Our current understanding of lake ecosystem response to climate change:

What have we really learned from the north temperate deep lakes?

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Outline

I. Introduction
II. Research Questions
III. Methodology
    (i) Literature Review
    (ii) Modeling Experiments
IV. Results and Discussion
V. Conclusions




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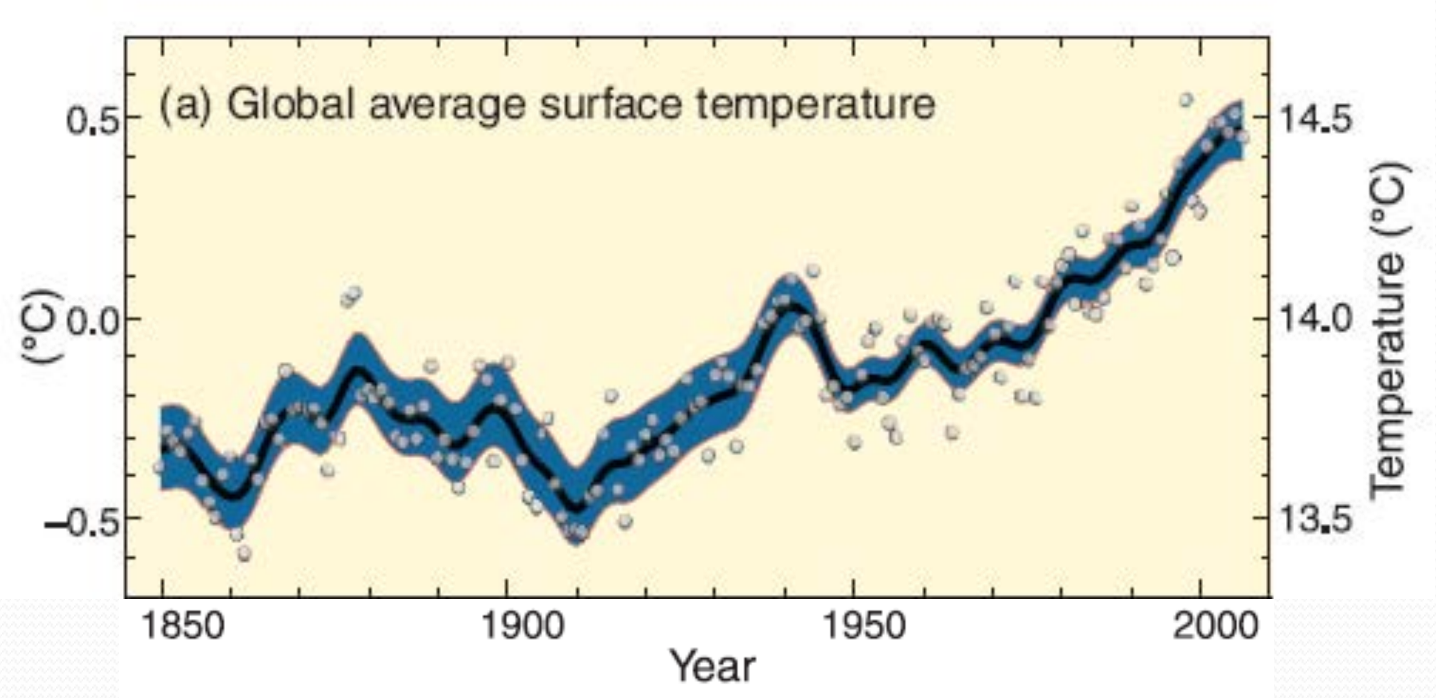
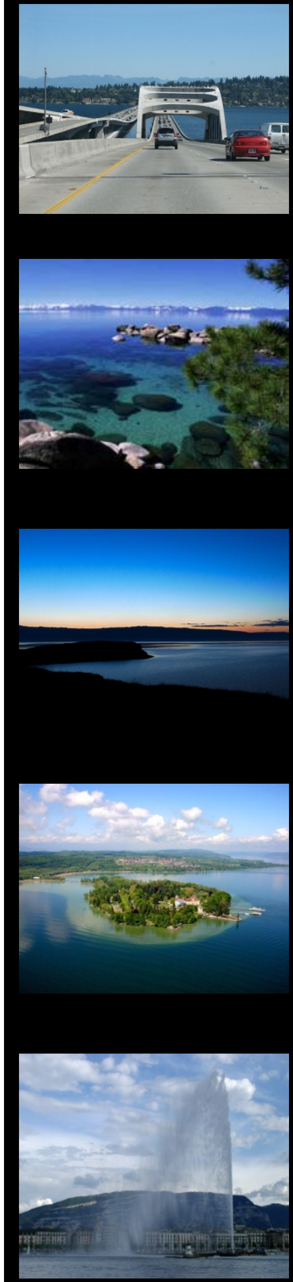
I. Introduction

Global warming

- The global mean air temperature has increased by 0.7±0.2 ^{o}C during the 20th century



Source: IPCC Synthesis report (2007)



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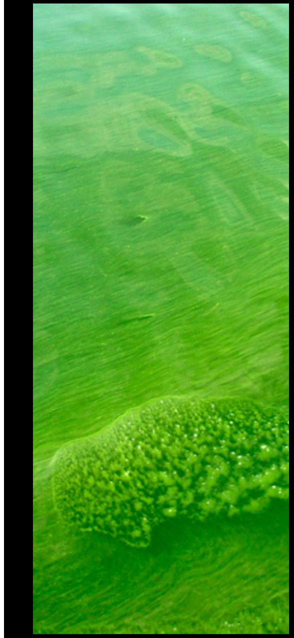
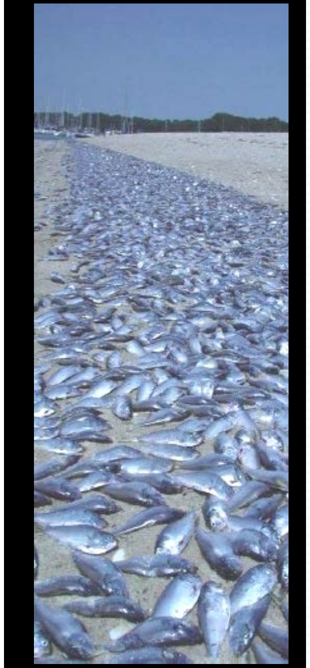
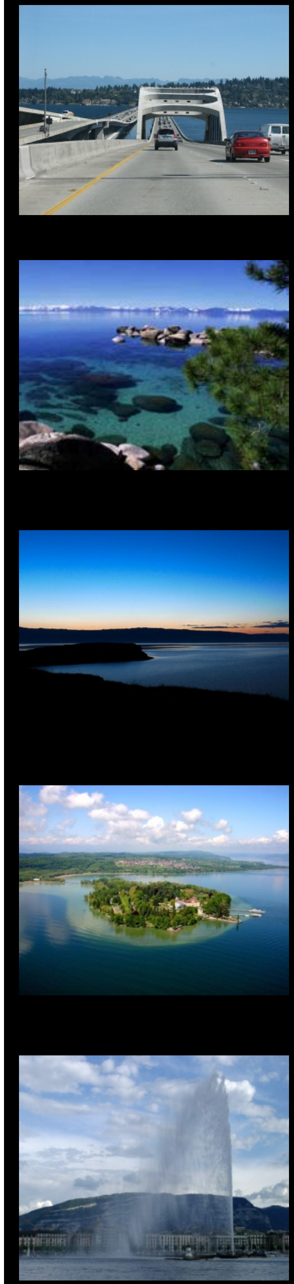




II. Research Questions

1. How does the change in the thermal structure affect the chemical (nutrients) and biological (planktonic food-webs) properties of the lakes?
2. To what extent do the structural shifts in lake functioning induced from nutrient enrichment can be further accentuated from warming temperatures?
3. To what extent do the high temperatures promote cyanobacteria dominance in freshwater ecosystems?
4. What is the role of zooplankton community in modulating the phytoplankton response to a warmer climate?



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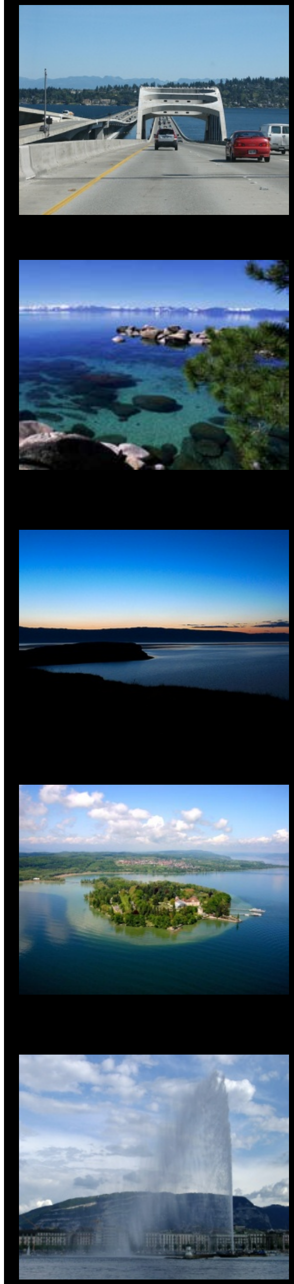
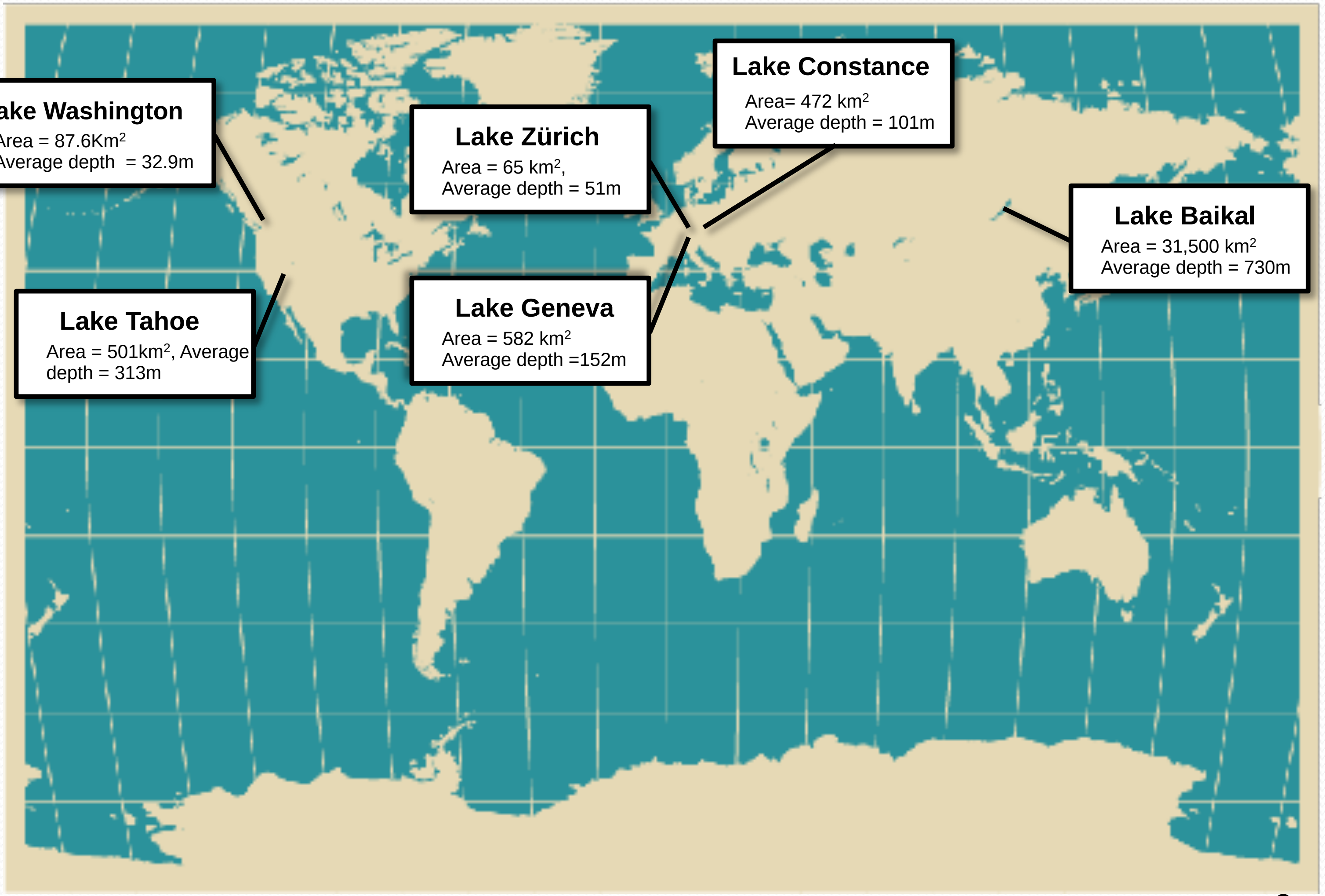
III. Methodology
Literature review





