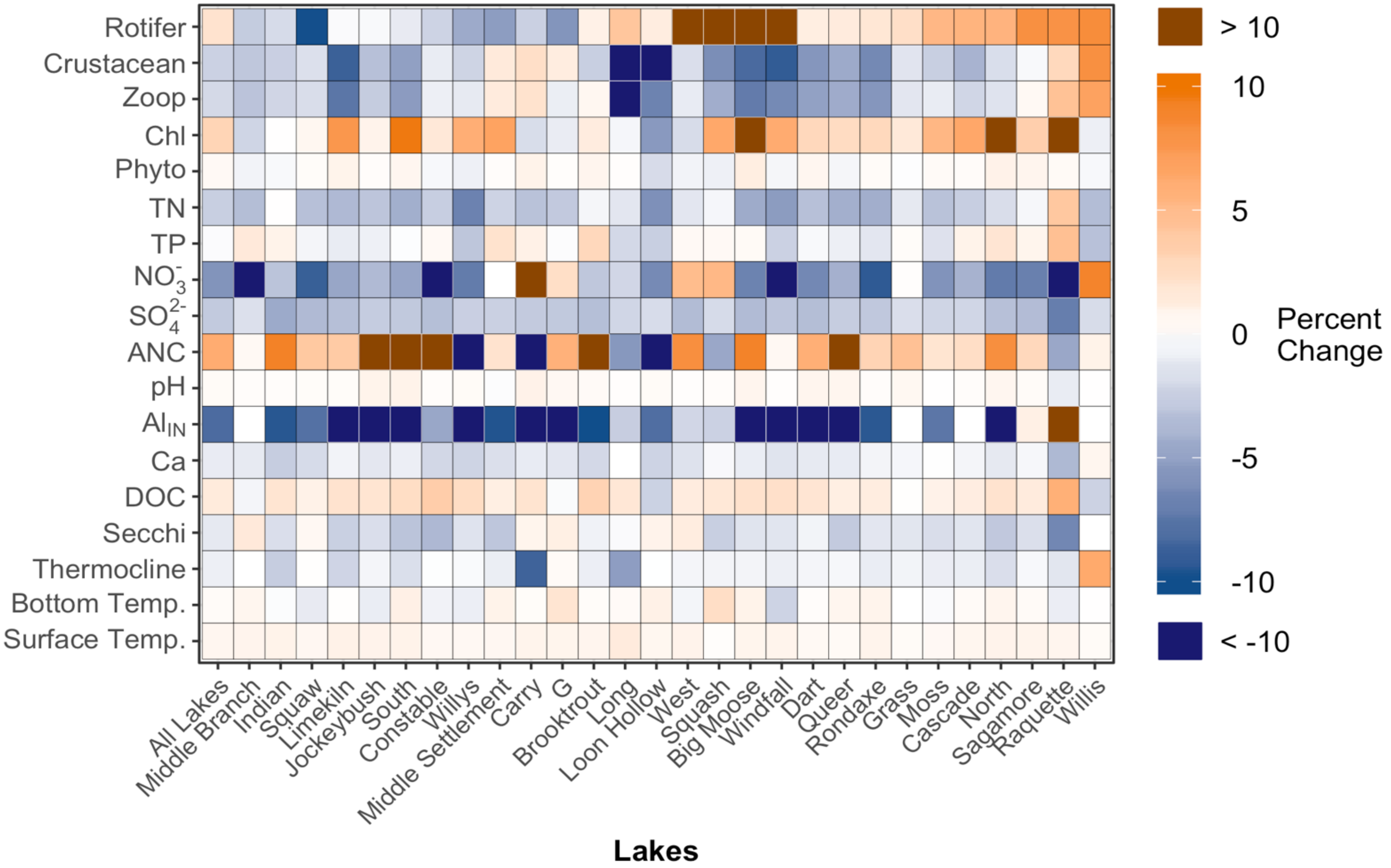
NY State monitoring ecological effects of acid deposition

Biological monitoring: 28 lakes, ~20 years



Chemical, physical monitoring: 52 lakes, ~30 years





Rotifer
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pH
Al_{IN}
Ca
DOC
Secchi
Thermocline
Bottom Temp.
Surface Temp.
All Lakes
Middle Branch
Indian
Squaw
Limekiln
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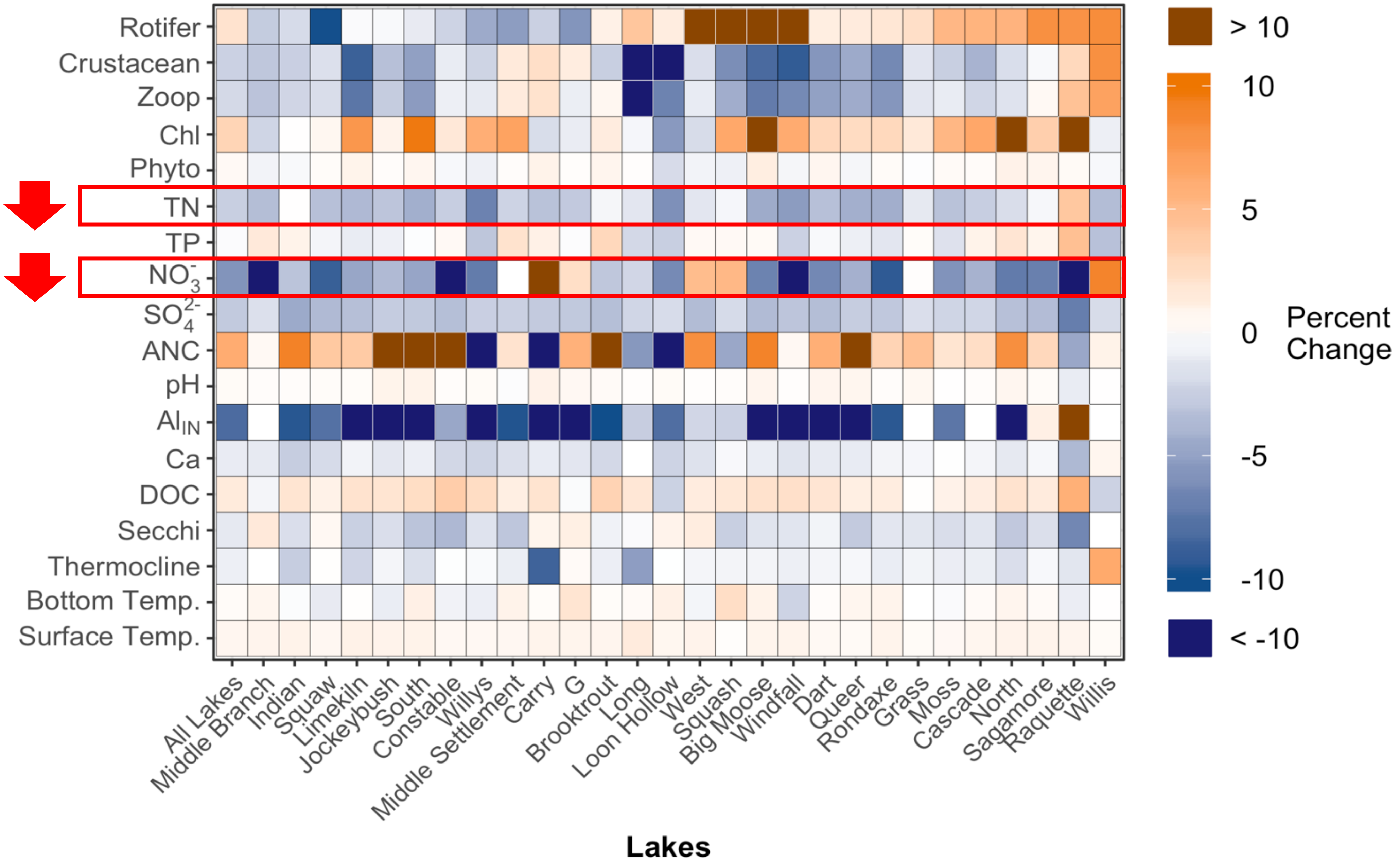

