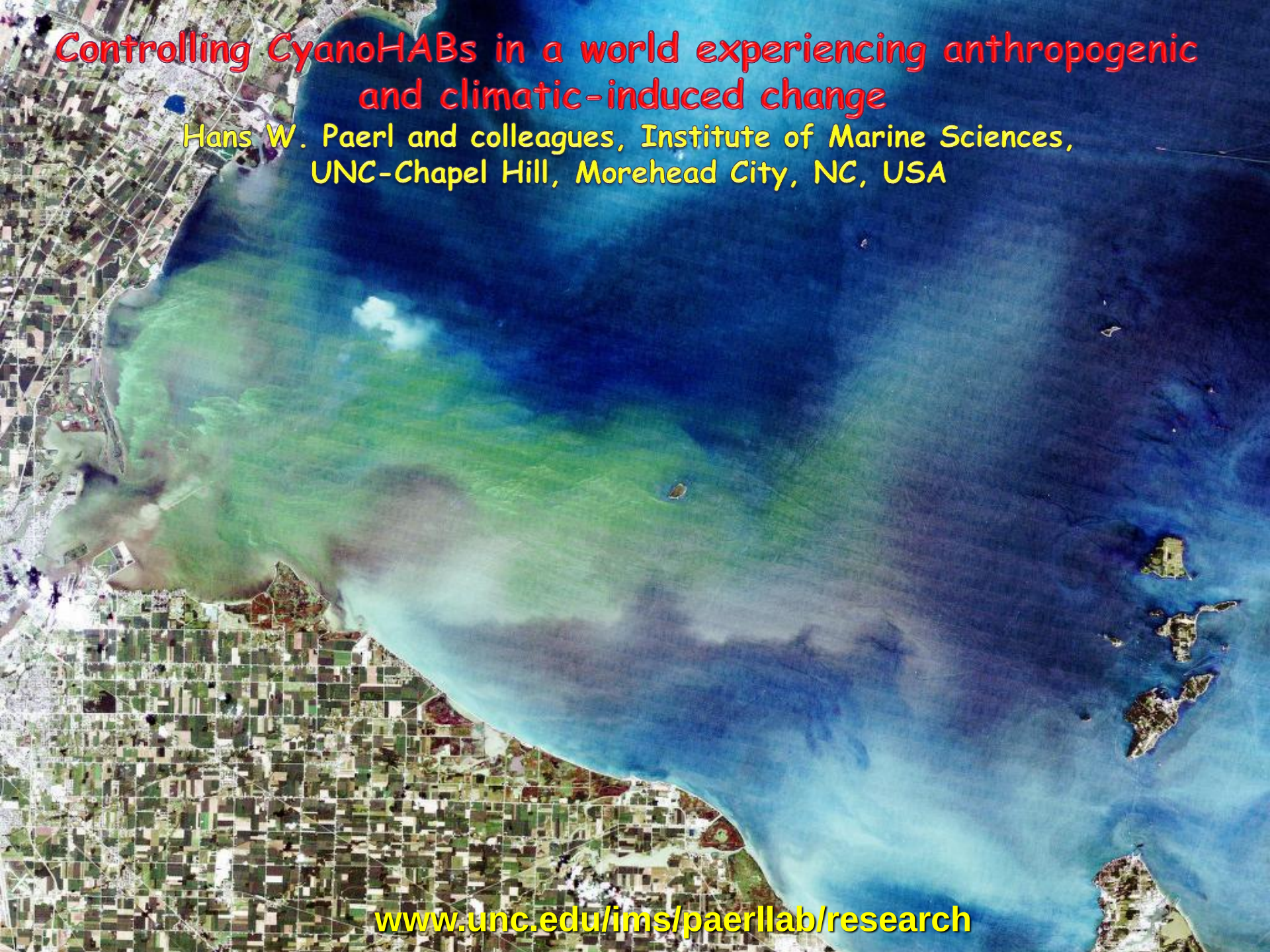


An aerial photograph of a coastal region. On the left, a land area with a grid-like pattern of fields and some buildings is visible. A large, irregularly shaped area of bright green water, representing a cyanobacterial bloom, extends from the land into the darker blue ocean. The bloom has a distinct shape, somewhat resembling a map of North America. To the right of the bloom, the water is a deep blue, and several small, rocky islands are visible. The text of the slide is overlaid on the top portion of the image.

Controlling CyanoHABs in a world experiencing anthropogenic and climatic-induced change

Hans W. Paerl and colleagues, Institute of Marine Sciences,
UNC-Chapel Hill, Morehead City, NC, USA

www.unc.edu/ims/paerllab/research

Cyanobacterial Harmful Blooms (CyanoHABs): Symptomatic of human and climatic alteration of aquatic environments

Urban, agricultural and industrial expansion



Increasing nutrient (Nitrogen & Phosphorus) inputs



Water use and hydrologic modification play key roles



Climate (change) plays a key interactive role

Blooms are intensifying and spreading



Why the concern about HABs?

- Toxic to zooplankton, fish, shellfish, domestic animals and humans
 - Cause hypoxia and anoxia, leading to fish kills
 - Odor and taste problems
- loss of drinking water recreational, fishing use/sustainability



It's a global problem

- **Freshwater Ecosystems**
(lakes, reservoirs, streams, rivers)



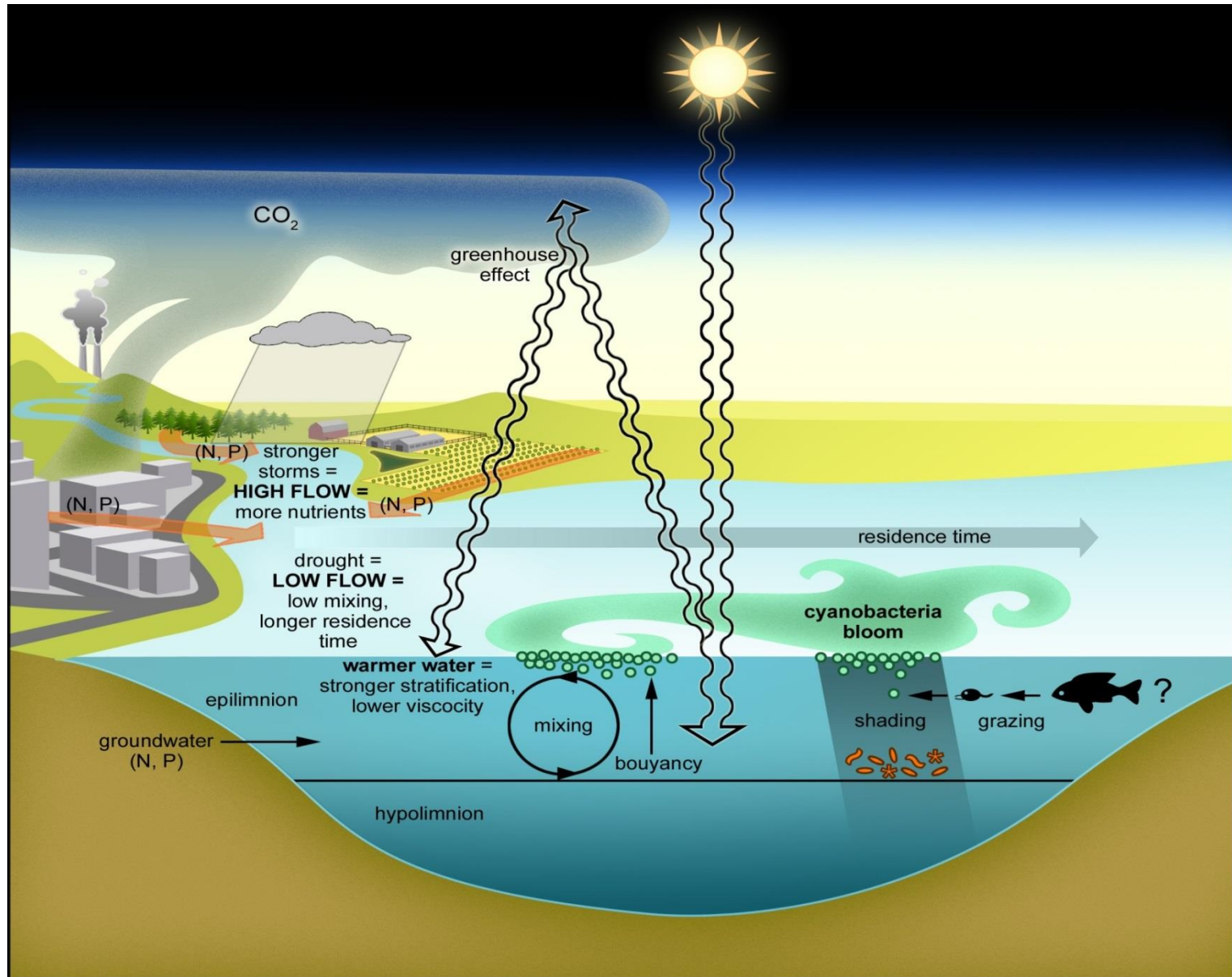
- **Estuaries**



- **Coastal waters & seas**



What Controls CyanoHABS? Interacting Physical, Chemical & Biotic Factors



Nutrients: N and P inputs have long been recognized as playing a key role in bloom dynamics, but there's a controversy.....