Lake Washington
Area = 87.6Km^2
Average depth = 32.9m

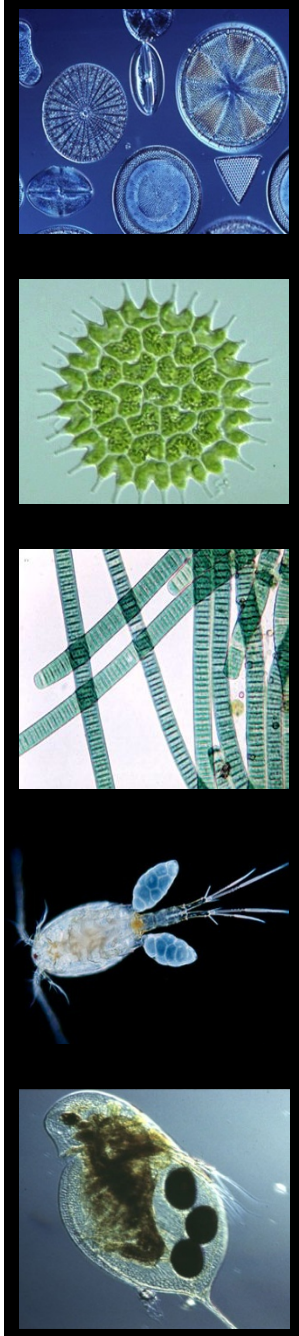
Lake Zürich
Area = 65 km^2,
Average depth = 51m

Lake Constance
Area= 472 km^2
Average depth = 101m

Lake Baikal
Area = 31,500 km^2
Average depth = 730m

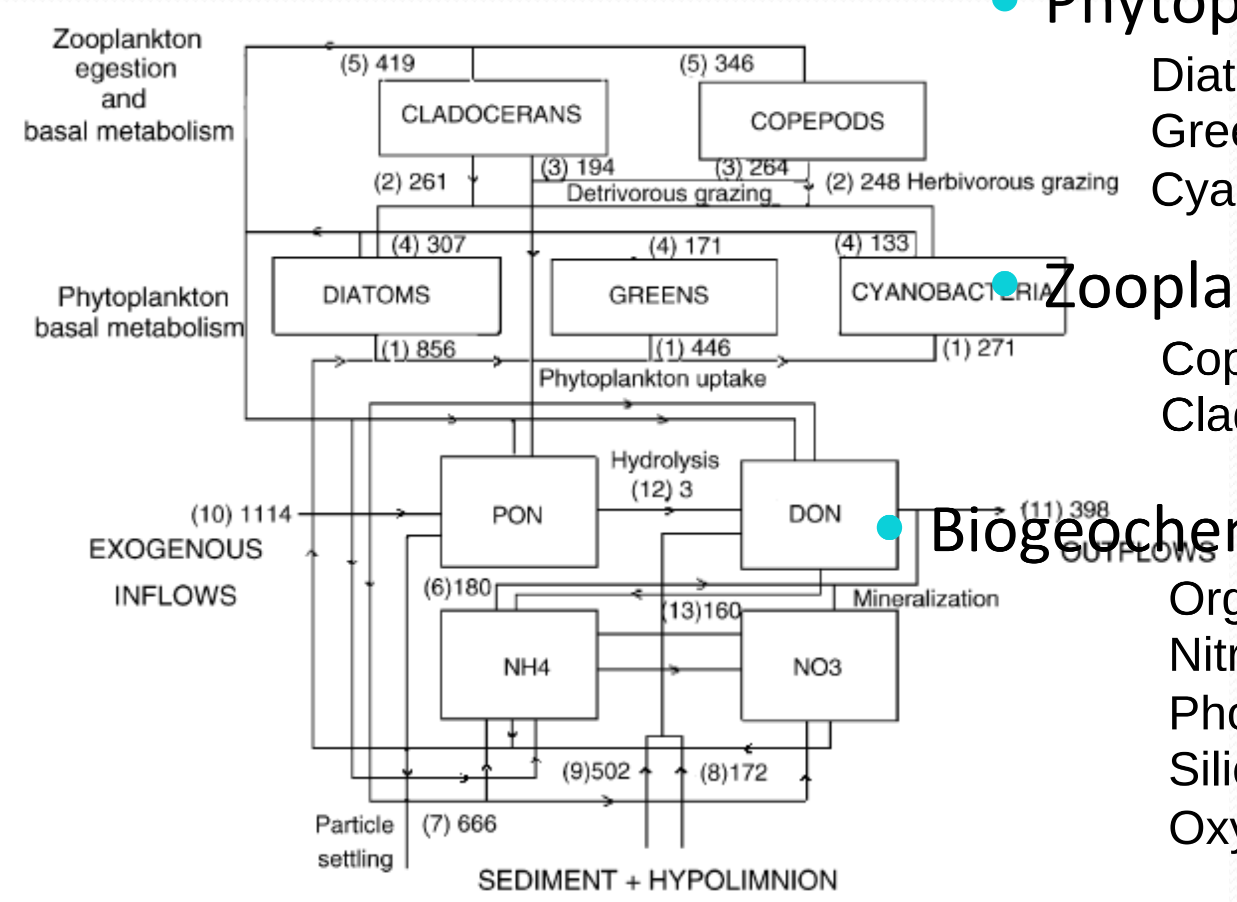
Lake Tahoe
Area = 501km^2, Average depth = 313m

Lake Geneva
Area = 582 km^2
Average depth =152m



III. Methodology
Modeling experiments

Aquatic Biogeochemical Model



- Phytoplankton
  - Diatoms
  - Greens
  - Cyanobacteria
- Zooplankton
  - Copepods
  - Cladocerans
- Biogeochemical cycle
  - Organic carbon
  - Nitrogen
  - Phosphorous
  - Silica
  - Oxygen

III. Methodology
Modeling experiments

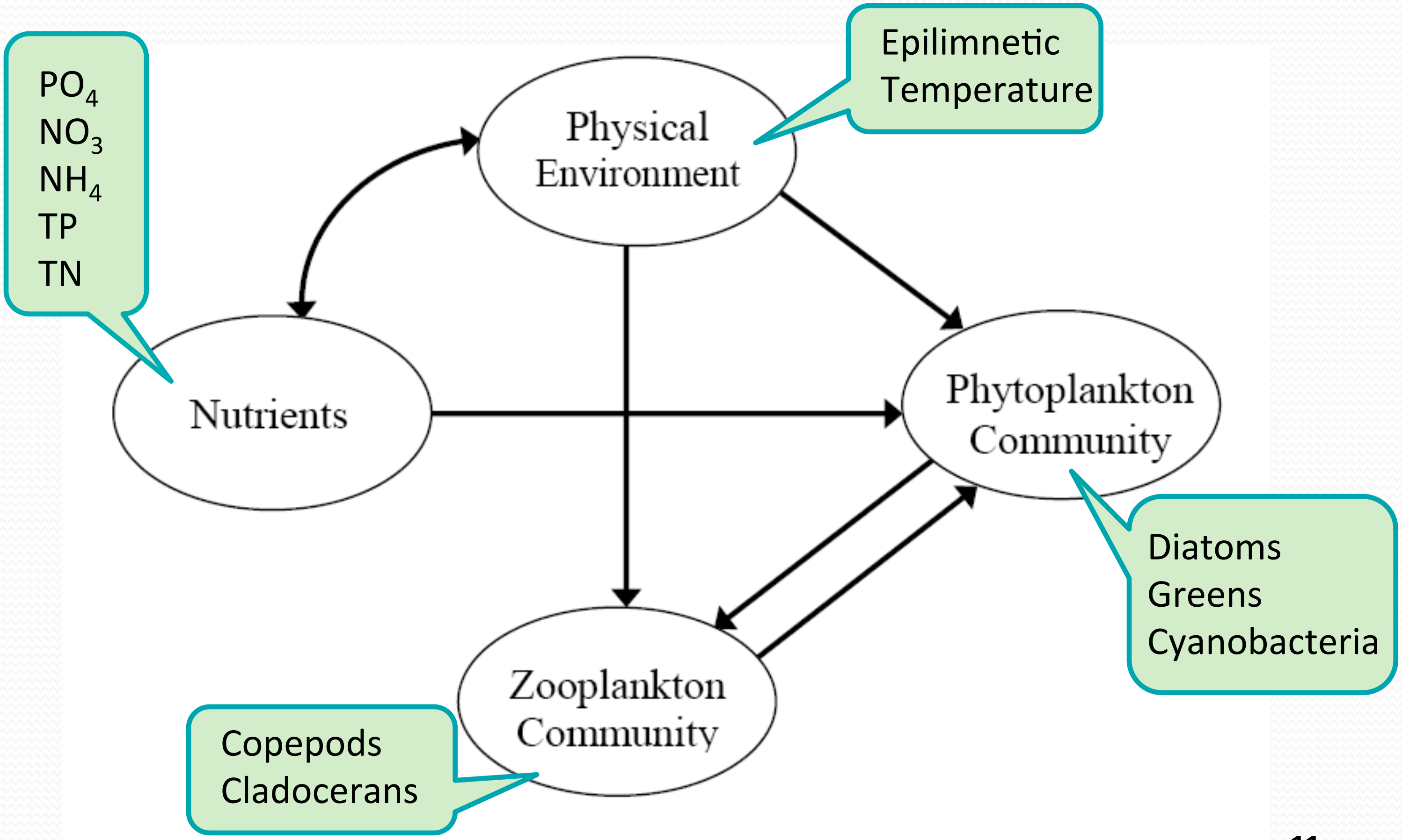
Structural Equation Model (SEM)

- SEM is a multivariate statistical method that accounts for factor and path analysis
- “A priori” statistical method - hypothetical structure of the system, reflecting the best knowledge available, is tested against the observed covariance structure

III. Methodology

Modeling experiments

Structural Equation Model (SEM)