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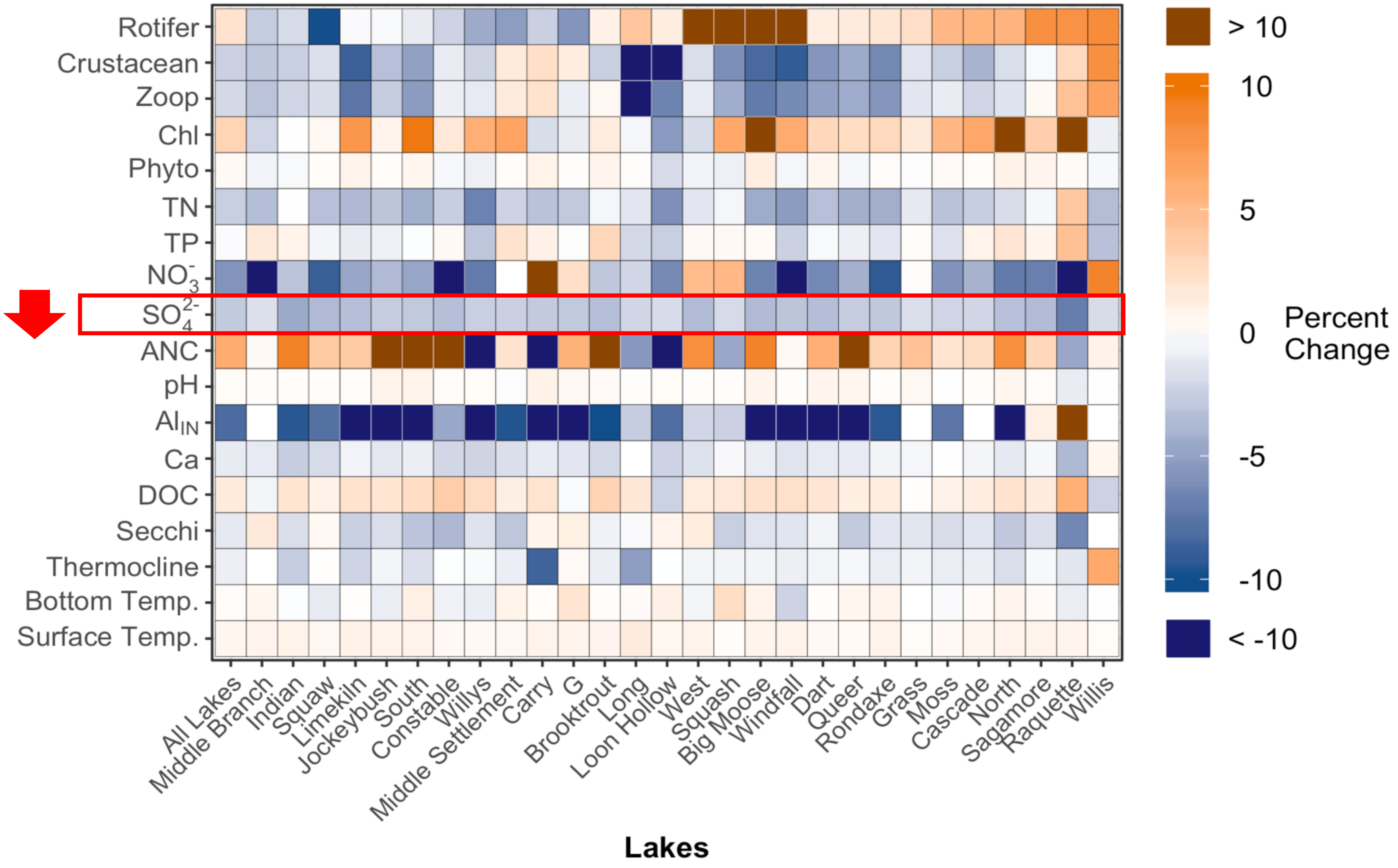
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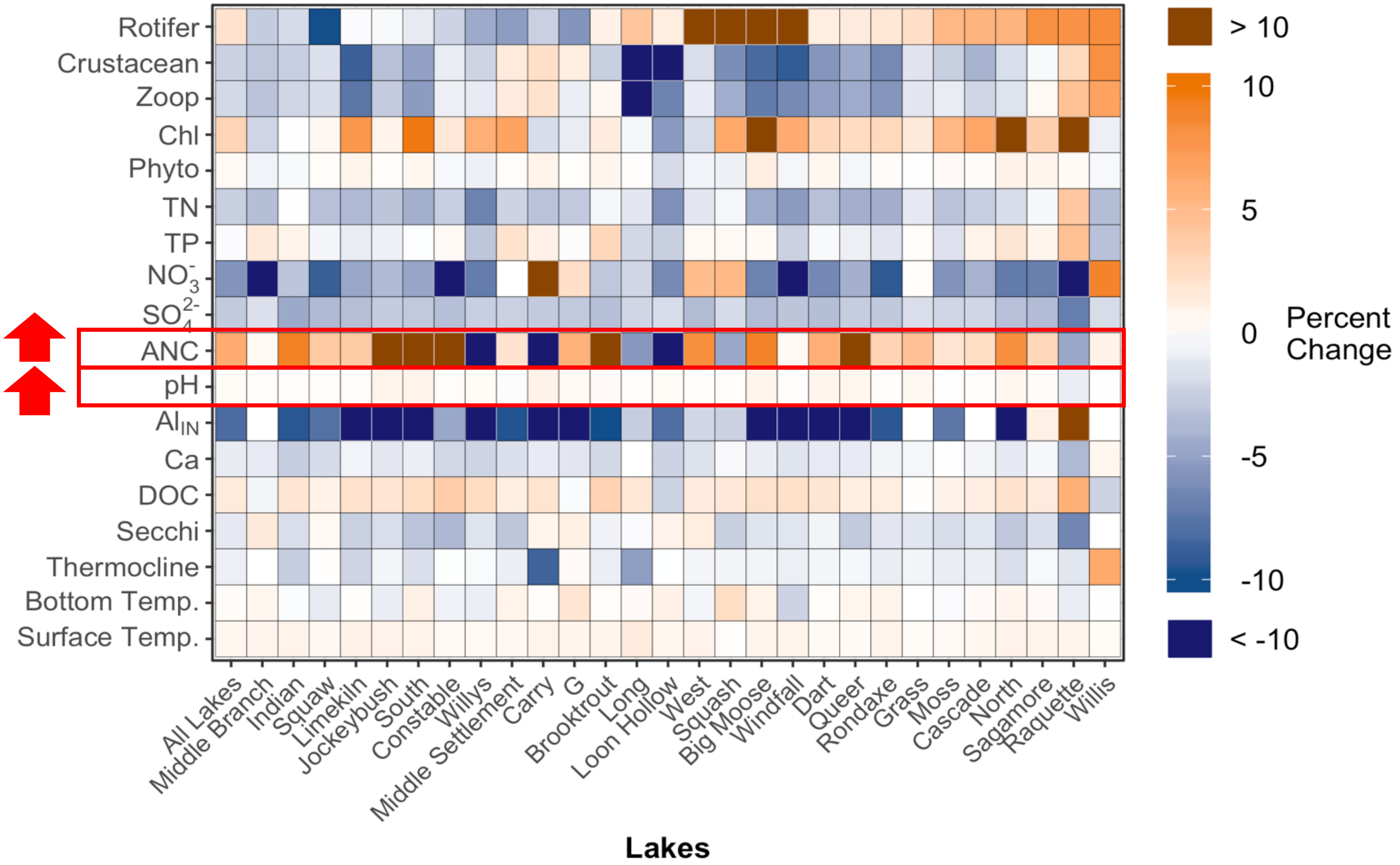