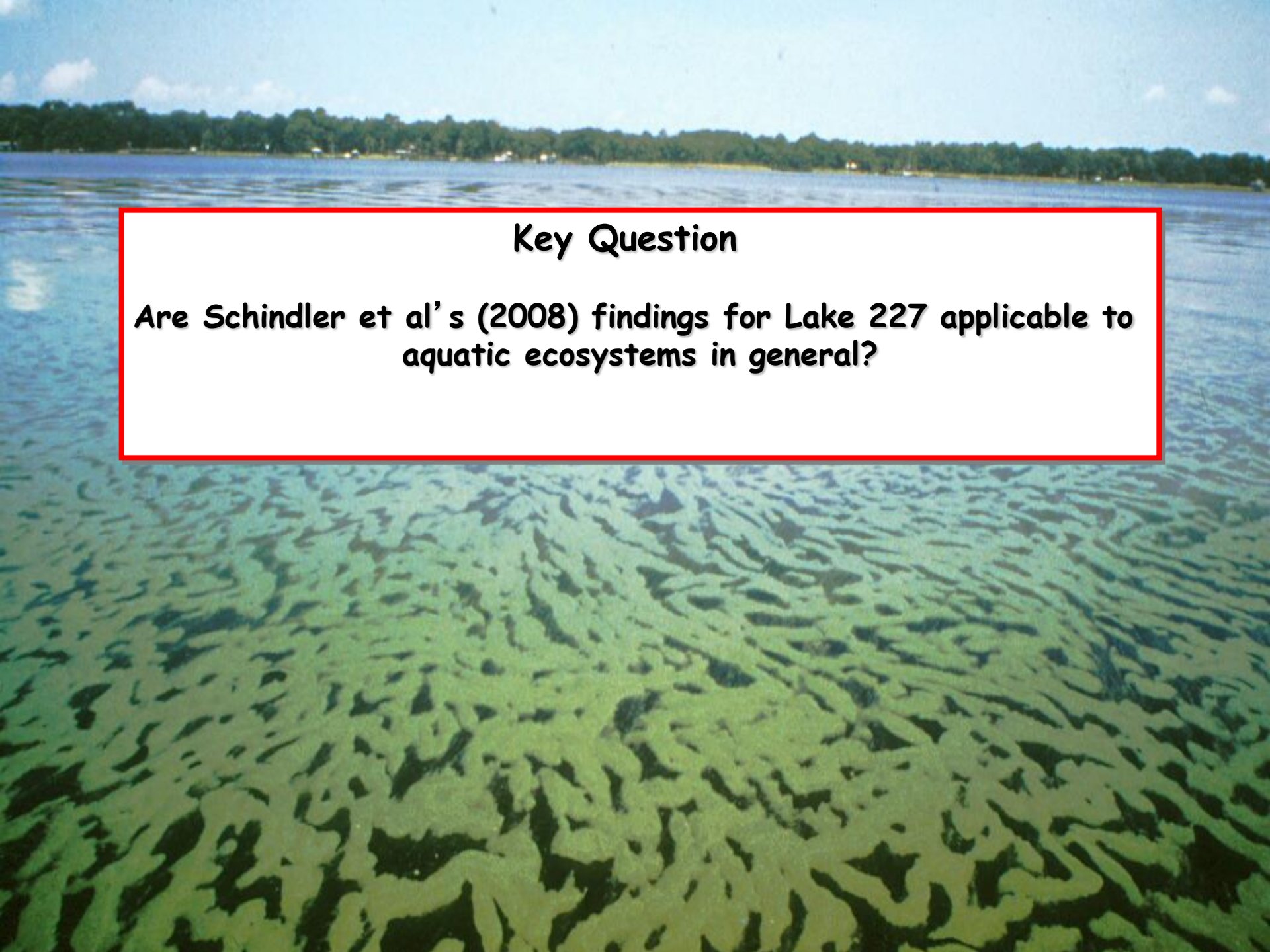
“Eutrophication of lakes cannot be controlled by reducing nitrogen input: Results of a 37-year whole-ecosystem experiment”

Schindler et al. Proceedings of the National Academy of Science USA 105:11254-11258 (2008).

Conclusion by Schindler et al. (2008) (based on one lake: Lake 227) assumes that CyanoHAB N₂ fixation will supply ecosystem N needs
Therefore, why worry about N? Argument extended to estuarine and coastal systems



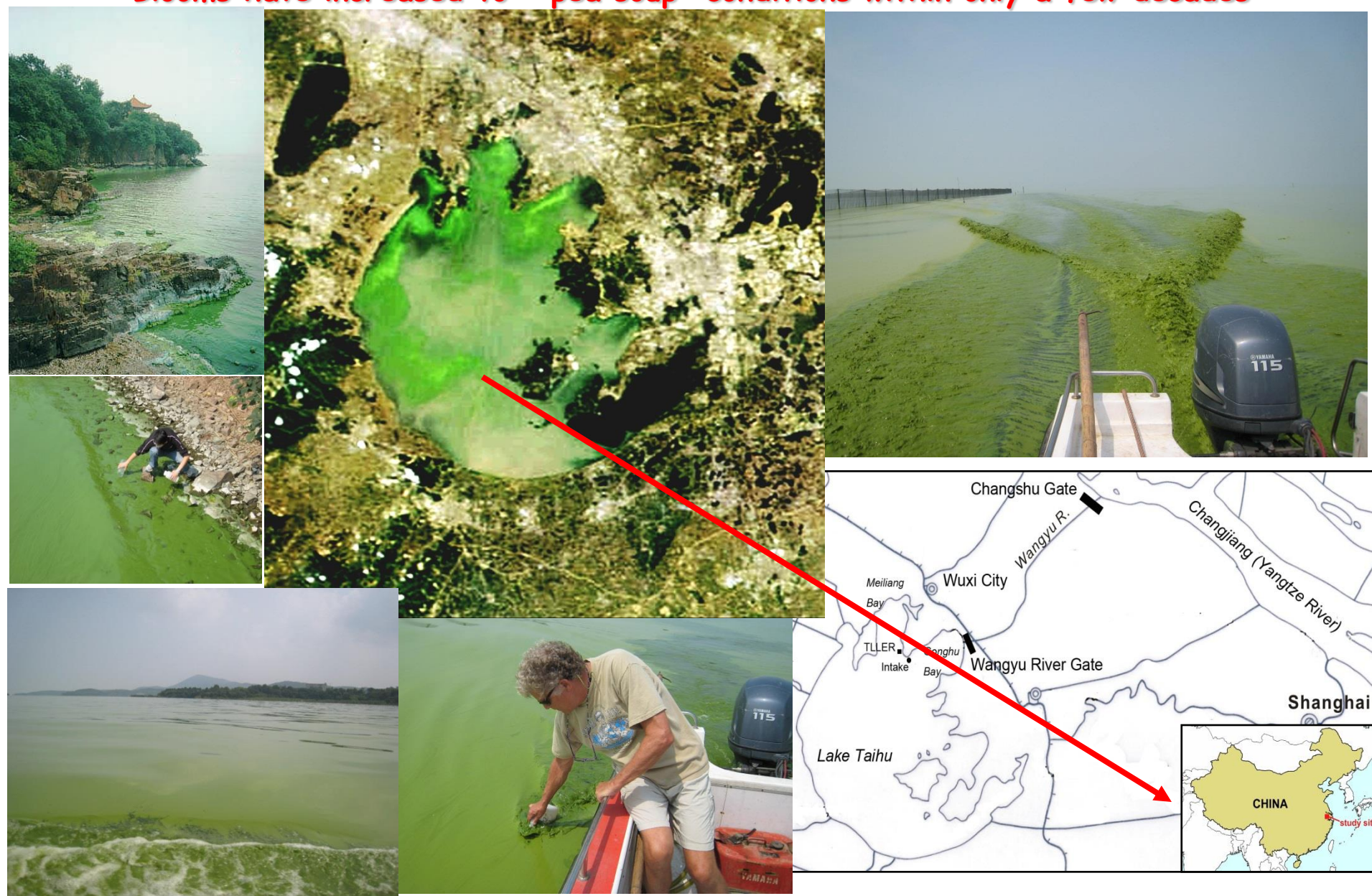
These assumption have been challenged
(Lewis and Wurtsbaugh 2008; Conley et al., 2009; Paerl 2009; Scott & McCarthy 2010; Lewis et al. 2011)



Key Question

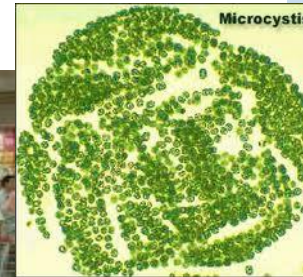
Are Schindler et al's (2008) findings for Lake 227 applicable to aquatic ecosystems in general?