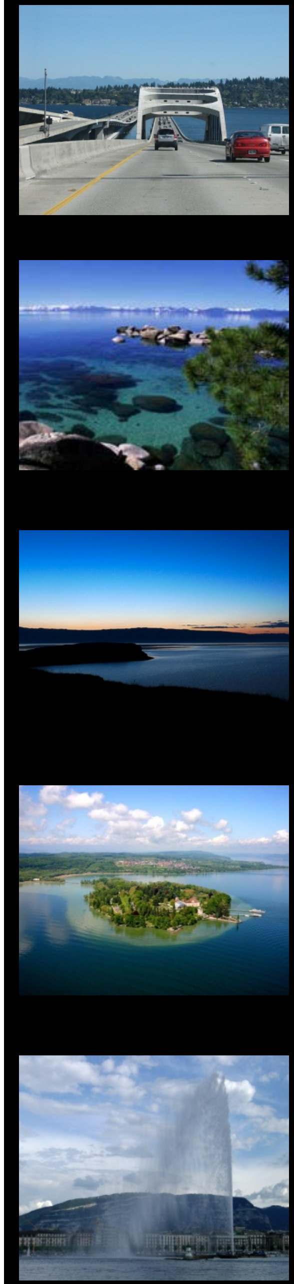


PO_4
NO_3
NH_4
TP
TN

Epilimnetic
Temperature

Diatoms
Greens
Cyanobacteria

Copepods
Cladocerans



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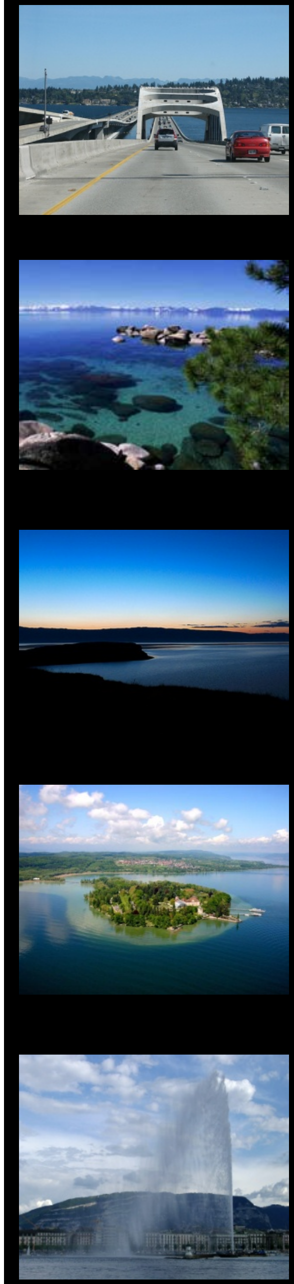


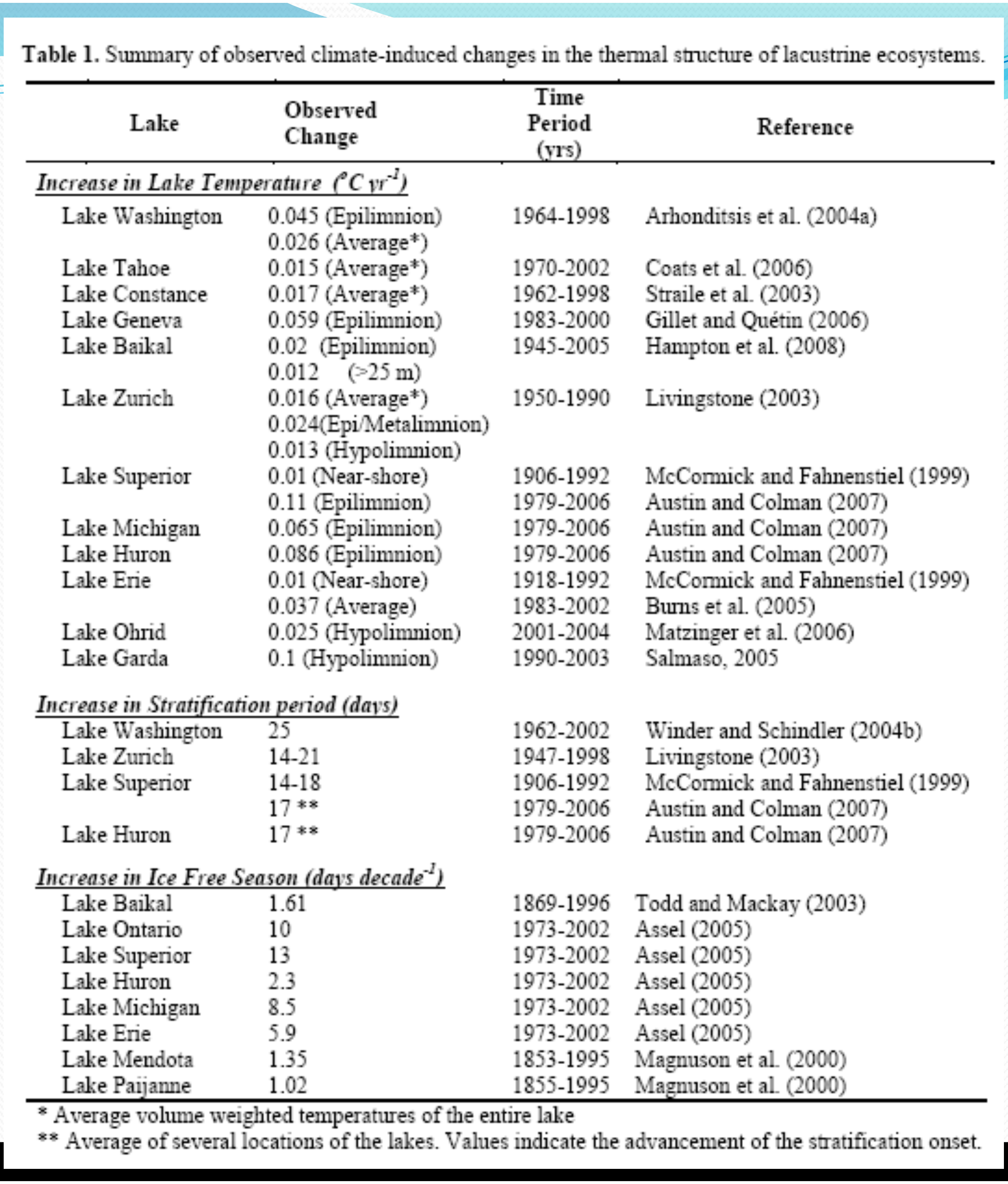
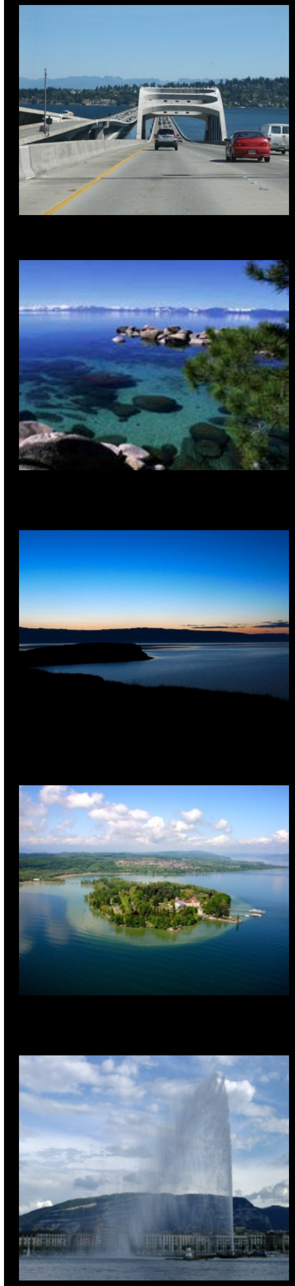


Table 1. Summary of observed climate-induced changes in the thermal structure of lacustrine ecosystems.

Lake	Observed Change	Time Period (yrs)	Reference
Increase in Lake Temperature ($^{\circ}C\ yr^{-1}$)			
Lake Washington	0.045 (Epilimnion) 0.026 (Average*)	1964-1998	Arhonditsis et al. (2004a)
Lake Tahoe	0.015 (Average*)	1970-2002	Coats et al. (2006)
Lake Constance	0.017 (Average*)	1962-1998	Straile et al. (2003)
Lake Geneva	0.059 (Epilimnion)	1983-2000	Gillet and Quétin (2006)
Lake Baikal	0.02 (Epilimnion) 0.012 (>25 m)	1945-2005	Hampton et al. (2008)
Lake Zurich	0.016 (Average*) 0.024(Epi/Metalimnion) 0.013 (Hypolimnion)	1950-1990	Livingstone (2003)
Lake Superior	0.01 (Near-shore)	1906-1992	McCormick and Fahnenstiel (1999)
	0.11 (Epilimnion)	1979-2006	Austin and Colman (2007)
Lake Michigan	0.065 (Epilimnion)	1979-2006	Austin and Colman (2007)
Lake Huron	0.086 (Epilimnion)	1979-2006	Austin and Colman (2007)
Lake Erie	0.01 (Near-shore)	1918-1992	McCormick and Fahnenstiel (1999)
	0.037 (Average)	1983-2002	Burns et al. (2005)
Lake Ohrid	0.025 (Hypolimnion)	2001-2004	Matzinger et al. (2006)
Lake Garda	0.1 (Hypolimnion)	1990-2003	Salmaso, 2005
Increase in Stratification period (days)			
Lake Washington	25	1962-2002	Winder and Schindler (2004b)
Lake Zurich	14-21	1947-1998	Livingstone (2003)
Lake Superior	14-18	1906-1992	McCormick and Fahnenstiel (1999)
	17 **	1979-2006	Austin and Colman (2007)
Lake Huron	17 **	1979-2006	Austin and Colman (2007)
Increase in Ice Free Season (days decade^{-1})			
Lake Baikal	1.61	1869-1996	Todd and Mackay (2003)
Lake Ontario	10	1973-2002	Assel (2005)
Lake Superior	13	1973-2002	Assel (2005)
Lake Huron	2.3	1973-2002	Assel (2005)
Lake Michigan	8.5	1973-2002	Assel (2005)
Lake Erie	5.9	1973-2002	Assel (2005)
Lake Mendota	1.35	1853-1995	Magnuson et al. (2000)
Lake Paijanne	1.02	1855-1995	Magnuson et al. (2000)

* Average volume weighted temperatures of the entire lake

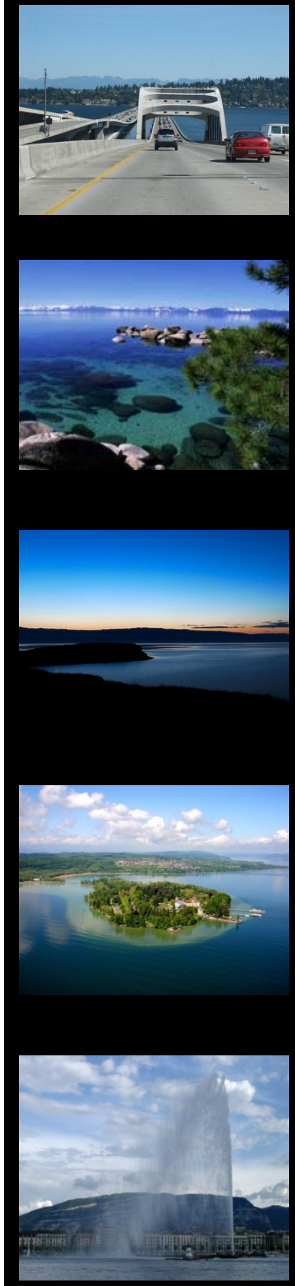
** Average of several locations of the lakes. Values indicate the advancement of the stratification onset.