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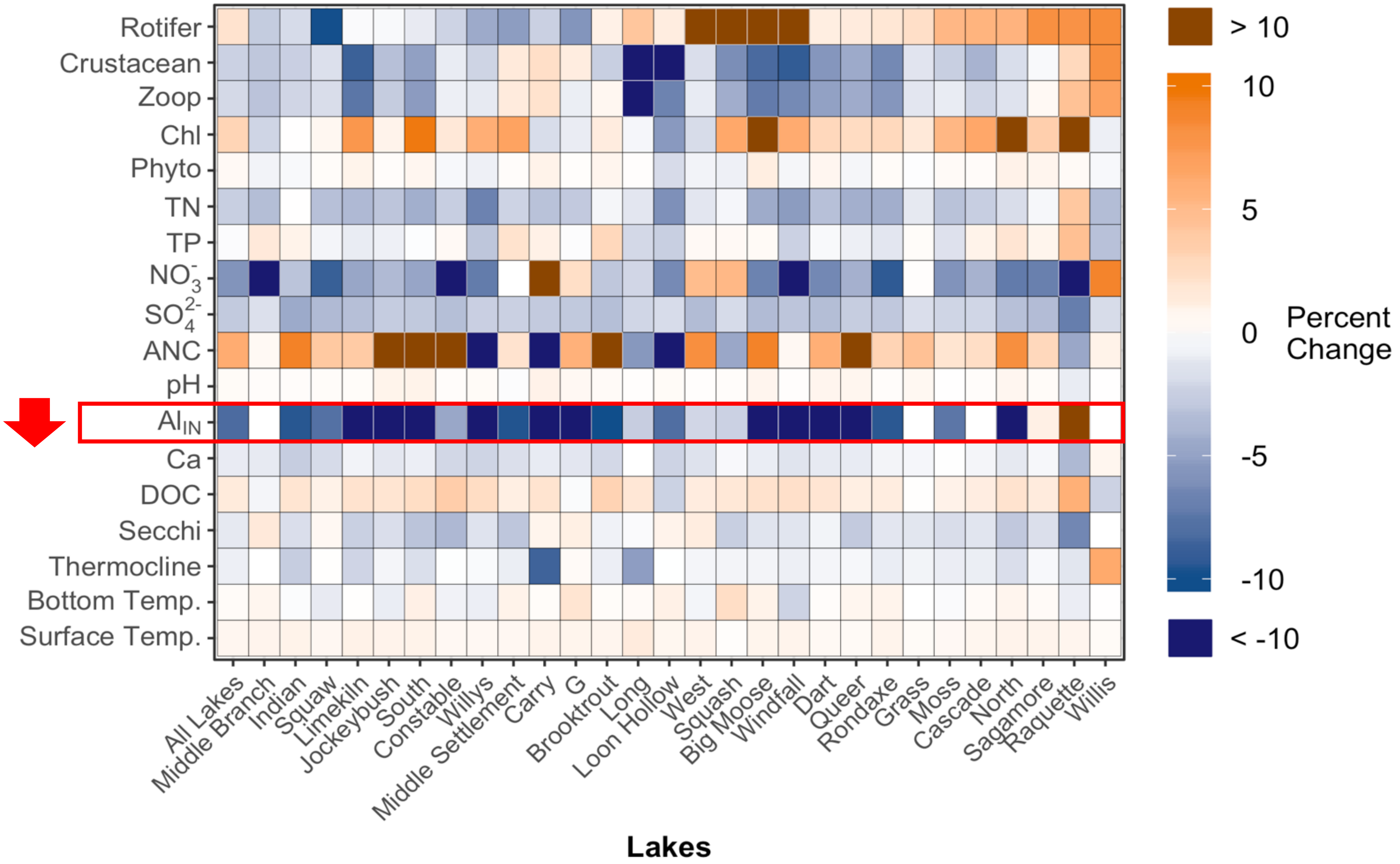

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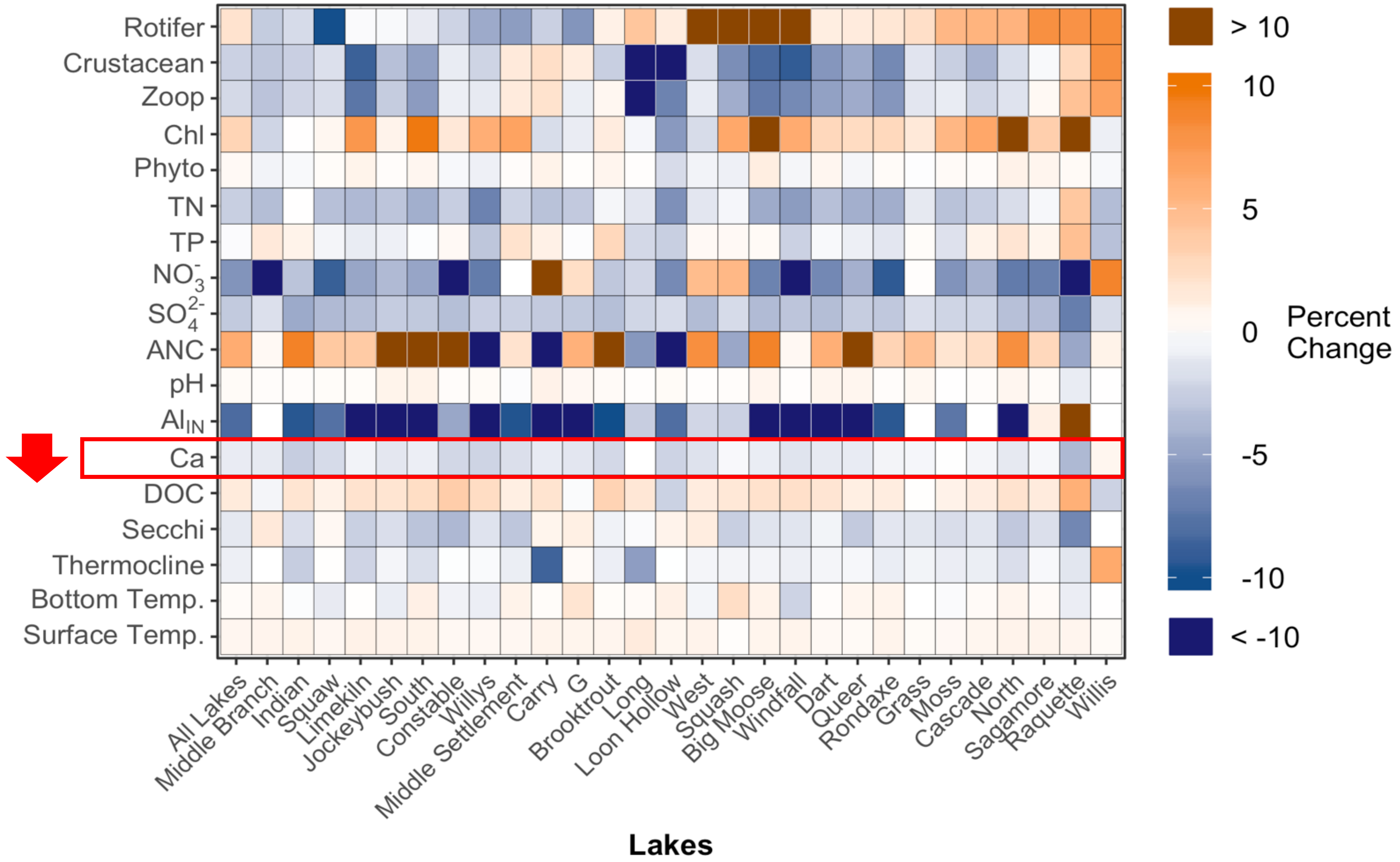