Lake Taihu 3rd largest lake in China. Nutrients (Lots!) associated with unprecedented human development in the Taihu Basin (Jiangsu Province). Results: Blooms have increased to “pea soup” conditions within only a few decades



The water crises (2007- ?) in the Taihu Basin:

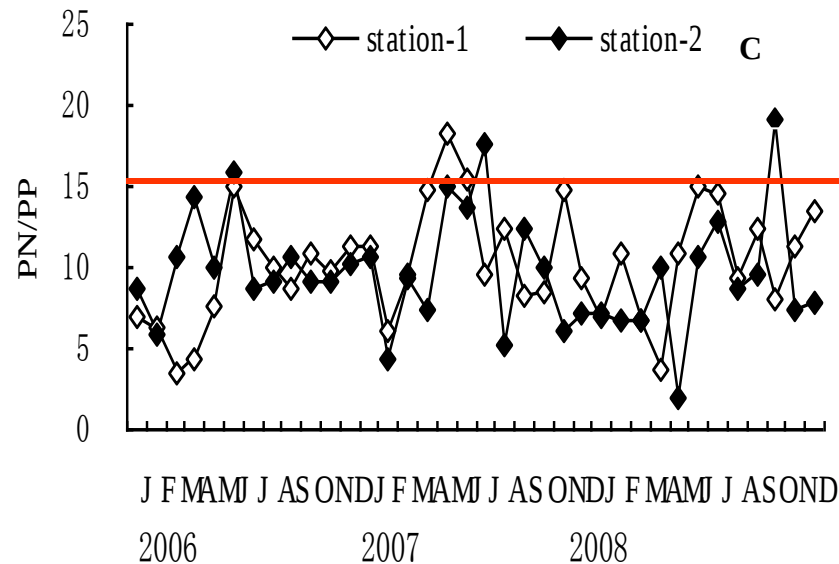
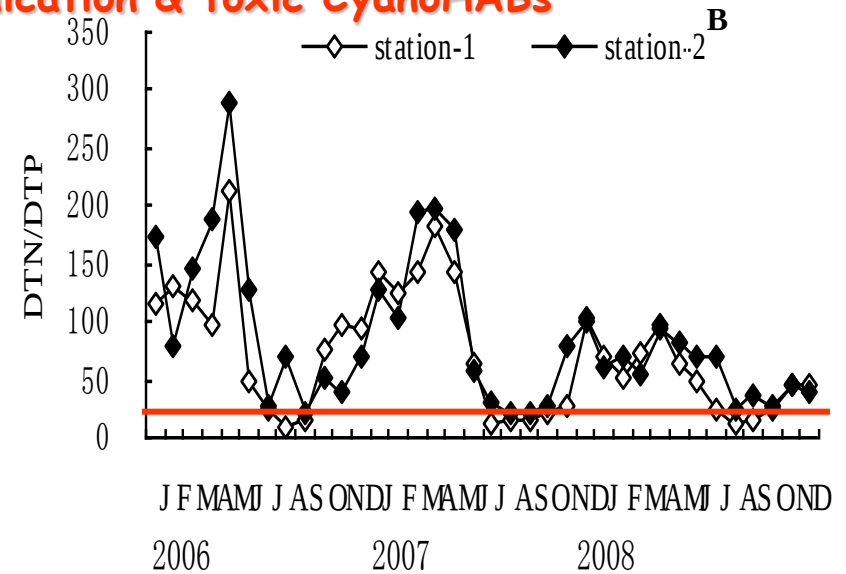
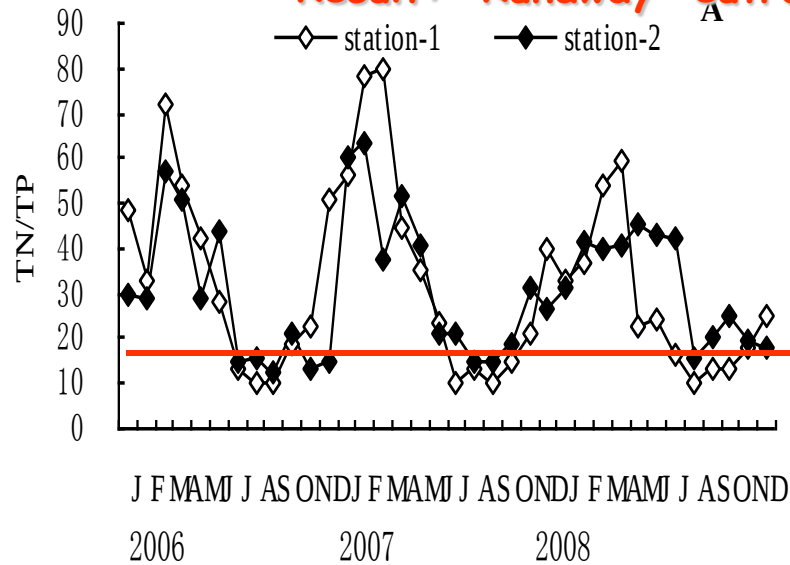
- Cessation drinking water use for >20 million (hepato- and neuro-toxins)
- Curtailed recreational use (contact dermatitis)
- Fisheries (commercial and recreational)
- Tourism???



The nutrient “problem” in Taihu (and other hypertrophic lakes)

N & P inputs exceed what's needed for balanced algal growth.

Result: “Runaway” eutrophication & toxic CyanoHABs

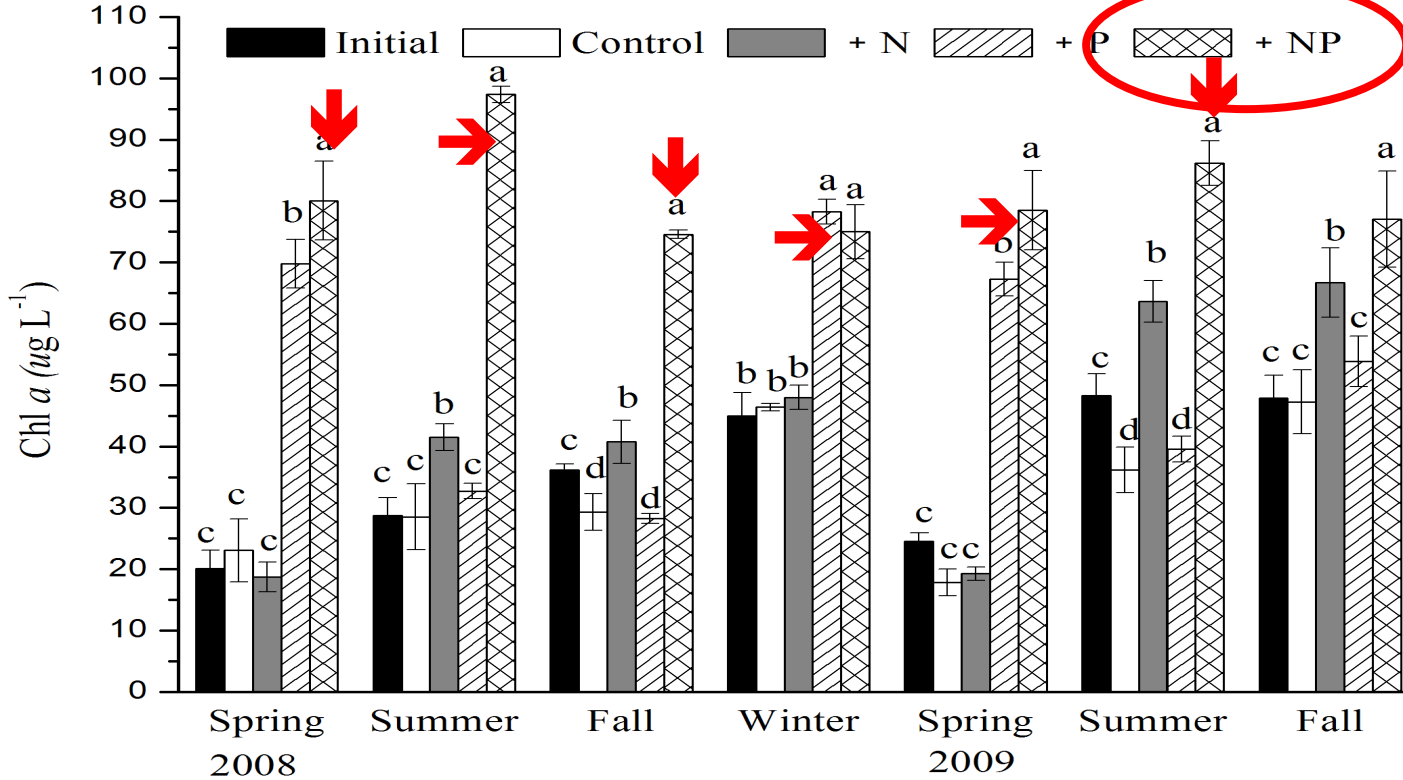


Nutrient (N&P) ratios in Taihu

Redfield (balanced growth)
~15:1 (N:P)

HYPOTHESIS
Dual (N & P) reductions will be
needed to stem eutrophication
and CyanoHABs

Effects of nutrient (N & P) additions on phytoplankton production (Chl *a*) in Lake Taihu, China: **Both N & P inputs matter!!**



Xu et al. 2010; Paerl et al. 2011

Oct. 2008

Control
(no nutrients)