IV. Results and Discussion

Thermal dynamics

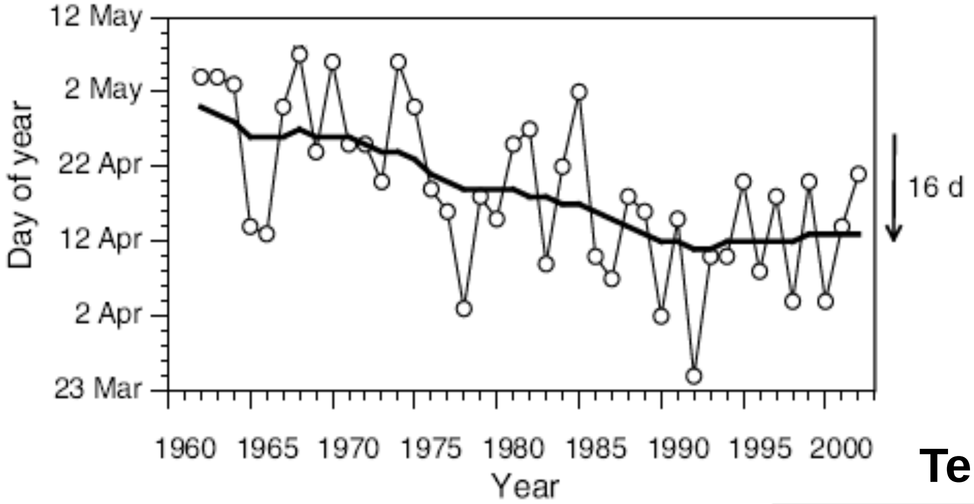
- The water temperature has increased approximately ranging between 0.01 -0.11 ^{o}C per year
- Stronger warming trend in the epilimnion than in the hypolimnion
- The increased differences between upper and deeper water created greater temperature gradient, resulting in stronger stratification
- Longer stratification
- Increased ice-free period