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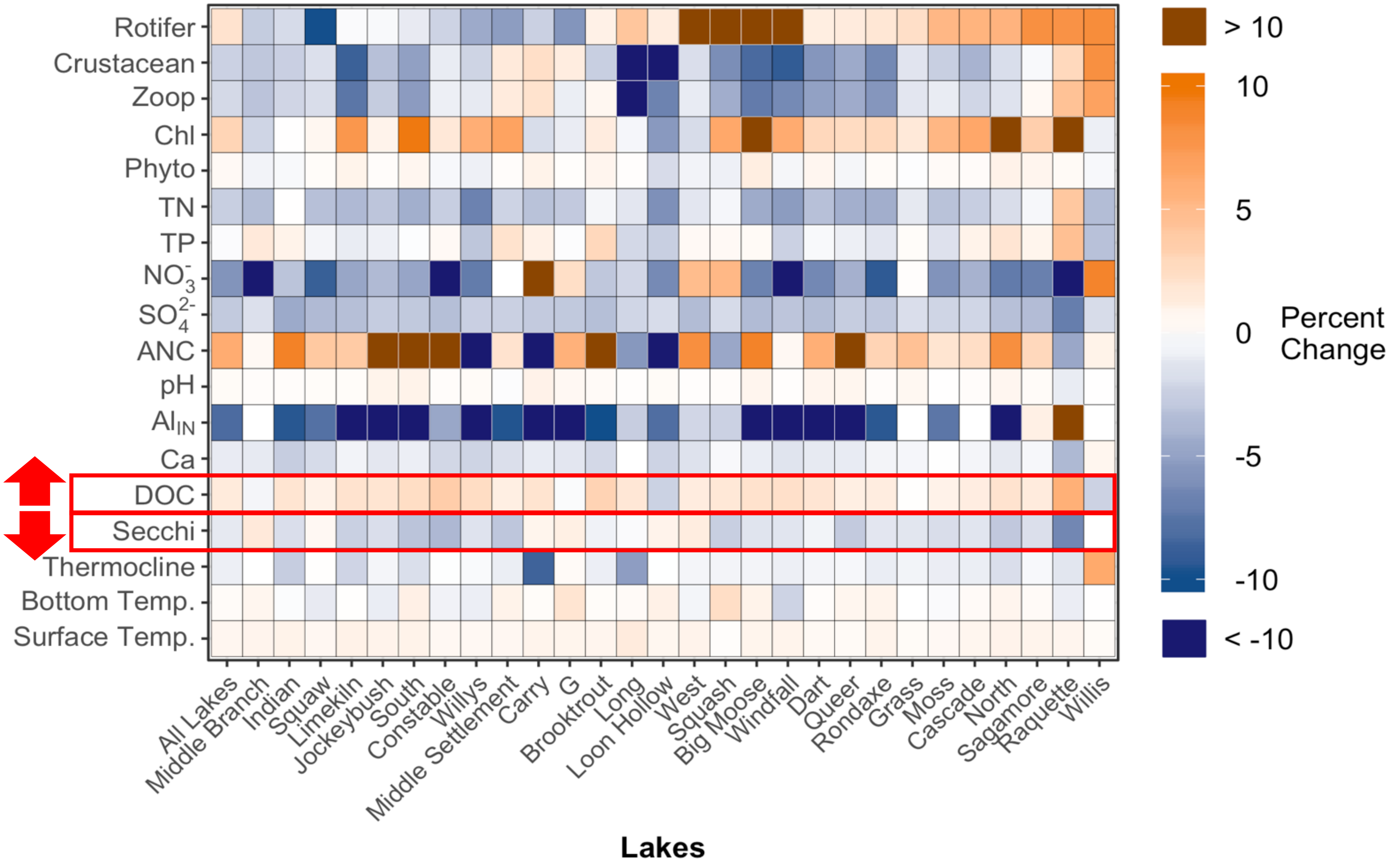
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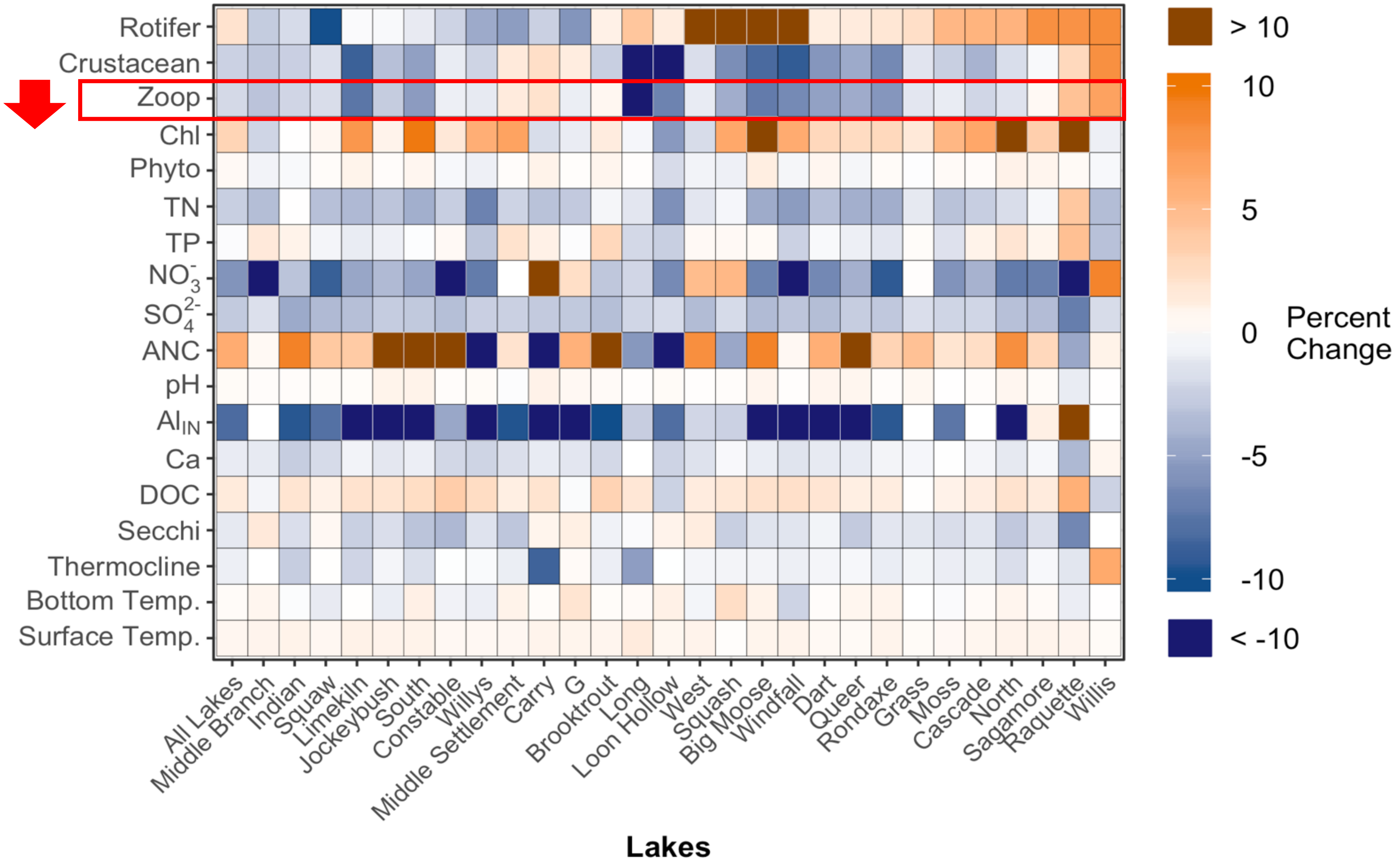