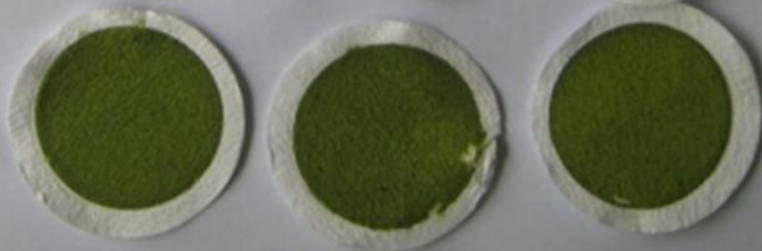
+ N- NO_3^-



+ P- PO_4^{3-}



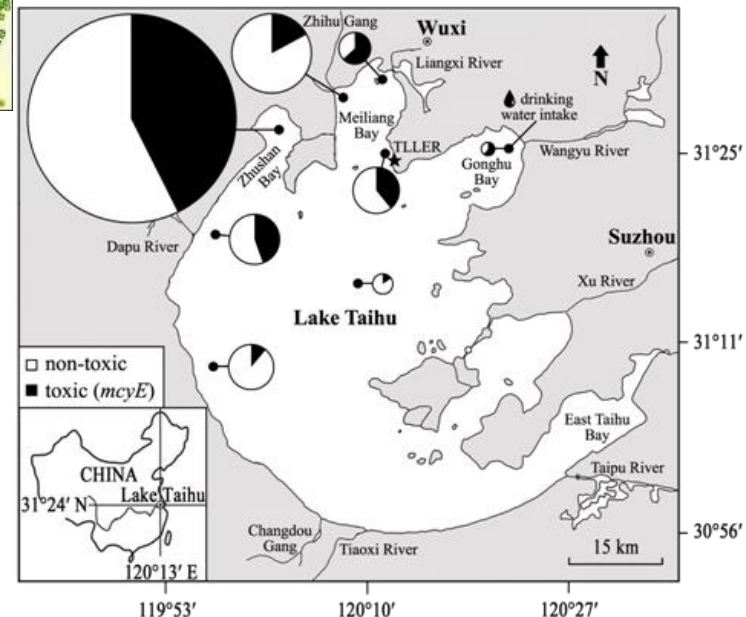
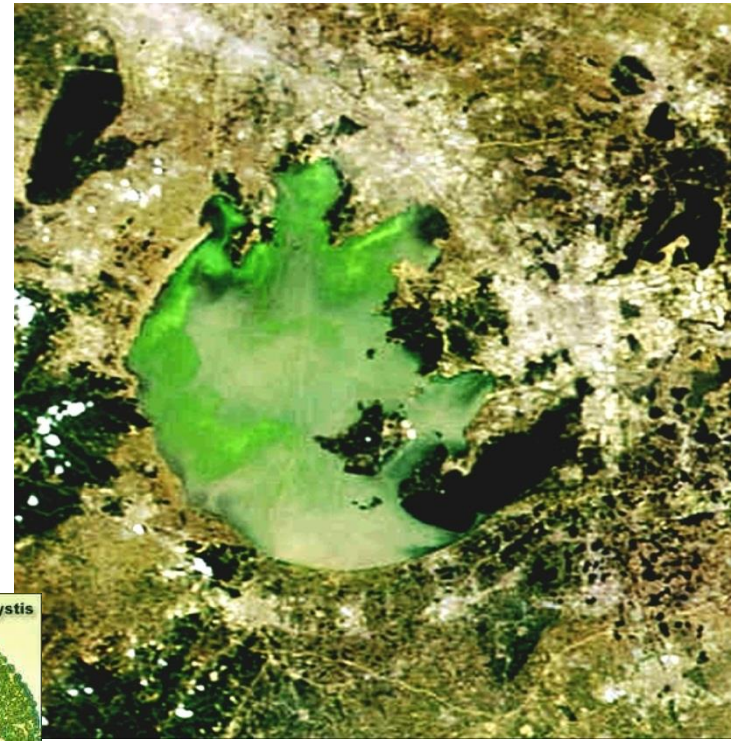
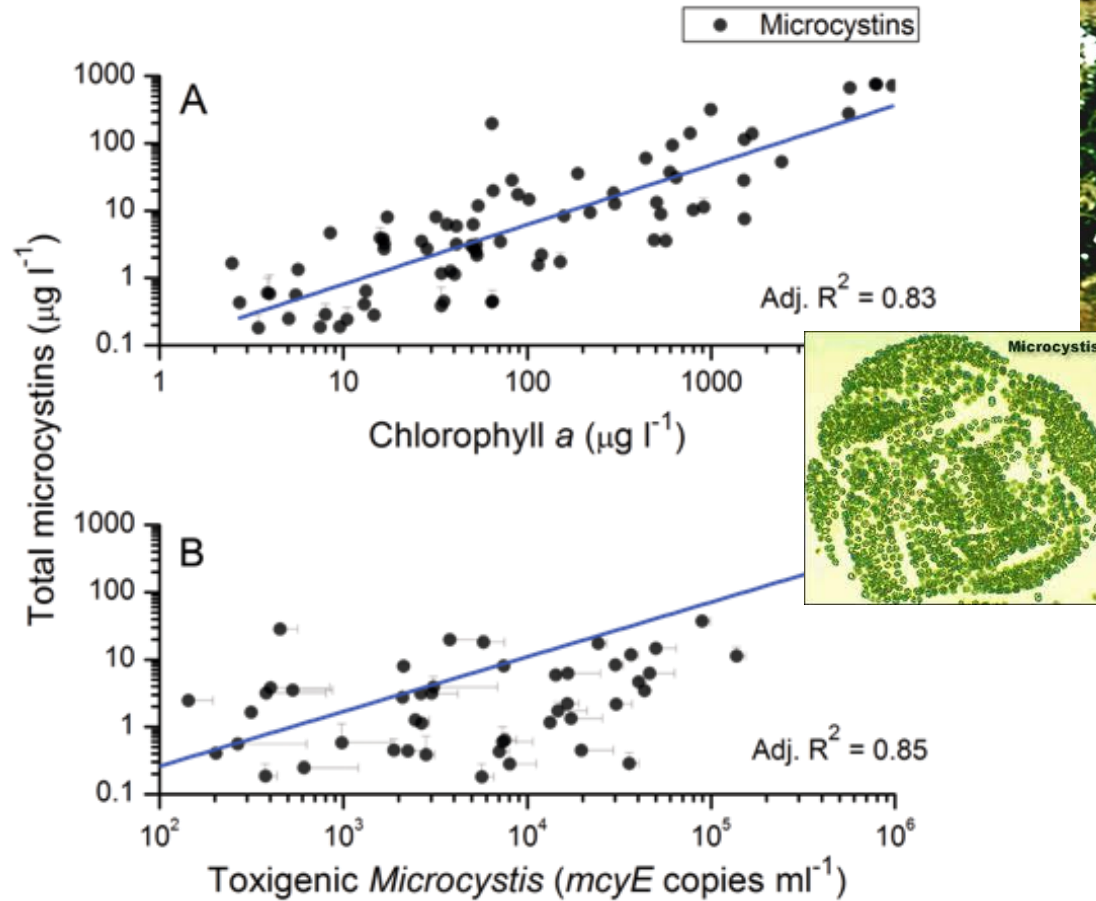
+ N + P



CyanoHAB Toxicity

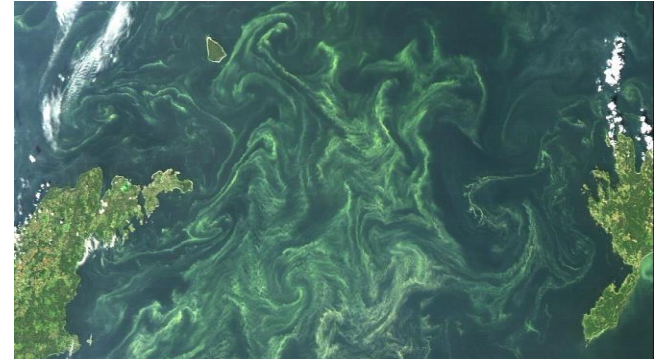
Related to nutrient inputs and biomass

Chlorophyll a is a sensitive, relevant and easy to use indicator



Otten et al., 2011, 2012; Wilhelm et al., 2011

Is Taihu a “looking glass” for hypertrophic shallow ecosystems worldwide?