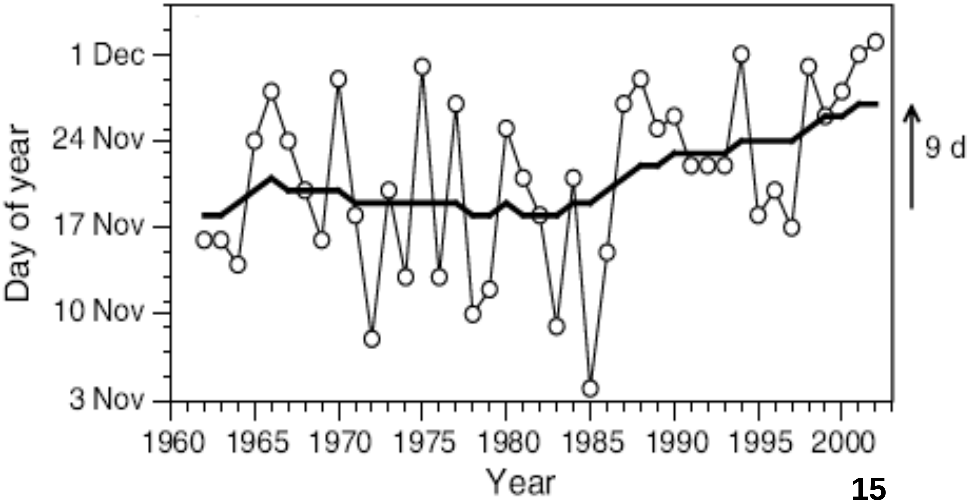
IV. Results and Discussion

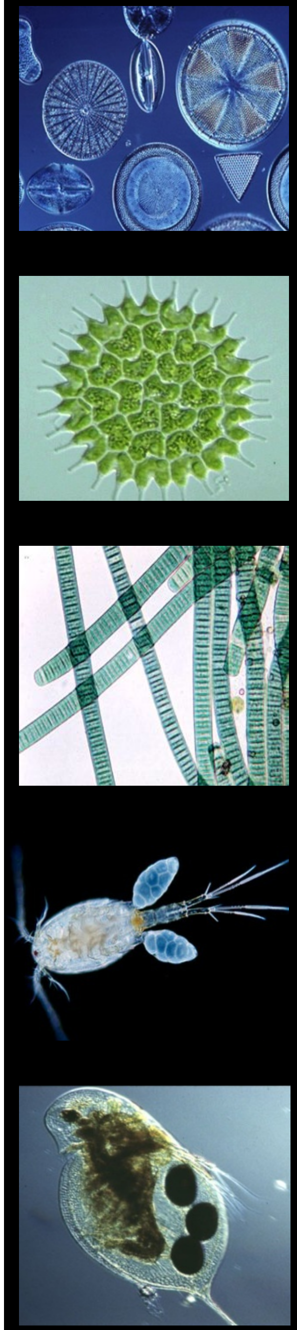
Thermal dynamics

Onset of stratification



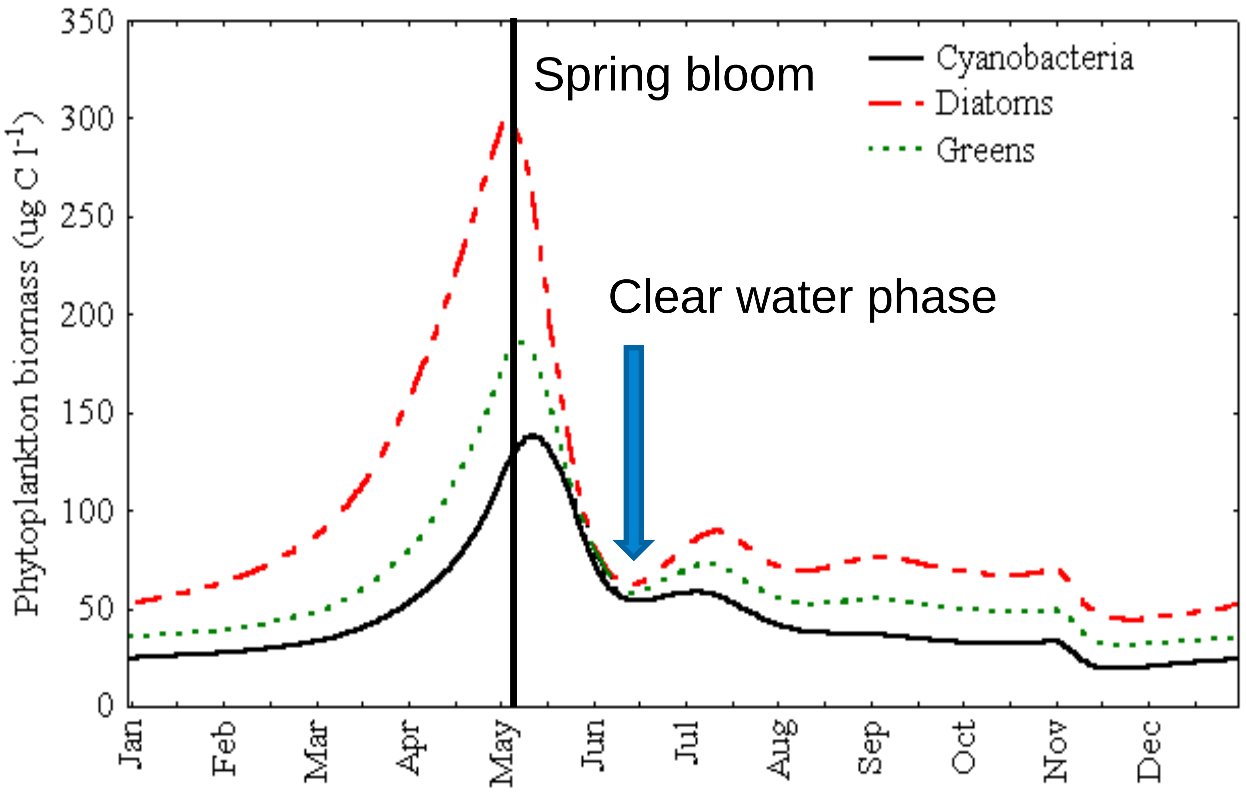
Termination of stratification





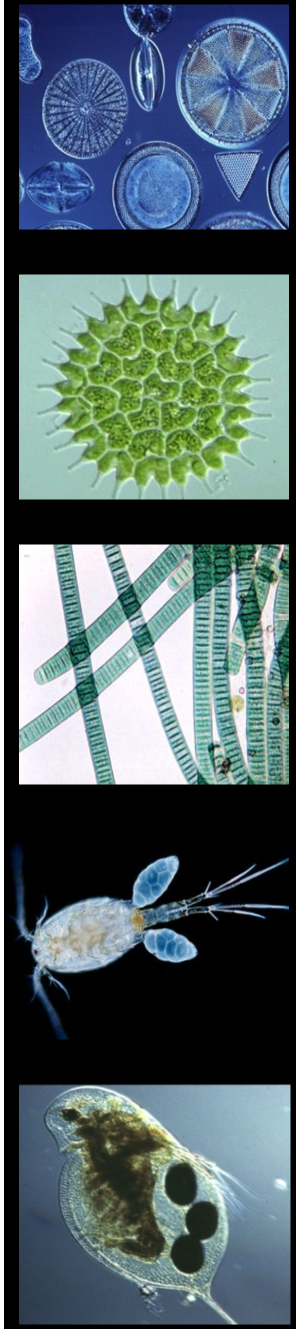
IV. Results and Discussion

Spring plankton dynamics



Spring bloom

Clear water phase

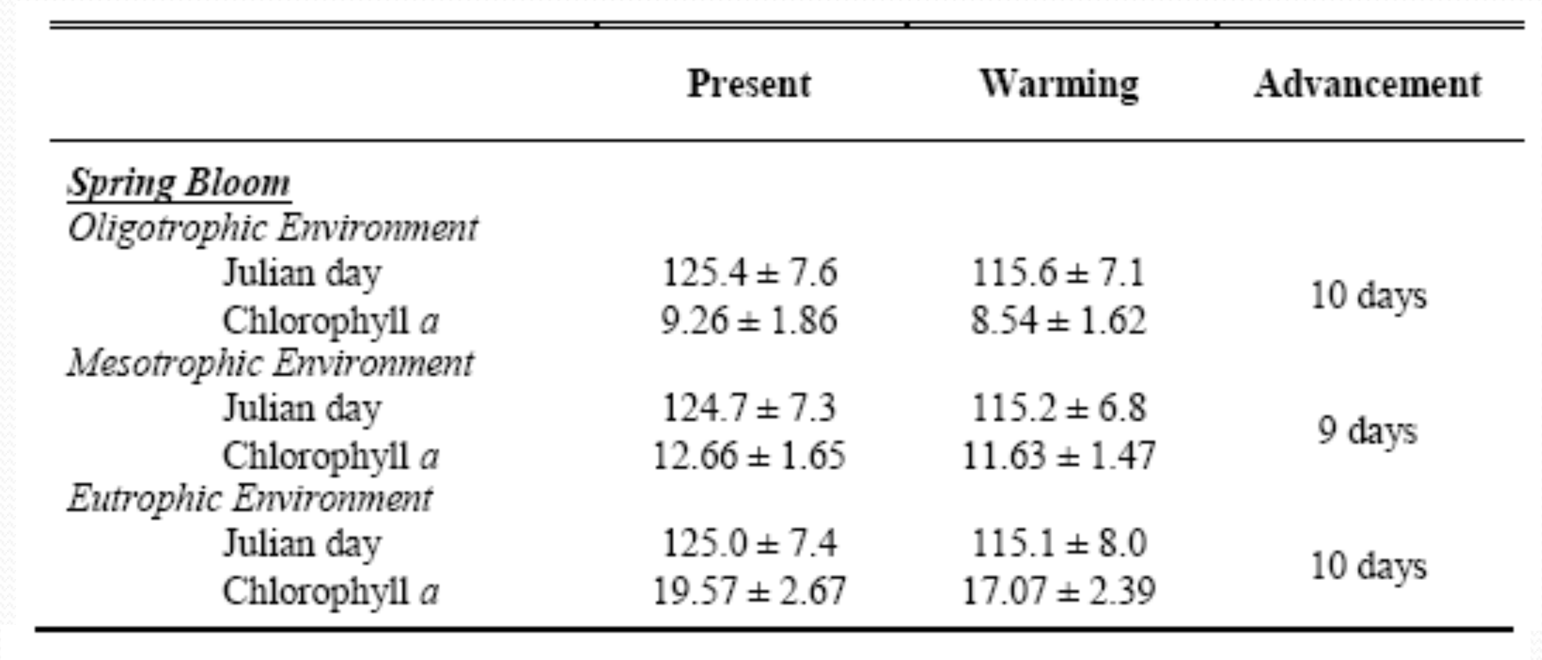


IV. Results and Discussion

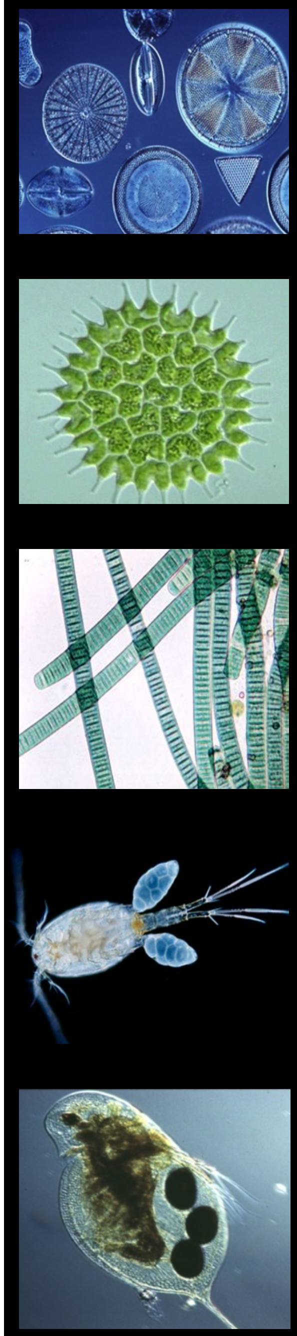
Spring plankton dynamics

Spring Bloom

- Advancement of spring bloom by 9 – 10 days



	Present	Warming	Advancement
Spring Bloom			
Oligotrophic Environment			
Julian day	125.4 ± 7.6	115.6 ± 7.1	10 days
Chlorophyll *a*	9.26 ± 1.86	8.54 ± 1.62	
Mesotrophic Environment			
Julian day	124.7 ± 7.3	115.2 ± 6.8	9 days
Chlorophyll *a*	12.66 ± 1.65	11.63 ± 1.47	
Eutrophic Environment			
Julian day	125.0 ± 7.4	115.1 ± 8.0	10 days
Chlorophyll *a*	19.57 ± 2.67	17.07 ± 2.39	

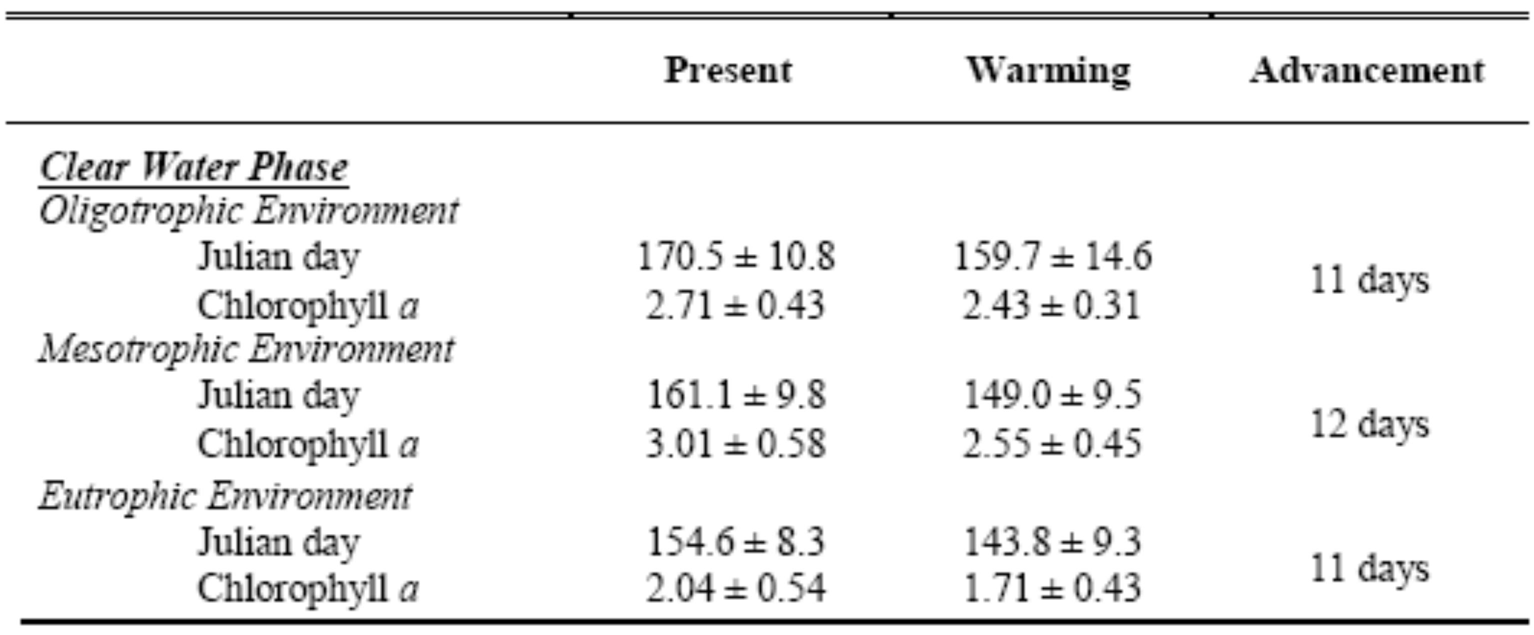


IV. Results and Discussion

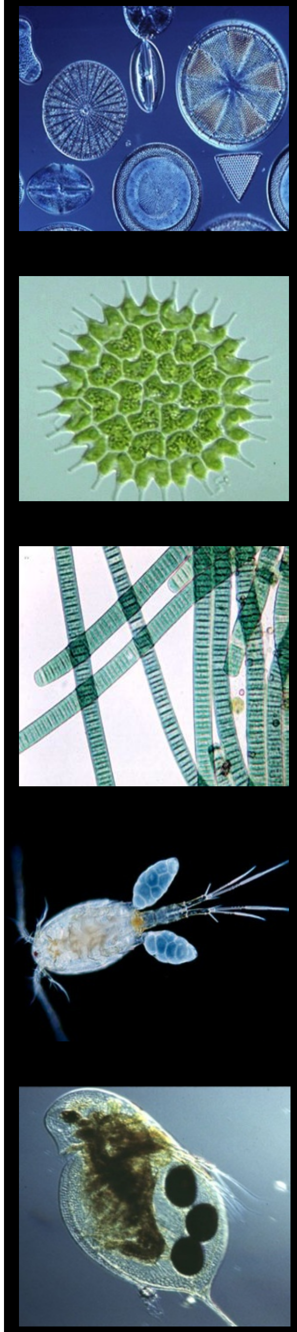
Spring plankton dynamics

Clear Water Phase

- Advancement of the clear water phase by 11 – 12 days



	Present	Warming	Advancement
Clear Water Phase			
Oligotrophic Environment			
Julian day	170.5 ± 10.8	159.7 ± 14.6	11 days
Chlorophyll *a*	2.71 ± 0.43	2.43 ± 0.31	
Mesotrophic Environment			
Julian day	161.1 ± 9.8	149.0 ± 9.5	12 days
Chlorophyll *a*	3.01 ± 0.58	2.55 ± 0.45	
Eutrophic Environment			
Julian day	154.6 ± 8.3	143.8 ± 9.3	11 days
Chlorophyll *a*	2.04 ± 0.54	1.71 ± 0.43	



IV. Results and Discussion

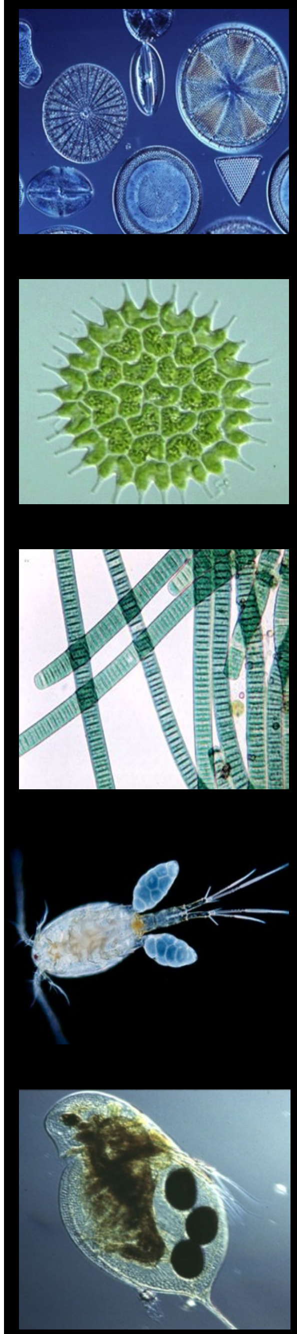
Spring plankton dynamics

Spring

- Contradictory results among lakes have been observed and NOT a globally-common ecological mechanism!

  (Lake Washington vs. Lake Constance)

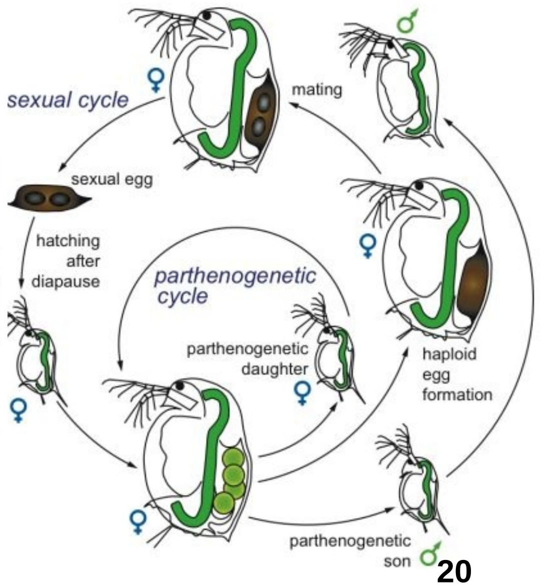
- What is the role of the herbivorous control in the timing of the clear water phase?