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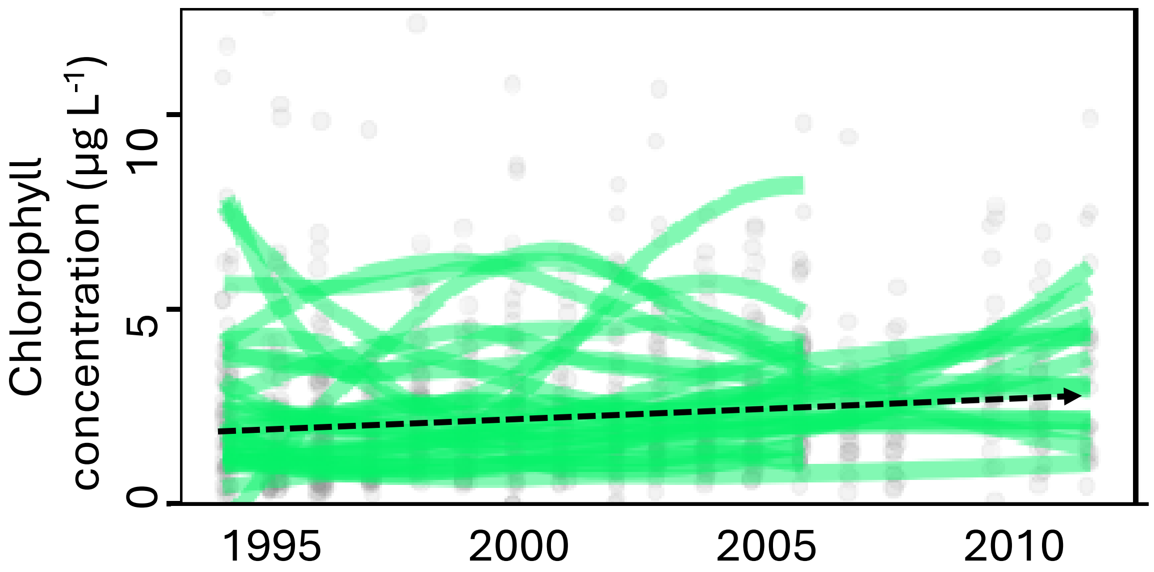
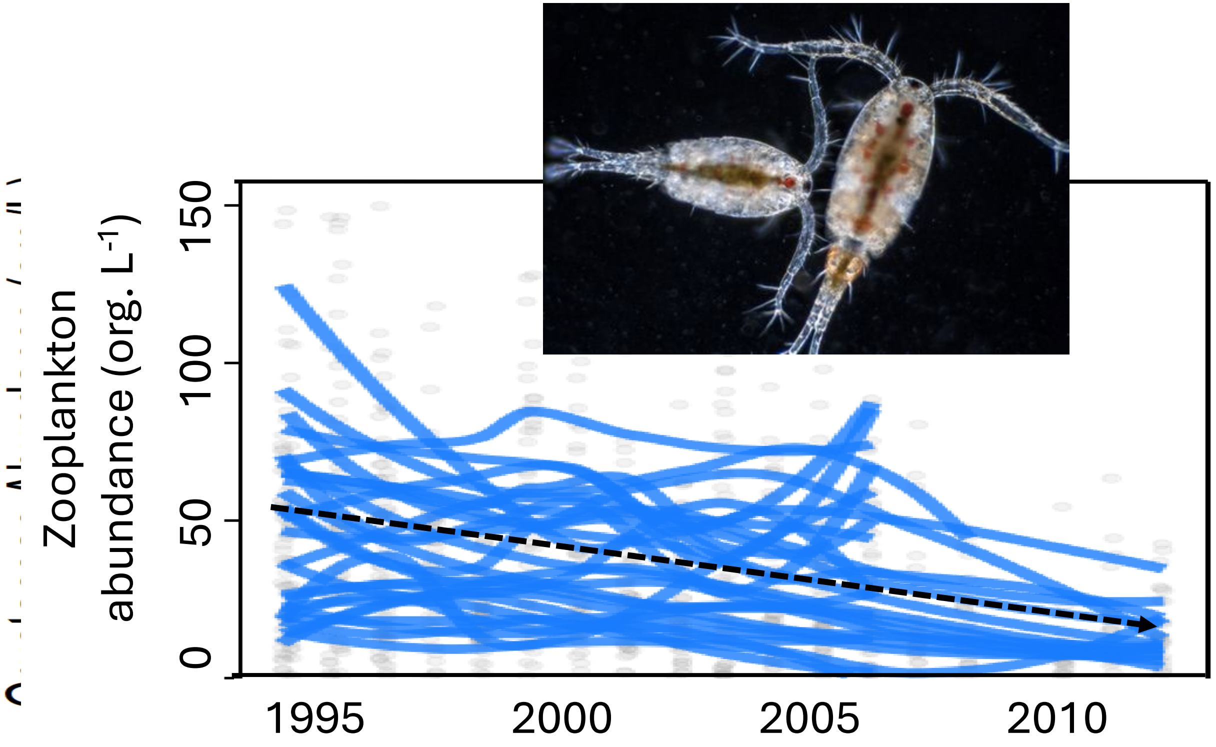
How have primary and secondary productivity been changing?