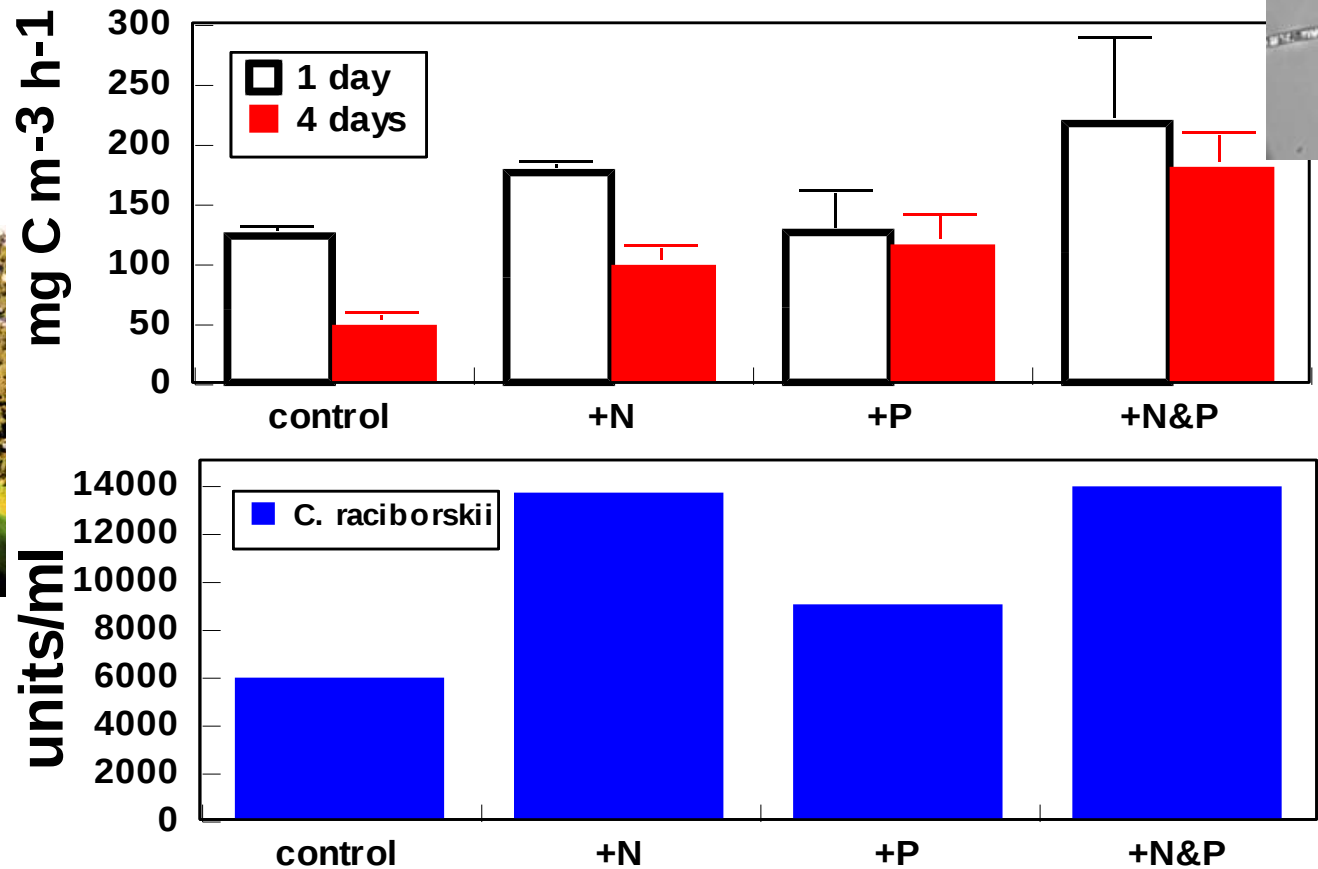


Florida lakes : *Cylindrospermopsis raciborskii*, rapidly-proliferating, **toxic** N_2 fixing cyanoHAB

- ❖ High P uptake and storage capacity
- ❖ High NH_4^+ uptake affinity (competes well for N)
 - ❖ N additions ($NO_3^- + NH_4^+$) often significantly increase growth (chl a and cell counts) and productivity
- ❖ N_2 fixer (can supply its own N needs)
- ❖ Tolerates low light intensities
 - ❖ Eutrophication/decreased transparency favors *Cylindro*
 - ❖ Often in water column with other cyanoHABs



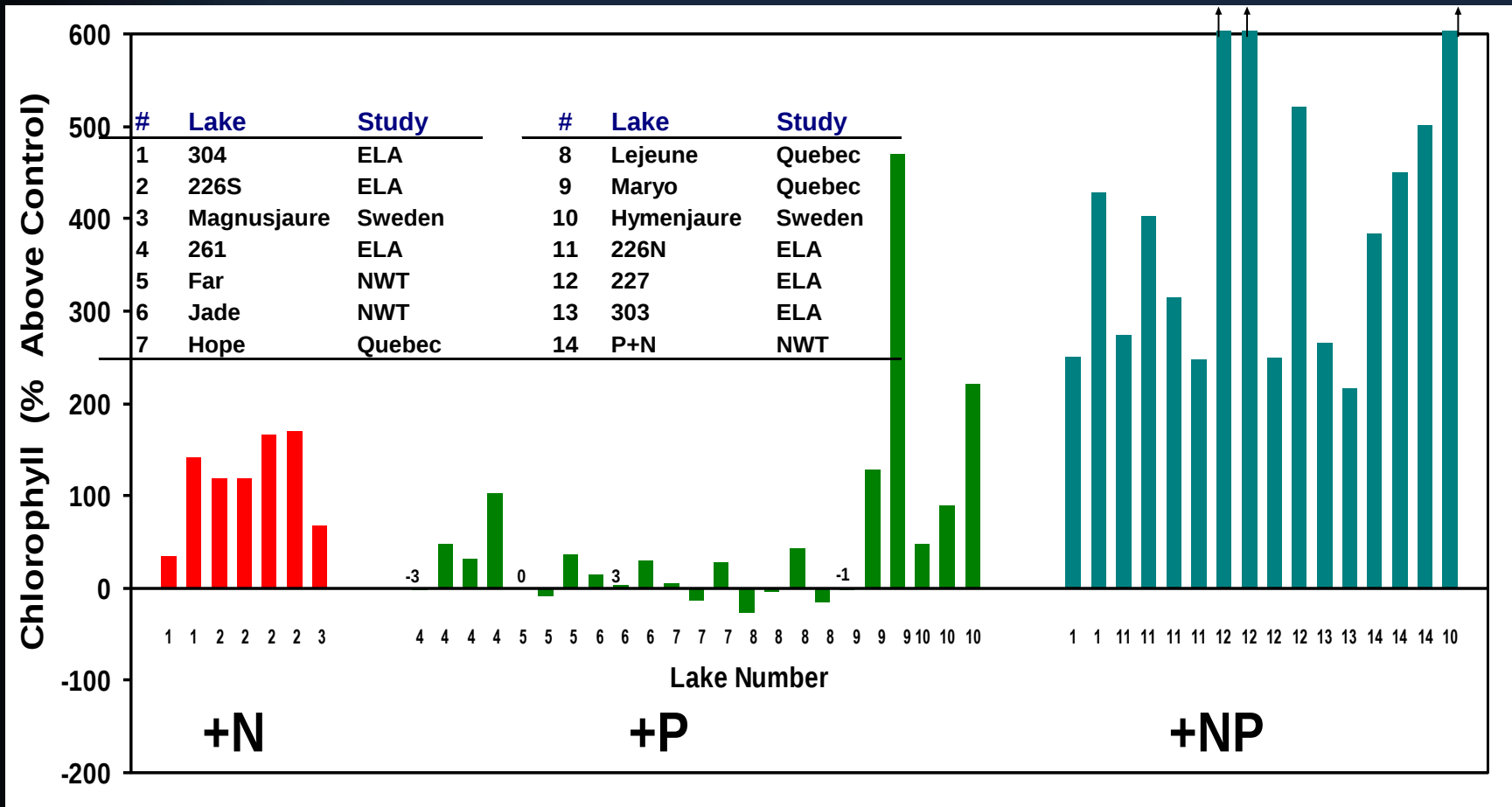
St. Johns R. System, FLorida: Nitrogen and Phosphorus Effects on CyanoHAB Growth and Bloom Potential (*Cylindrospermopsis raciborskii*)



Take home message: *Cylindrospermopsis raciborskii* is opportunistic
Dual N & P input constraints will likely be needed to control it

Piehl et al, 2009

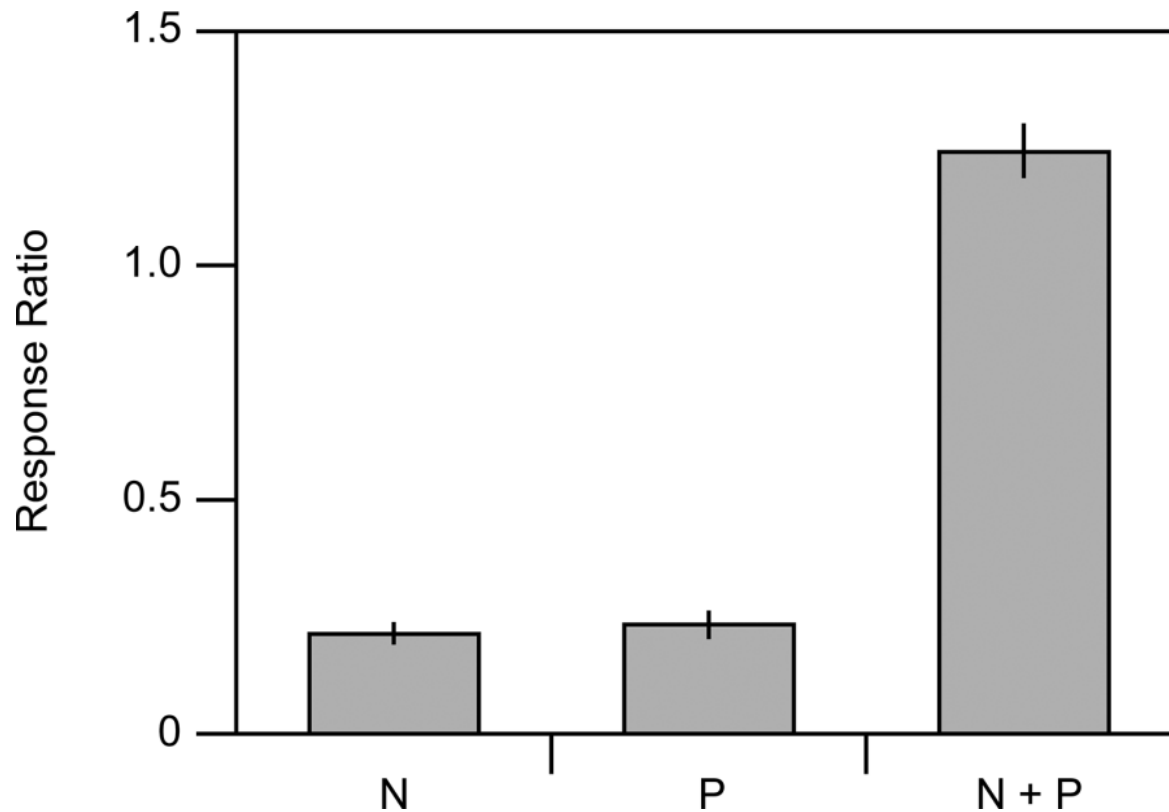
Whole-Lake Fertilization Experiments (Canada: ELA, Quebec, NWT, Sweden)