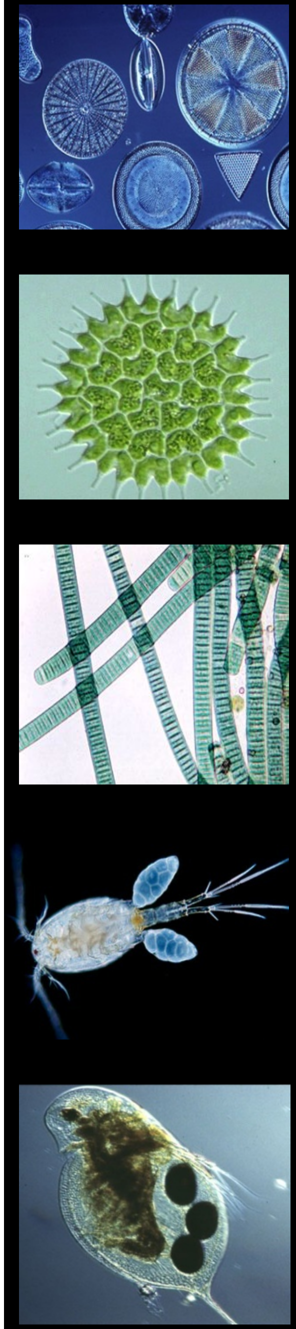


Overwintering versus emerging population strategies?

The development of an overwintering population of daphnids may parallel shifts in phytoplankton phenology due to climate warming (e.g., the Lake Constance patterns presented in Straile 2000)

A mismatch between zooplankton and their phytoplankton prey is likely to occur when photoperiod is the dominant cue for termination of diapauses (e.g., the Lake Washington trends reported in Winder and Schindler 2004a,b)

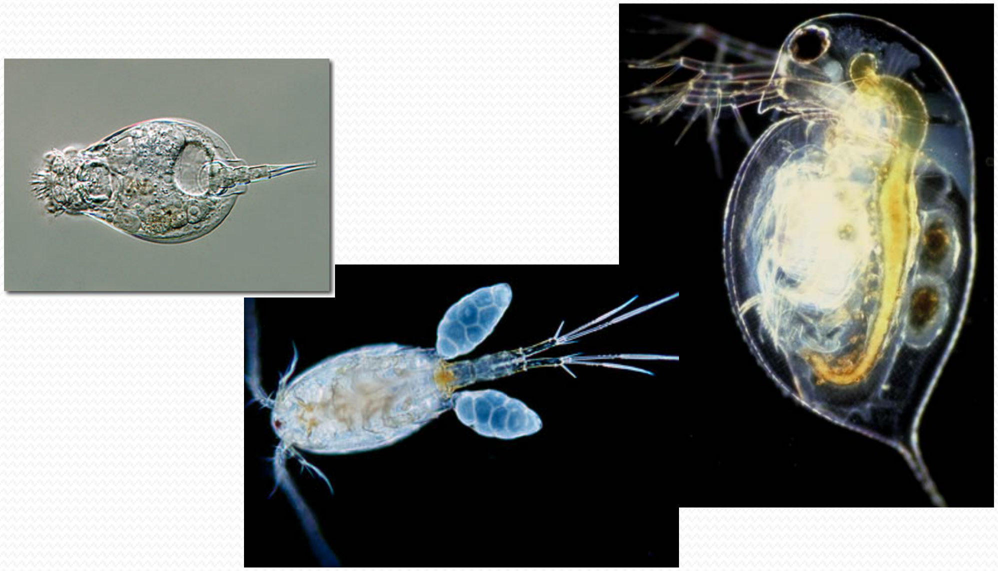




IV. Results and Discussion

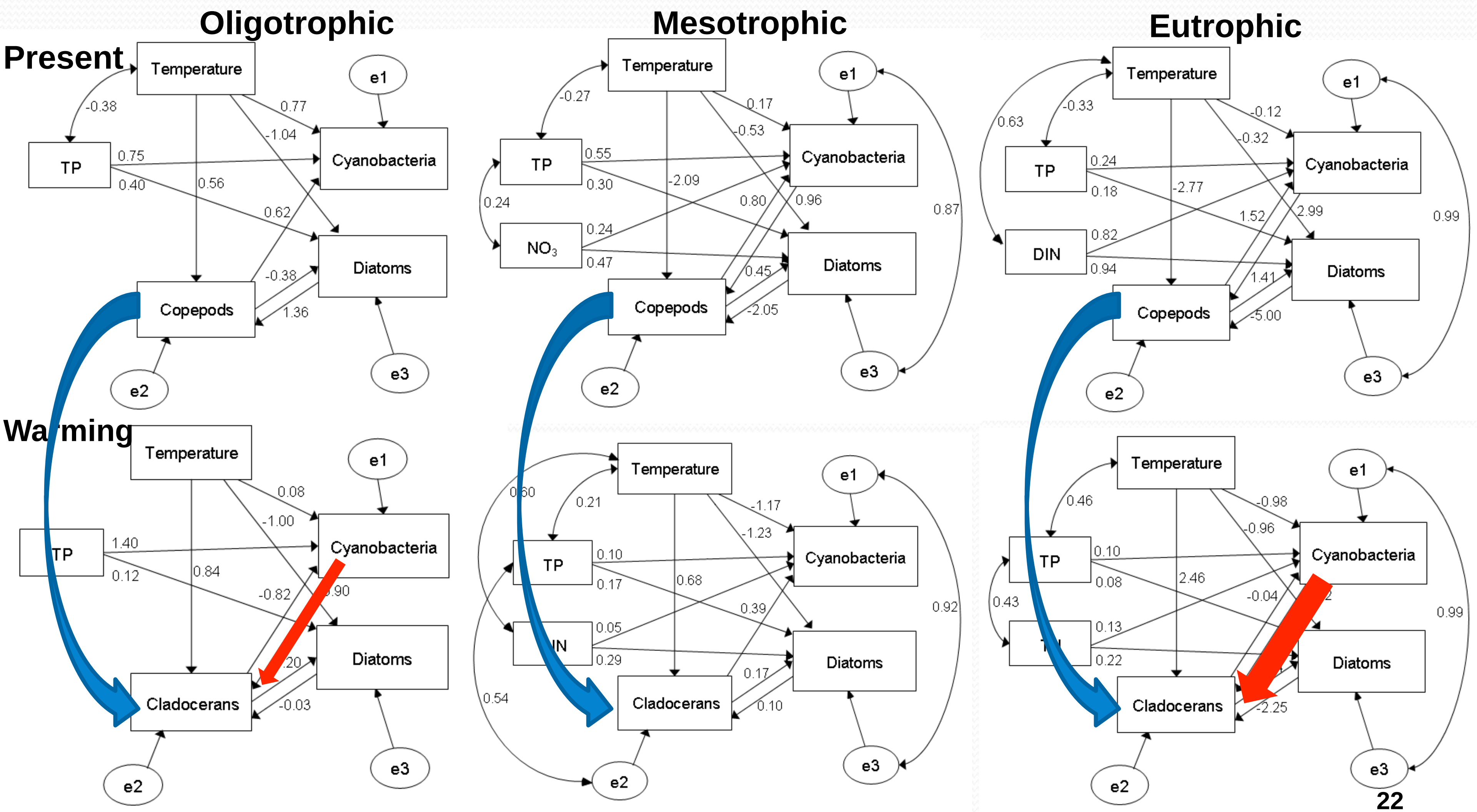
Spring plankton dynamics

- The match-mismatch hypothesis depends on the reproductive strategies of the dominant zooplankters which in turn determine the timing of clear water phase