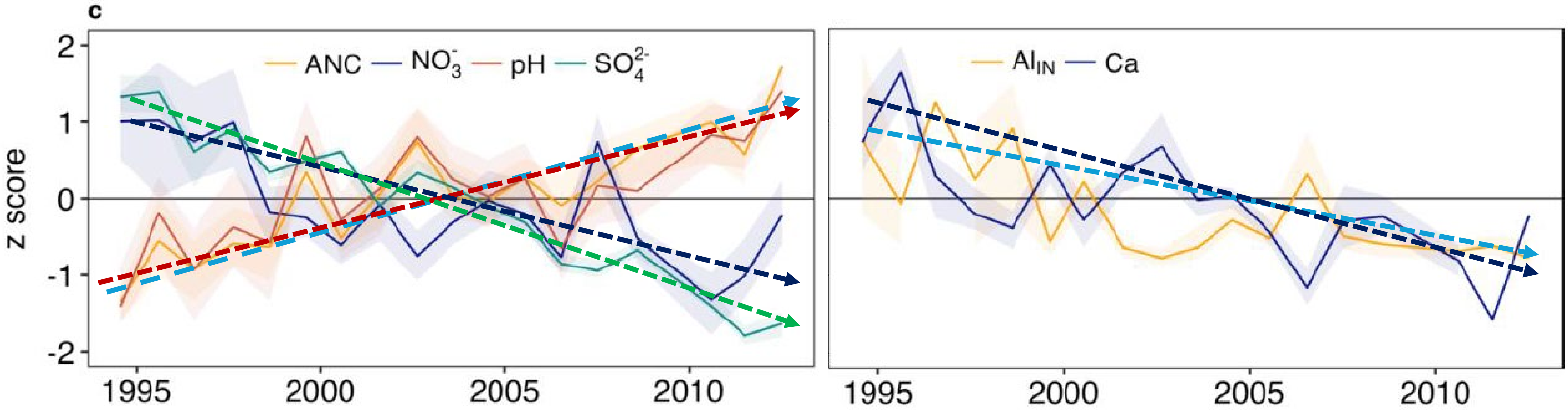


- Chlorophyll trend: 0.6 µg chlorophyll decade^{-1}.
- No corresponding trend in phytoplankton biovolume.

- Zooplankton trend: -25 organisms decade^{-1}
- ~60% reduction, 1994-2012.
- Trends driven largely by declines in calanoid copepod biomass
- *Leptodiaptomus minutus* ~48% of the crustacean zooplankton biomass

Leach et al. 2019

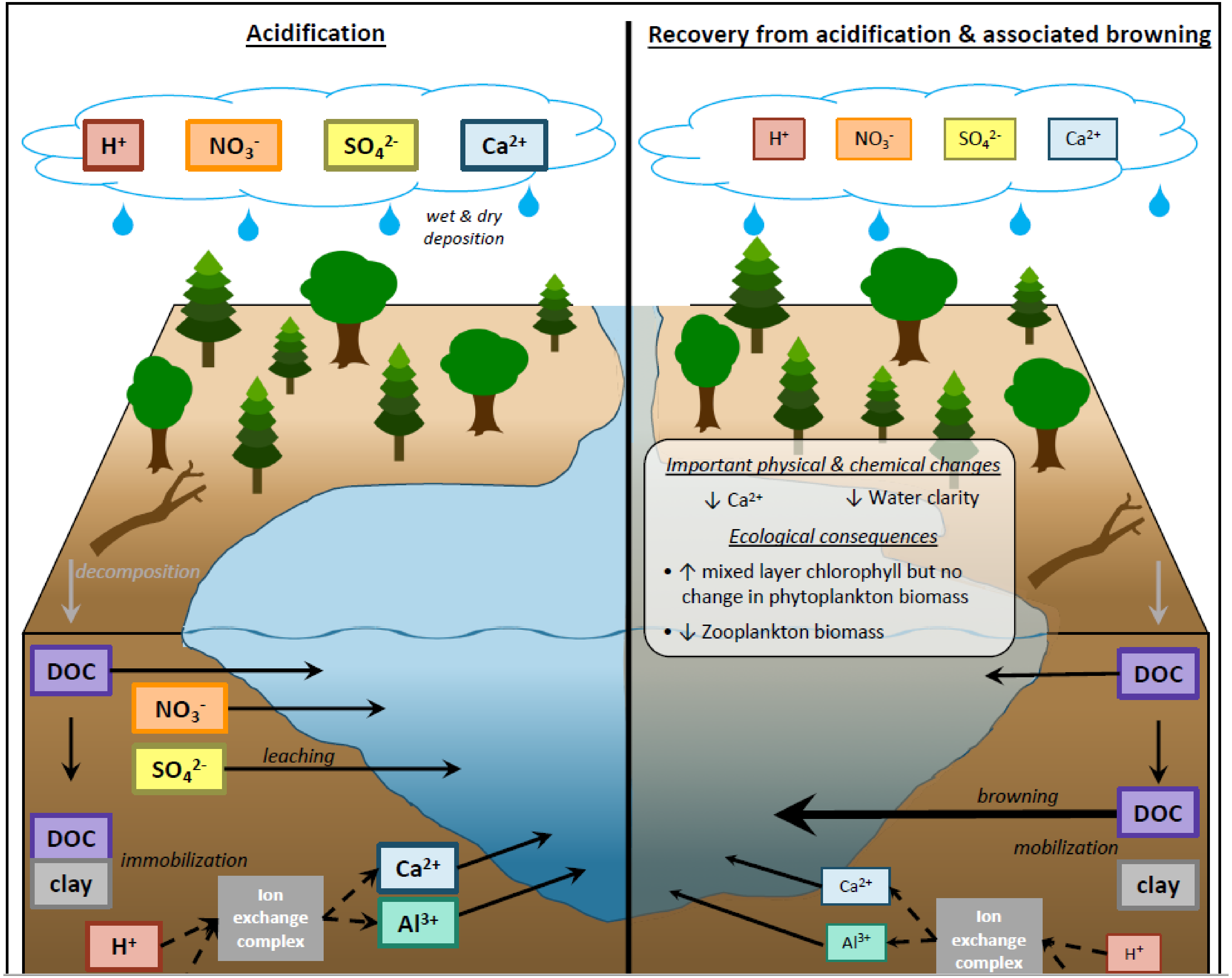
What's driving zooplankton losses? Many characteristics are changing…



ANC: **increasing** 9.65 μeq. L^{-1} $decade^{-1}$
pH: **Increasing** 0.19 pH $decade^{-1}$
Nitrate is **decreasing** -0.23 mg L^{-1} $decade^{-1}$
Sulfate is **decreasing** -1.09 mg L^{-1} $decade^{-1}$