Co-Limitation Dominant

Wurtsbaugh et al., 2012

A summary of N & P limitation in lakes worldwide

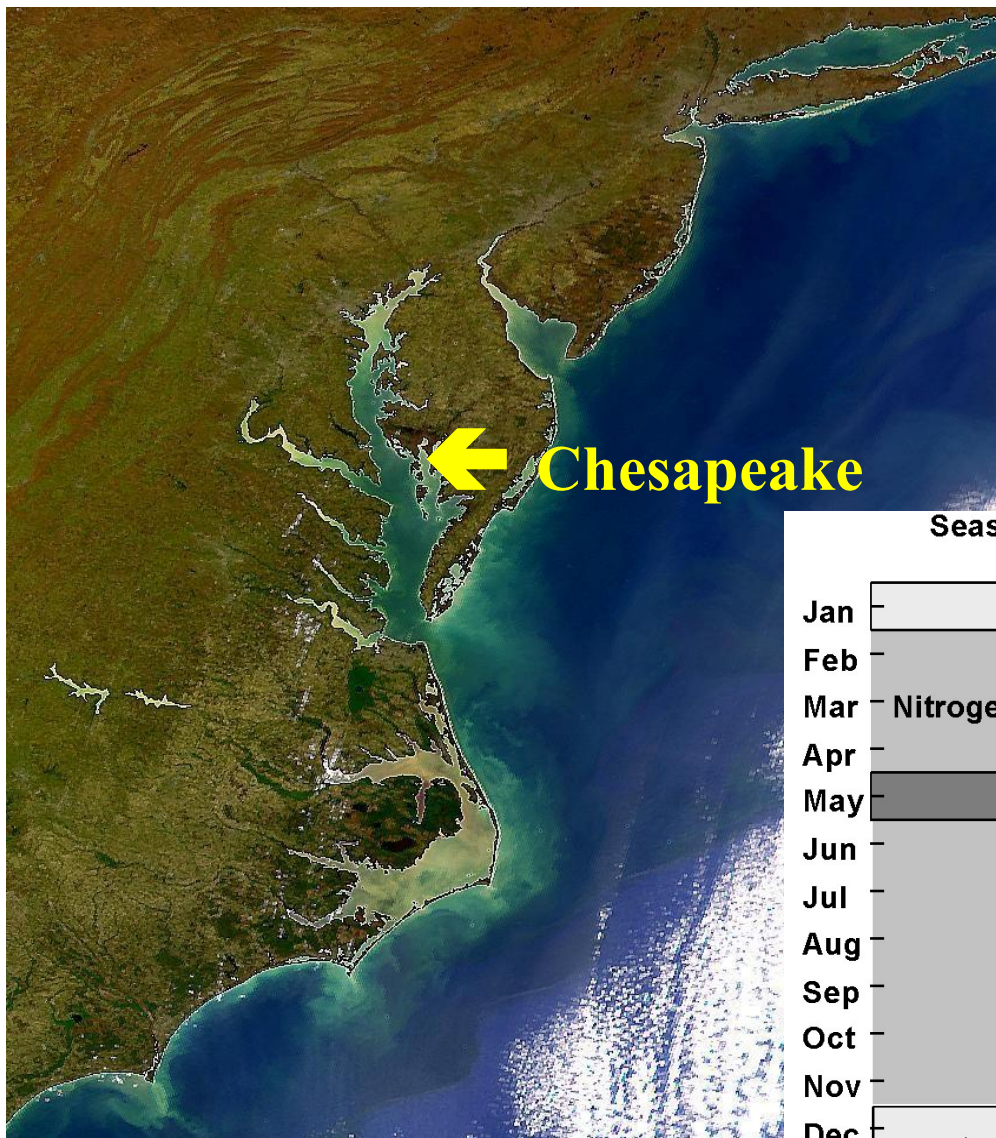


Lakes: N= 55

Lewis et al., ES&T 45:10300-10305 (2011)

Nutrient limitation along the freshwater to marine continuum

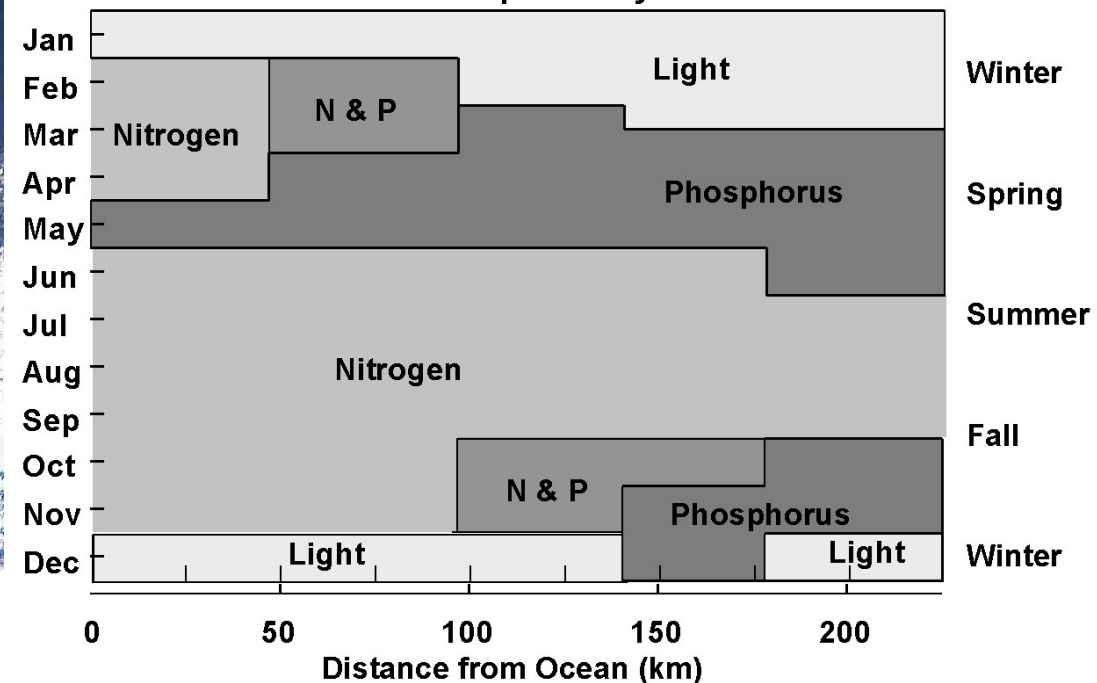
Estuaries with CyanoHABs: the Chesapeake Bay



Fisher et al. 1998

Seasonal & Spatial Patterns of Nutrient Limitation in Chesapeake Bay

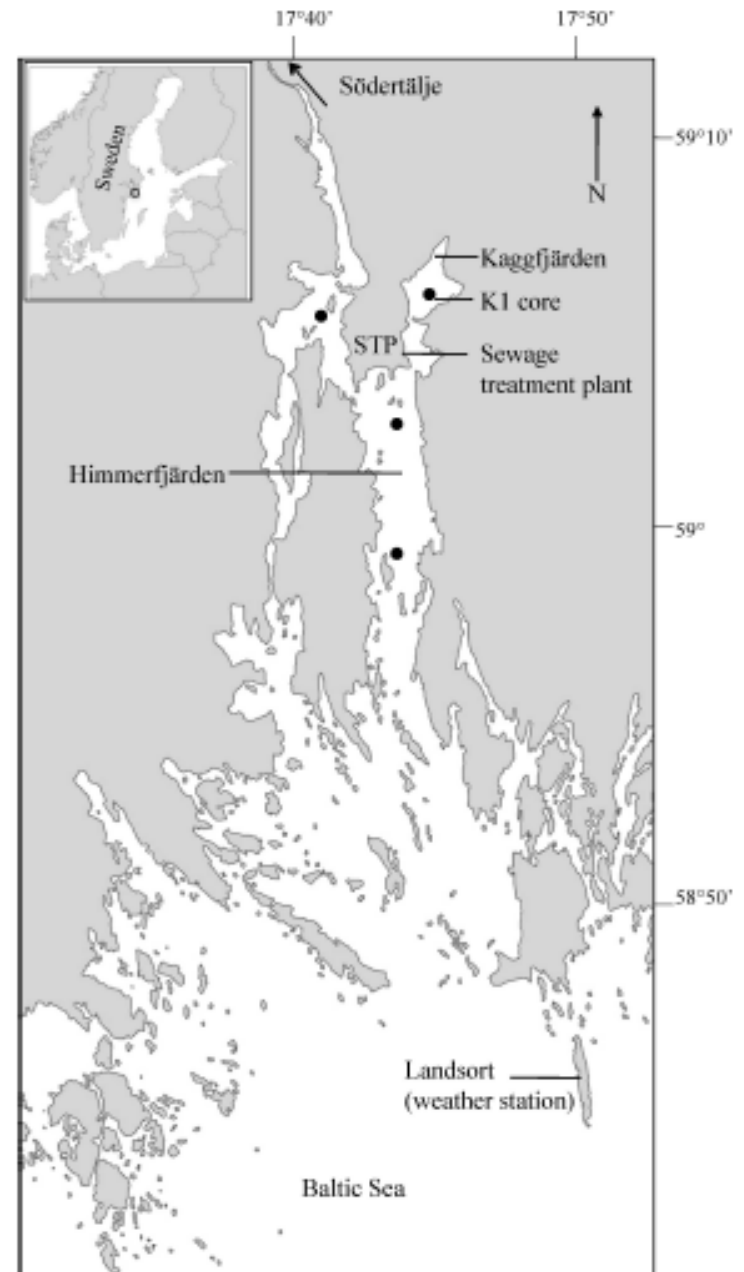
(Fisher et al. 1998)