IV. Results and Discussion

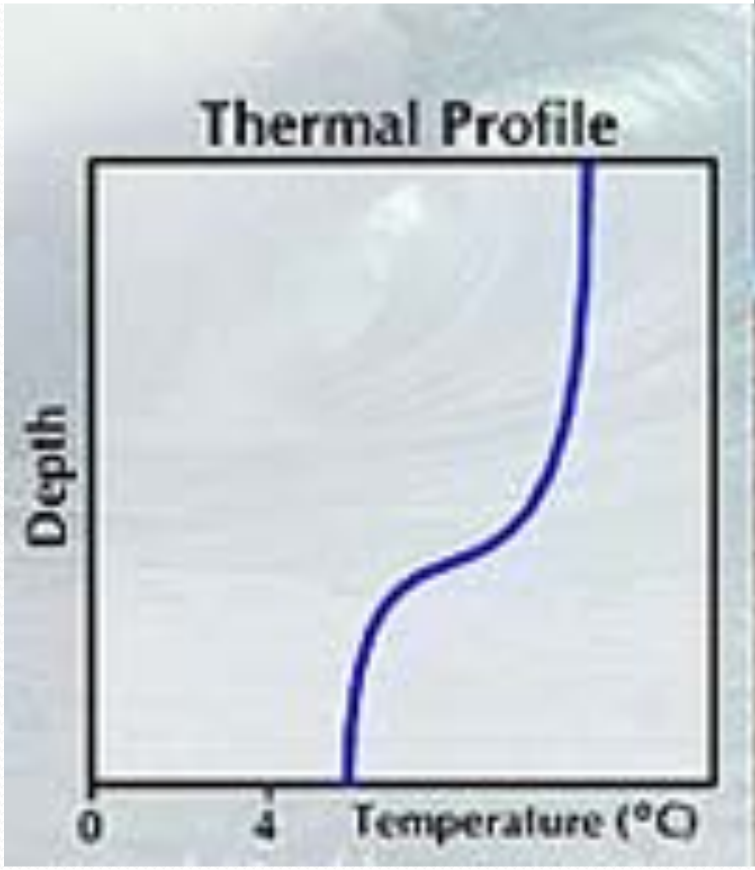
Spring plankton dynamics

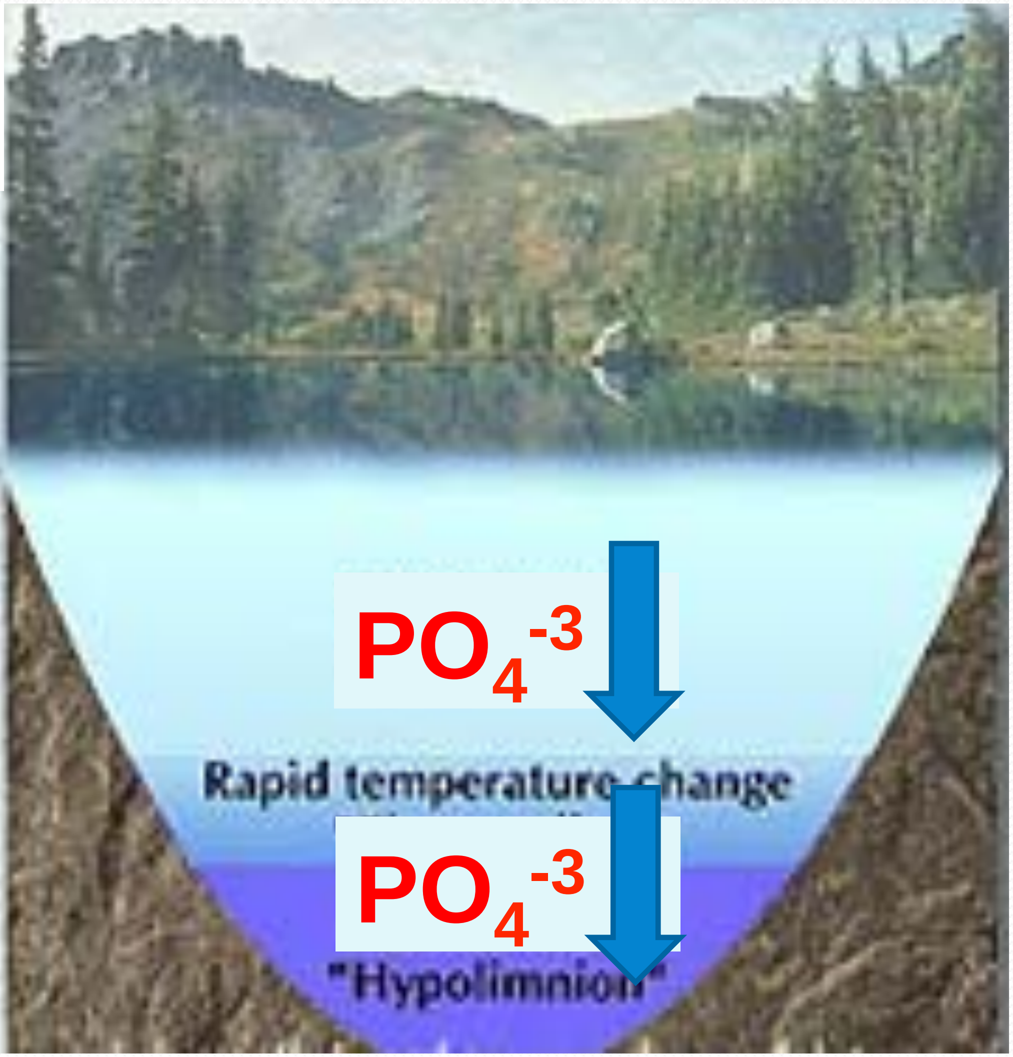


IV. Results and Discussion

Summer plankton dynamics

Summer Oligotrophic-Mesotrophic Environment





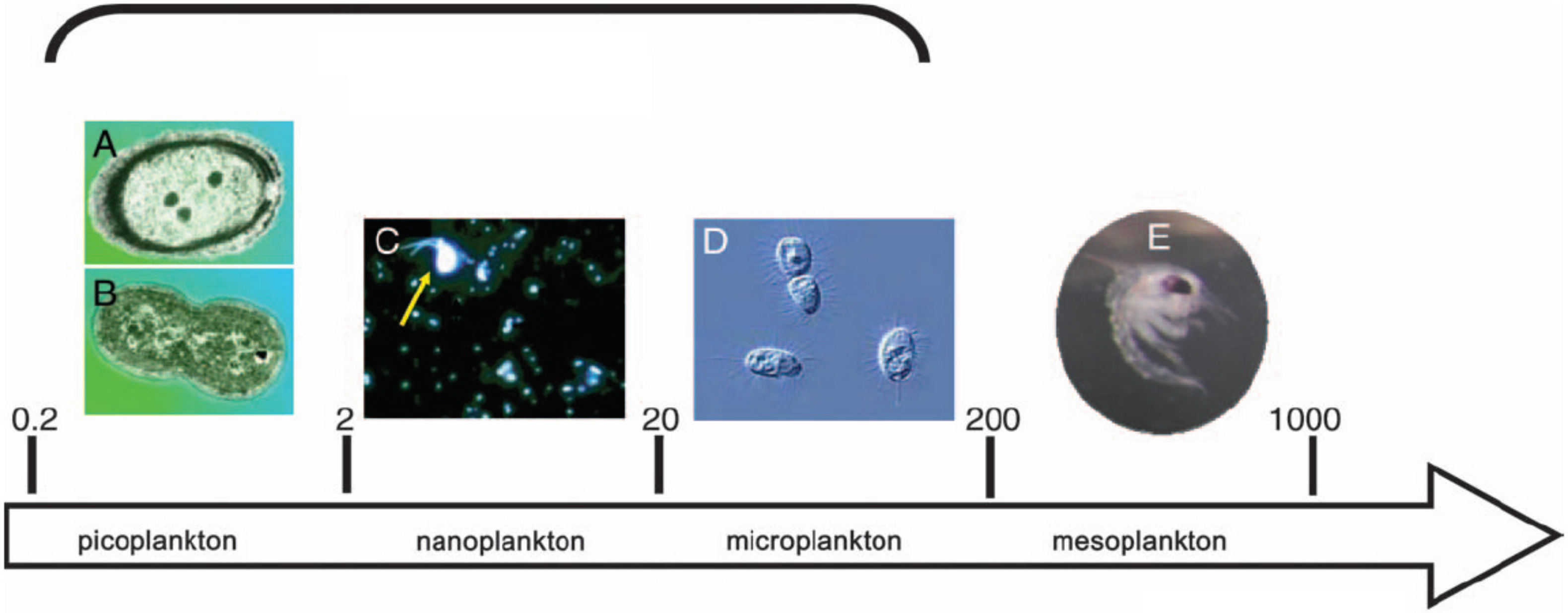
PO_4^{-3}

PO_4^{-3}

IV. Results and Discussion

Summer plankton dynamics

- Smaller algal cells are better adapted to the climate-induced prolonged stratification



IV. Results and Discussion

Summer plankton dynamics

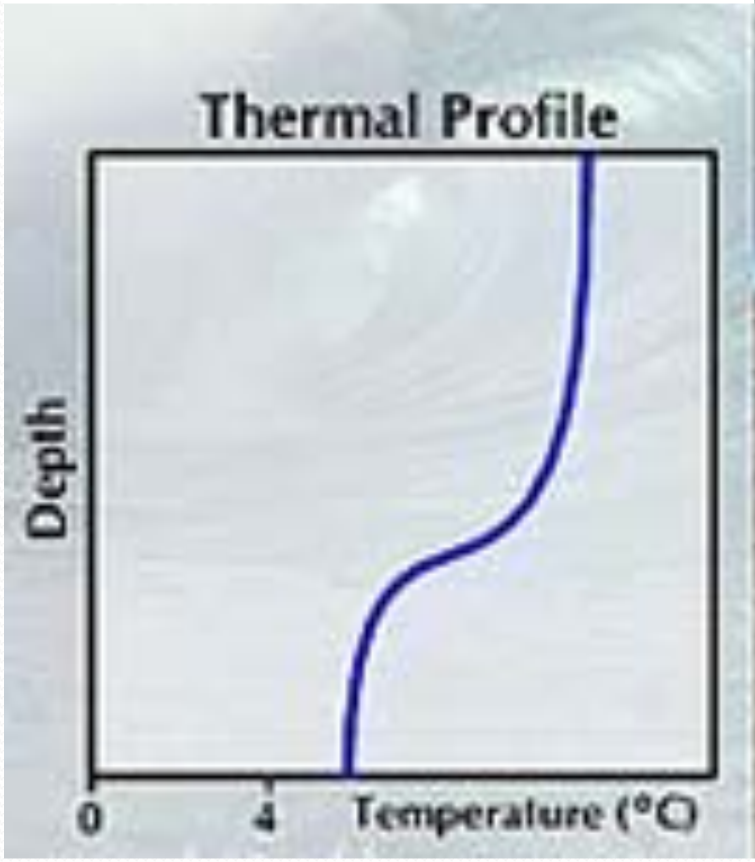
- "Is the mixture of widely edible but nutritionally variable picoplankton able to maintain the integrity of the zooplankton community?"