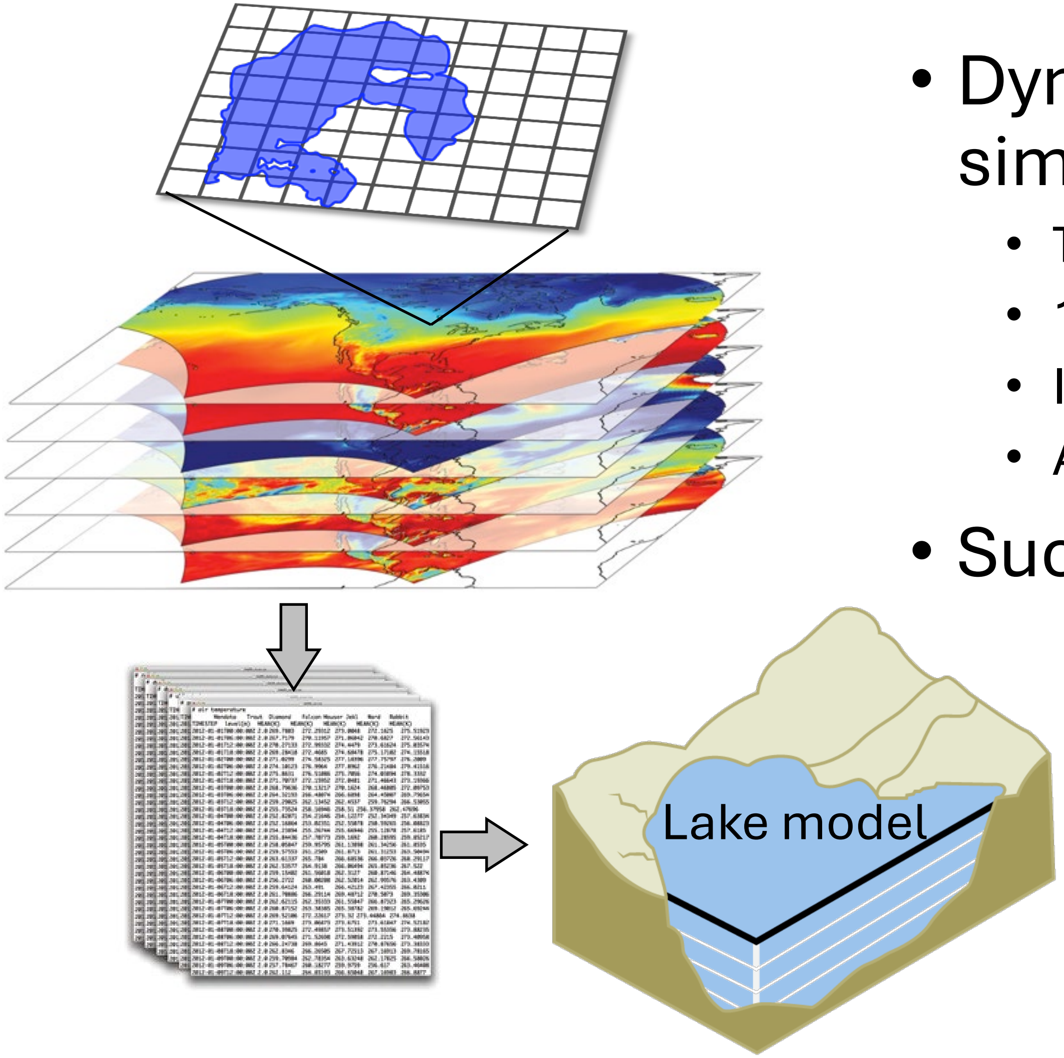
Al_{IN}: **decreasing** -8.9 μg L^{-1} $decade^{-1}$
Ca: **decreasing** -0.14 mg L^{-1} $decade^{-1}$
Many lakes crossing below 1-1.5 mg L^{-1} Ca, a critical threshold for crustacean zooplankton.

Leach et al. 2019

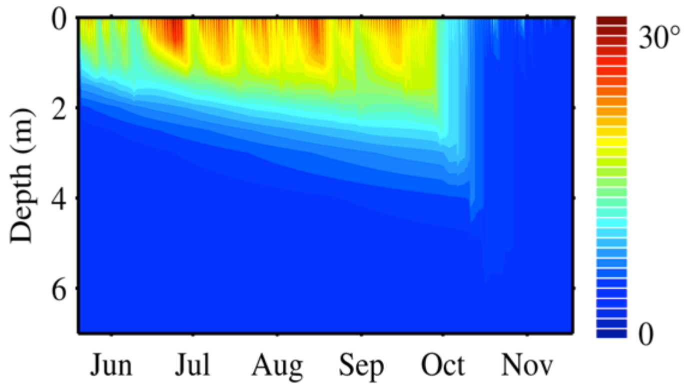


Acidification
Recovery from acidification & associated browning
H+
NO3-
SO42-
Ca2+
wet & dry deposition
decomposition
DOC
NO3-
SO42-
leaching
DOC
clay
immobilization
H+
Ion exchange complex
Ca2+
Al3+
Important physical & chemical changes
↓ Ca2+
↓ Water clarity
Ecological consequences
• ↑ mixed layer chlorophyll but no change in phytoplankton biomass
• ↓ Zooplankton biomass
DOC
DOC
browning
mobilization
clay
Ca2+
Al3+
Ion exchange complex
H+

Hydrodynamic modelling enables characterization of the effects of changing water clarity on lake temperatures at broad scales.

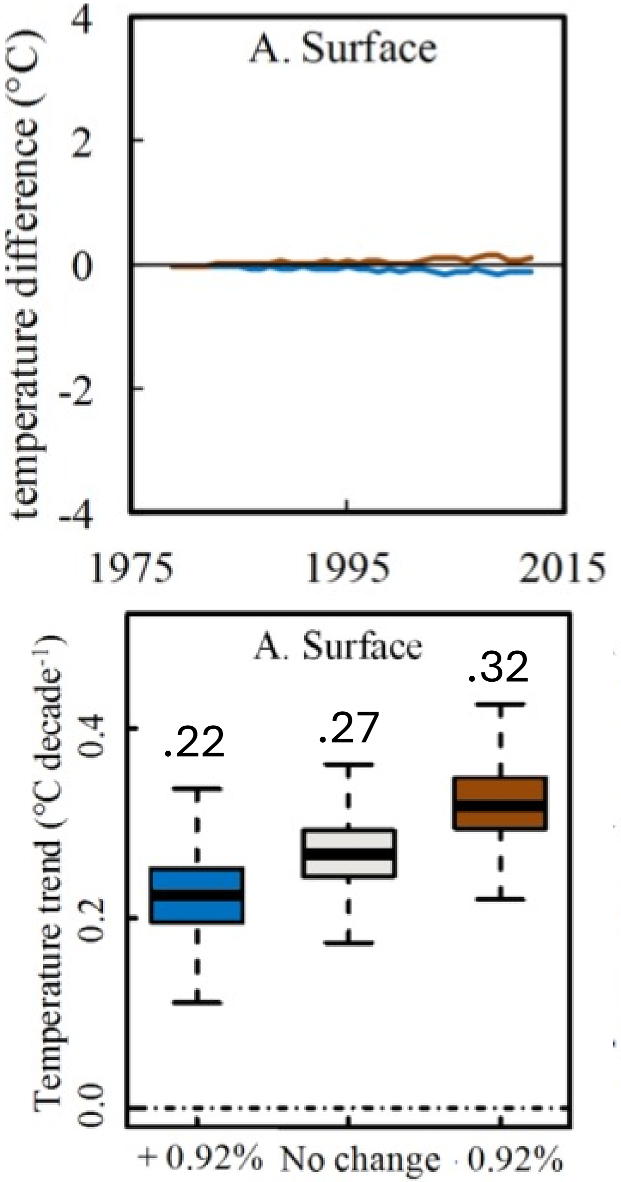


- Dynamic lake temperature simulations
  - Tested on 1,894 lakes
  - 1979-2012 (34 years)
  - Incorporated historical climate data
  - Altered water clarity at 0.92% yr^{-1}
- Successfully validated, RMSE 1.76 °C



Rose et al. 2016, L&O Letters

Changing water clarity can amplify or suppress climate-induced warming.