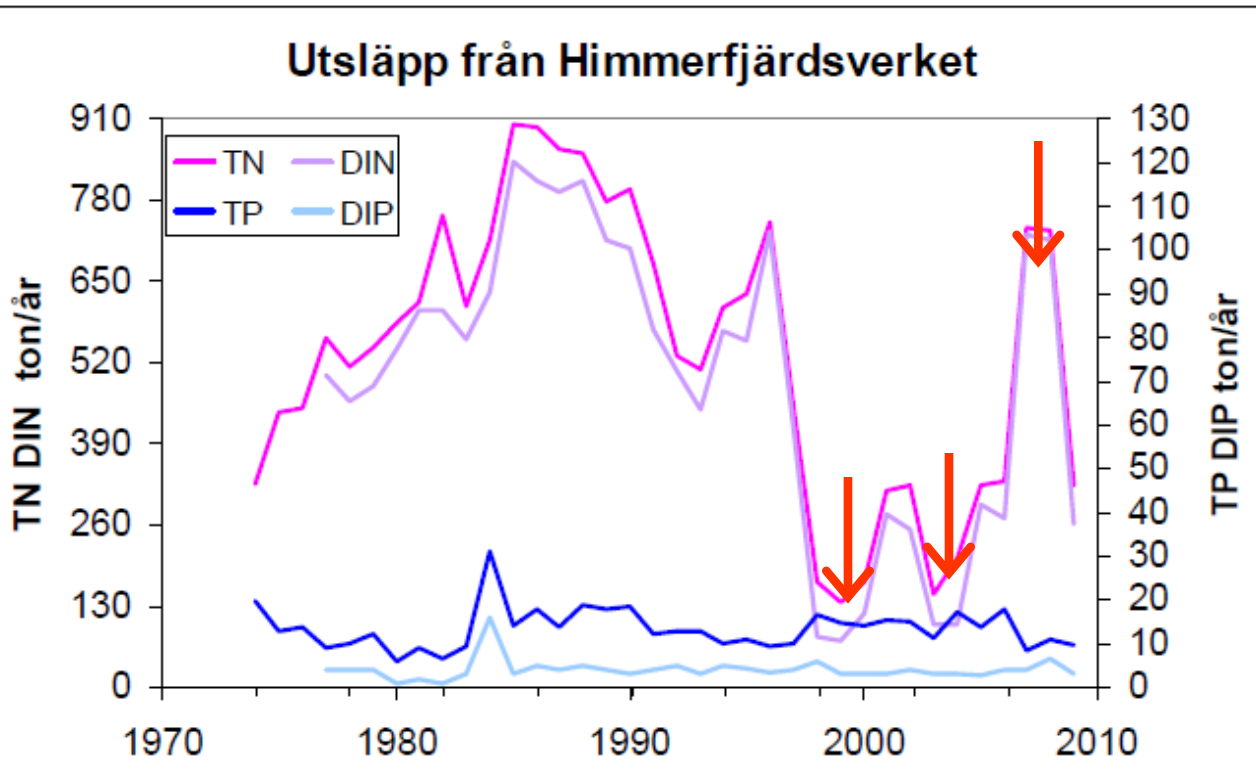
Nutrient load and phytoplankton (dominated by cyanobacteria) growth response in Himmerfjärden (freshwater to brackish), Sweden

Courtesy: Ulf Larsson & Ragnar Elmgren
Stockholm University

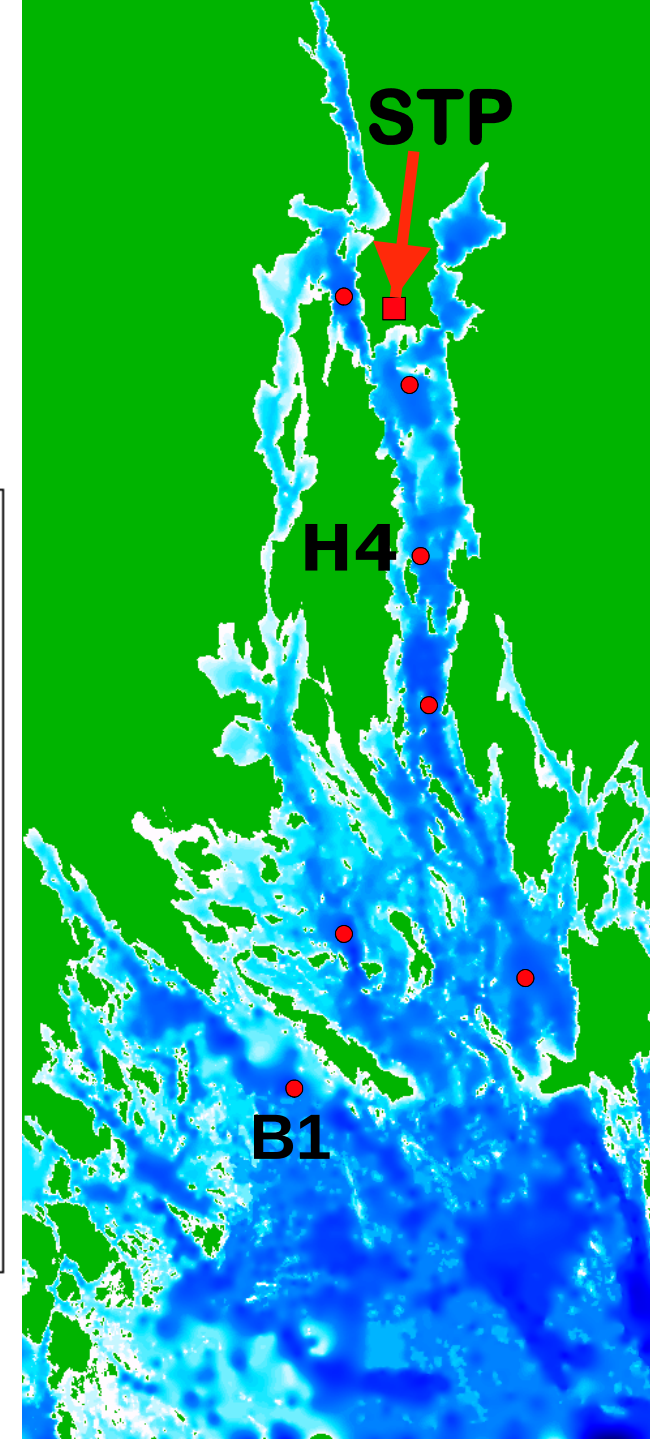


The Himmerfjärden case: Baltic coastal area
 with large Sewage treatment plant,
P removal since 1976
N removal started in 1993 (50%) & 2000 (80%).
No N removal 2004-2008
EFFECTS ON PHYTOPLANKTON (Chl a)?