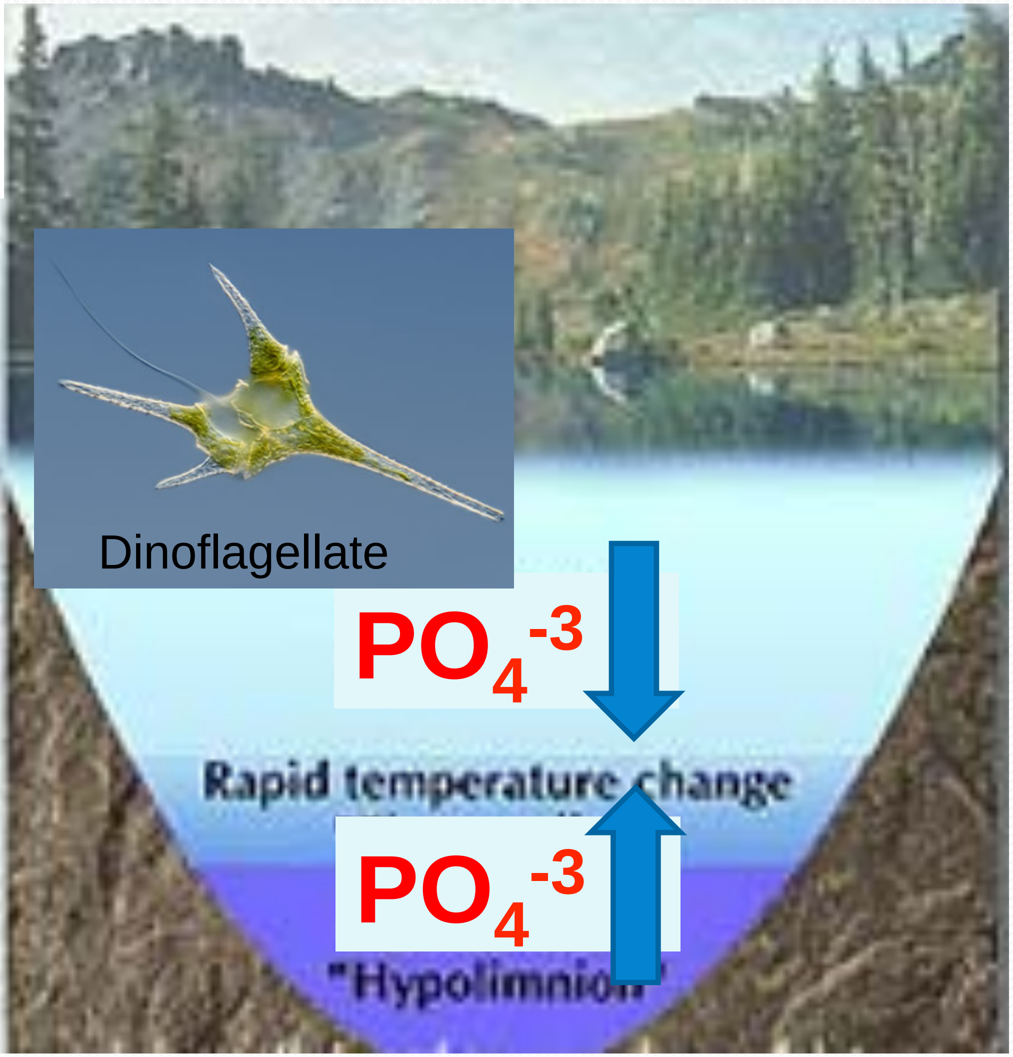
IV. Results and Discussion

Summer plankton dynamics

Summer

Eutrophic Environment





Dinoflagellate

PO_4^{-3}

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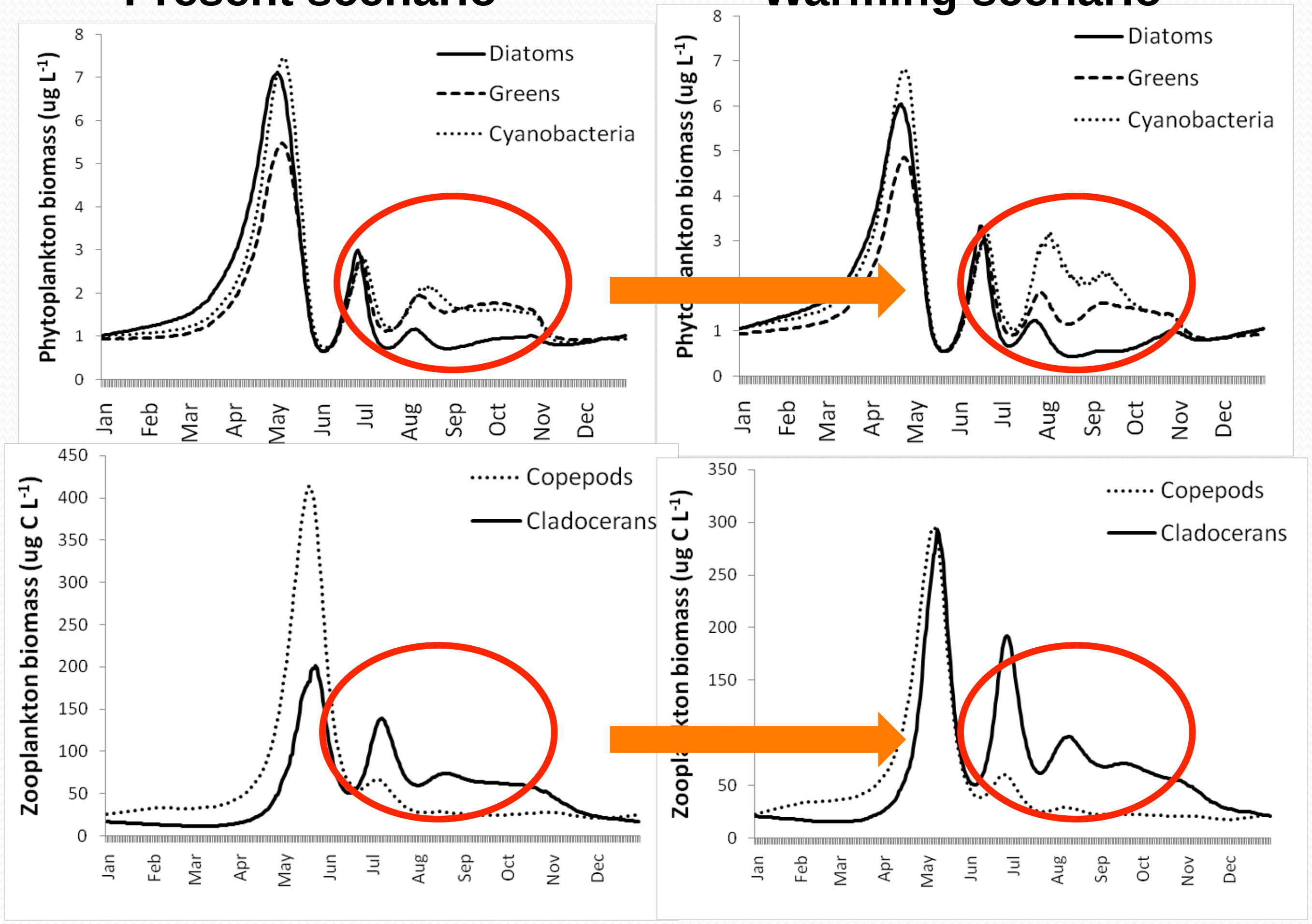
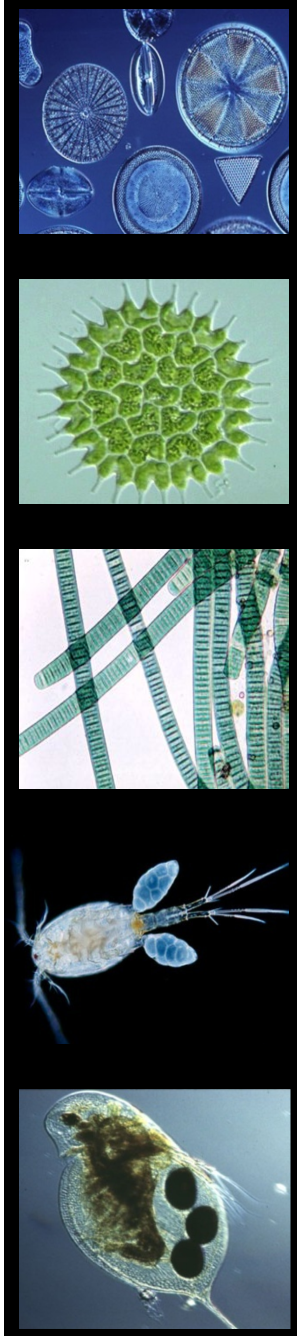
IV. Results and Discussion

Plankton dynamics

Present scenario **Warming scenario**





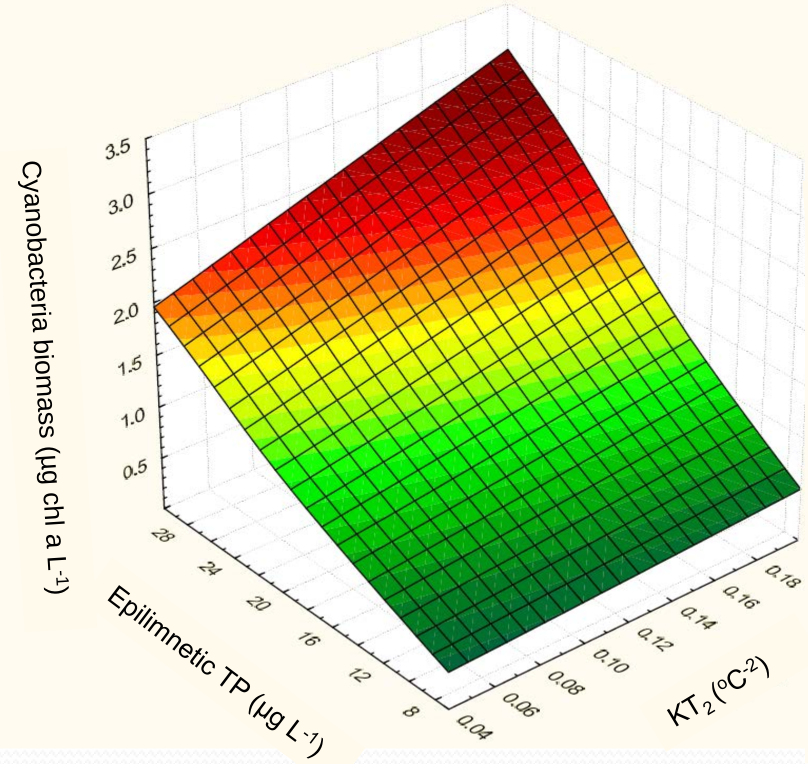
IV. Results and Discussion

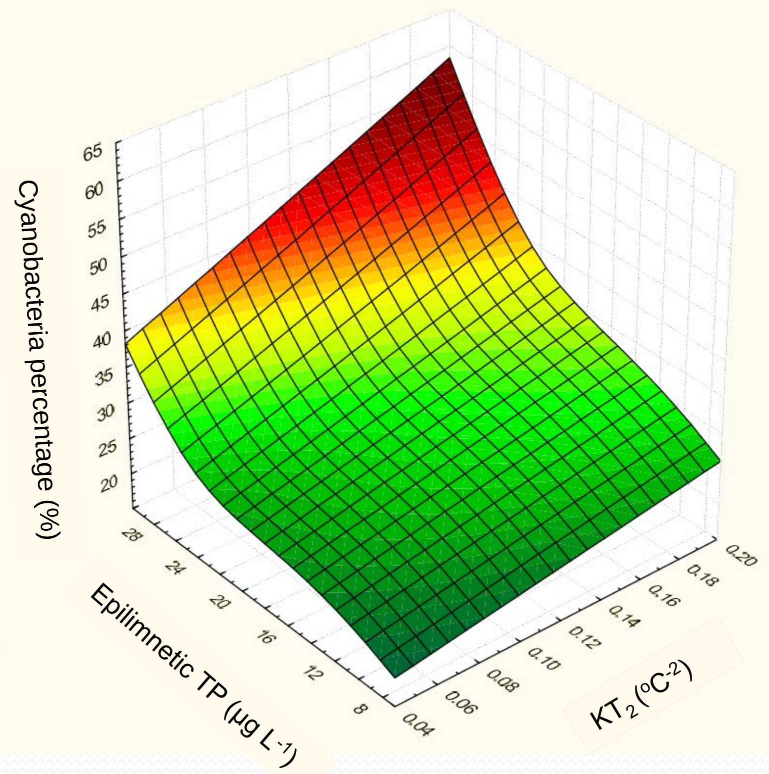
Prospect of cyanobacteria dominance

- Cyanobacteria has higher temperature optima, but inferior kinetics to low phosphorous level
- Strong and longer stratification under warming scenarios in summer is favorable condition cyanobacteria with lower sinking rate
- However, depleted PO_4 condition in epilimnion may create a delicate balance for competition among other functional groups

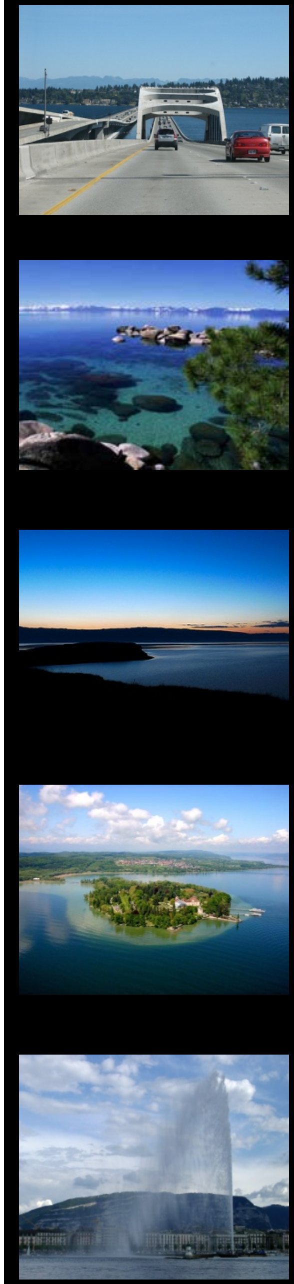
IV. Results and Discussion

Prospect of cyanobacteria dominance





Cyanobacteria can dominate the community with warmer temperatures, but conditional on phosphorous level



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Effects of Climate Change on Lake Phenology

Shifts in thermal structure

- Prolonged stratification
- Increased thermal stability
- Increased ice-free season

Biological response

- Advancement of spring bloom
- Advancement of clear water phase, but conditional on the type of zooplankton reproductive strategies
- Summer species adaptive to more severe nutrient limitation (i.e., picoplankton, mixotrophy)

V. Conclusion

Effects of Climate Change on Lake Phenology

- Potentially critical factors for future dynamics may be the internal nutrient regeneration mechanisms
- Prospect of cyanobacteria dominance, but can be regulated (i.e., nutrient loading)
- Prospect of climate warming to act as a destabilizing force in system functioning

Acknowledgements

Special thanks to:

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