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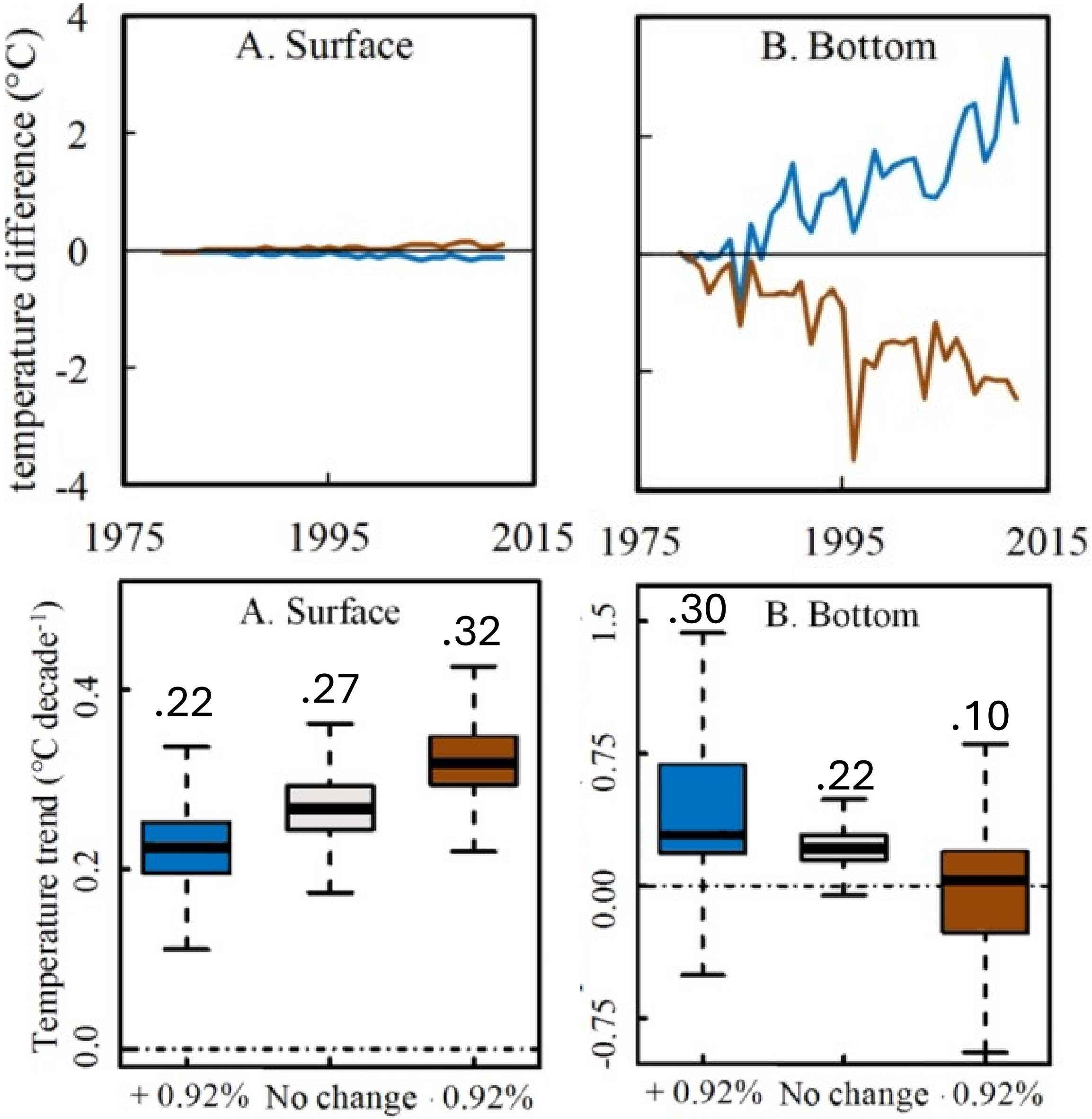

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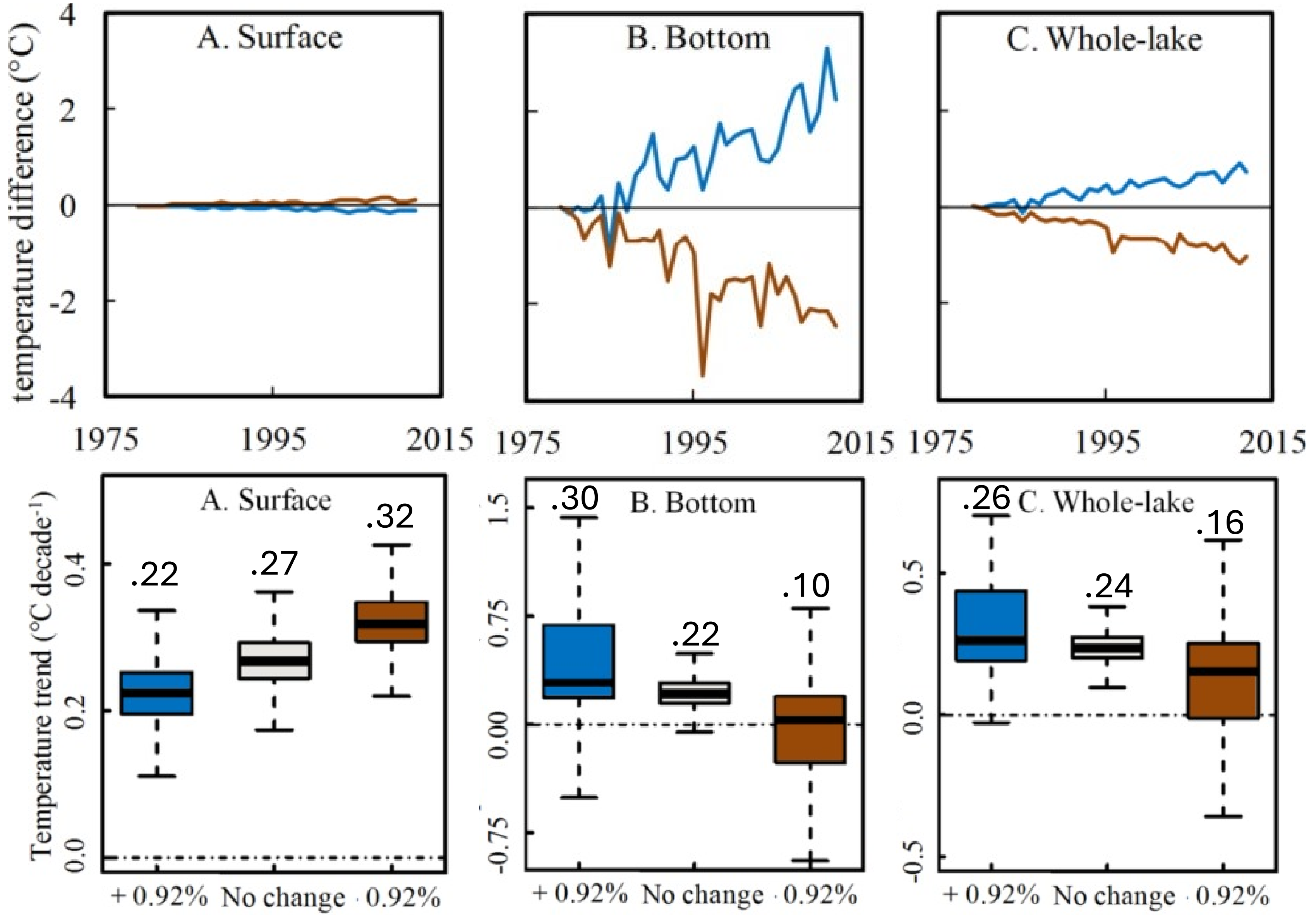

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