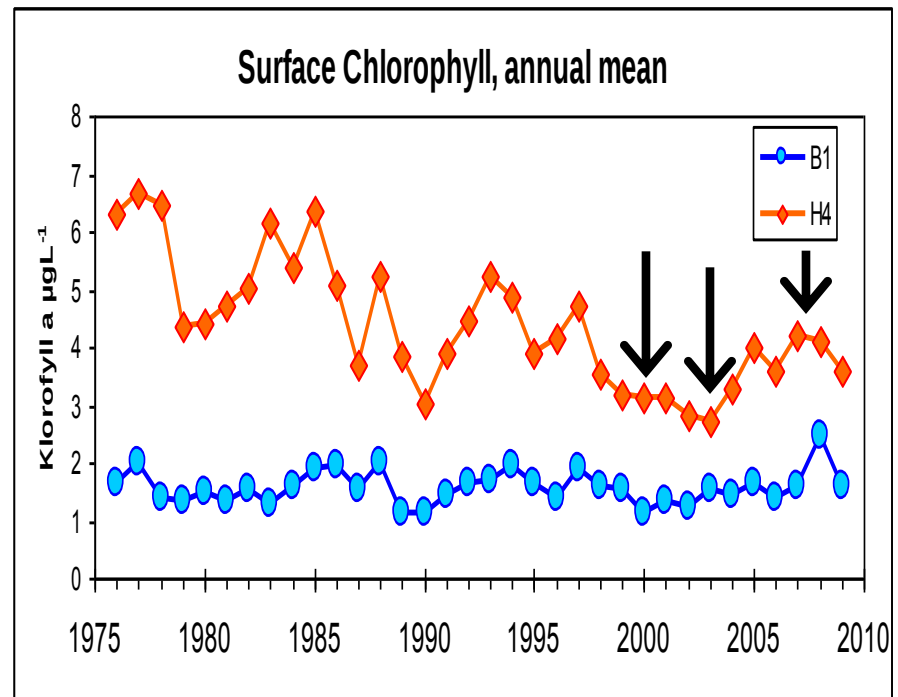
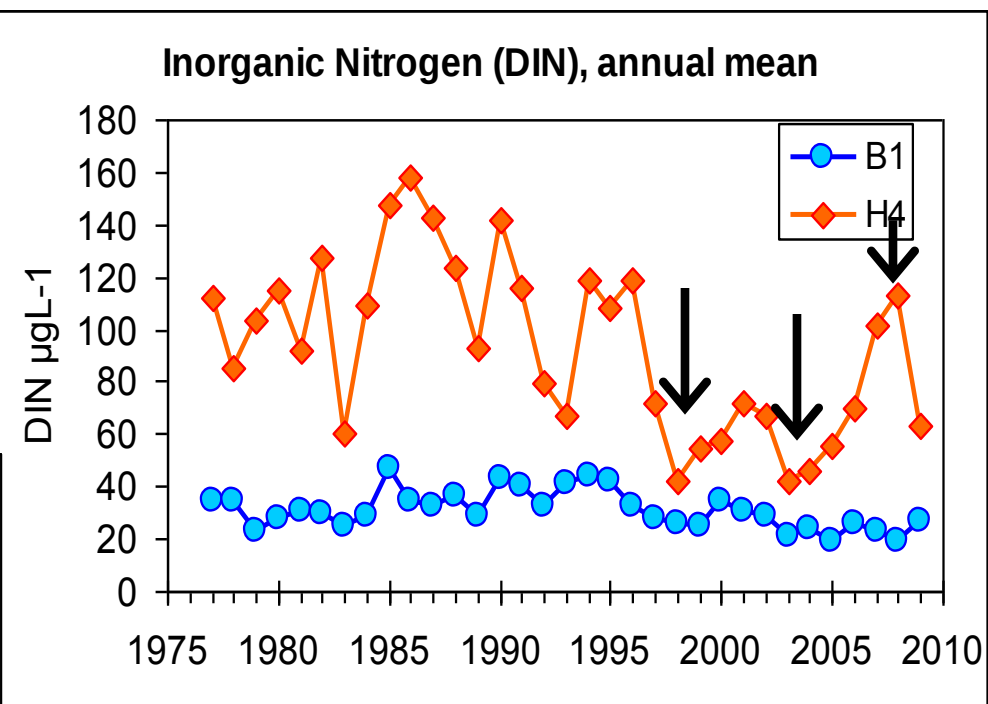
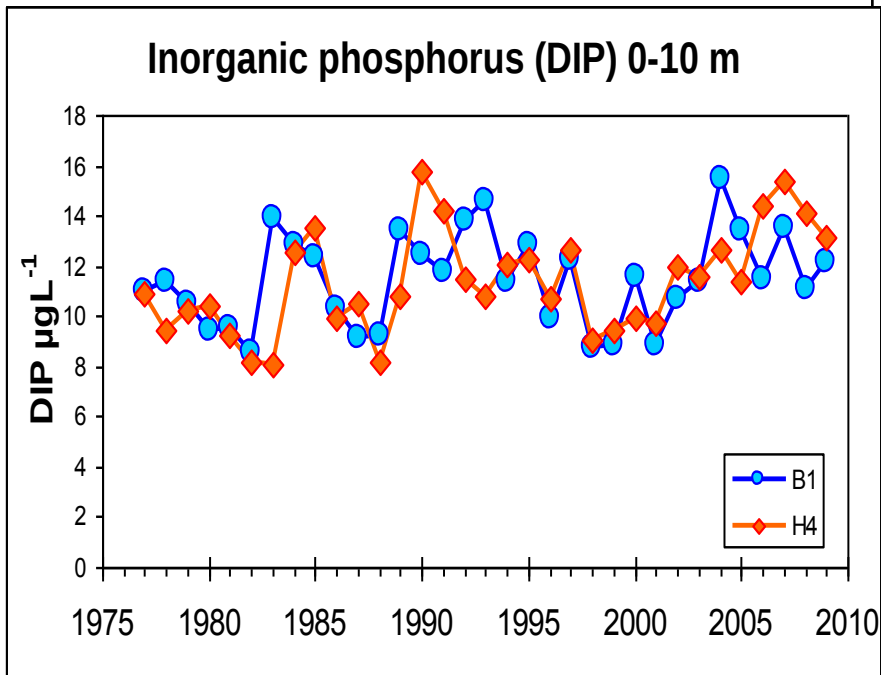
Plant loads , tonnes/ year



H4 = Eutrophicated station
B1 = Reference station



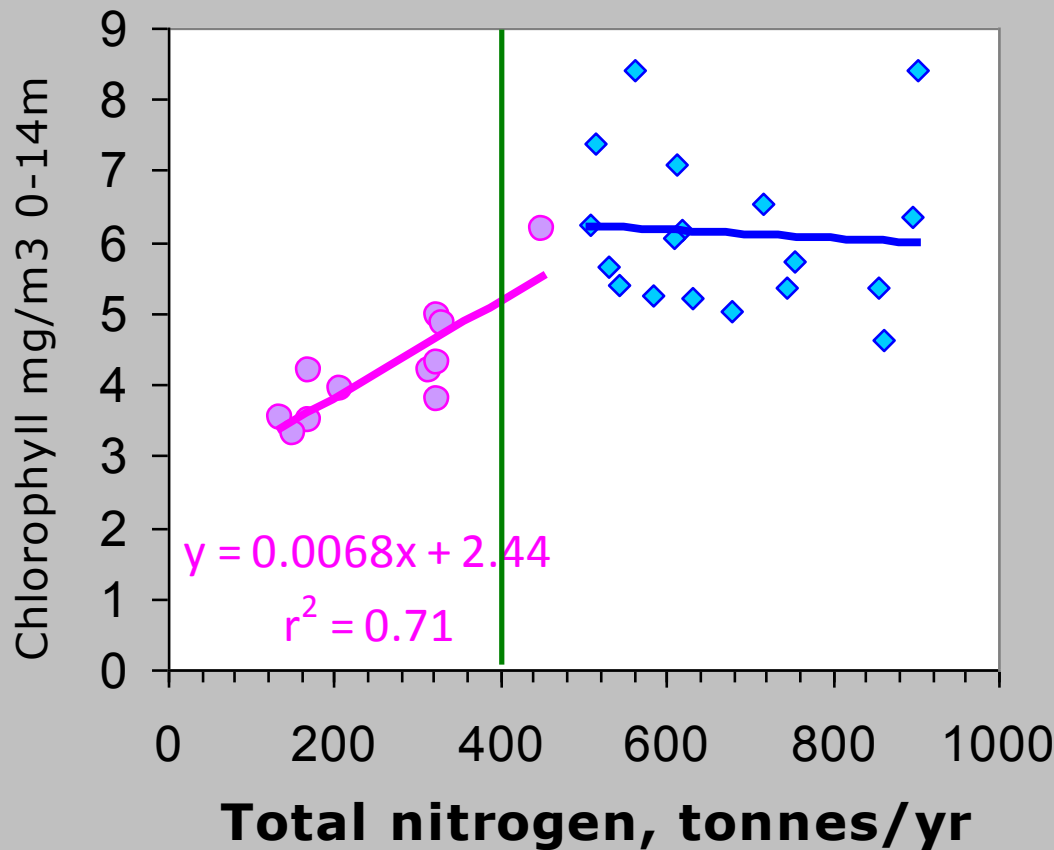
The results: Reducing DIN inputs reduced Chl a



Larsson and Elmgren, 2012

Developing a N loading-bloom threshold

Himmerfjärden Chlorophyll a vs tot-N from sewage plant



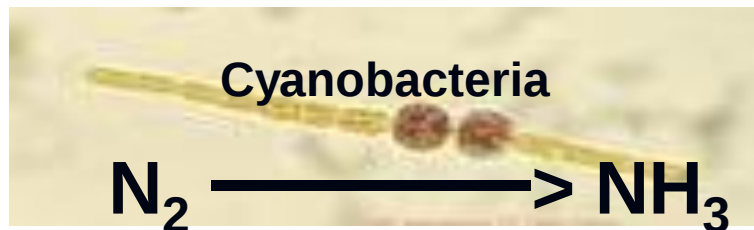
**Lowering nitrogen
discharge below 400
tonnes/yr clearly
reduced local
phytoplankton biomass.**

Source:
Ulf Larsson, pers.comm.

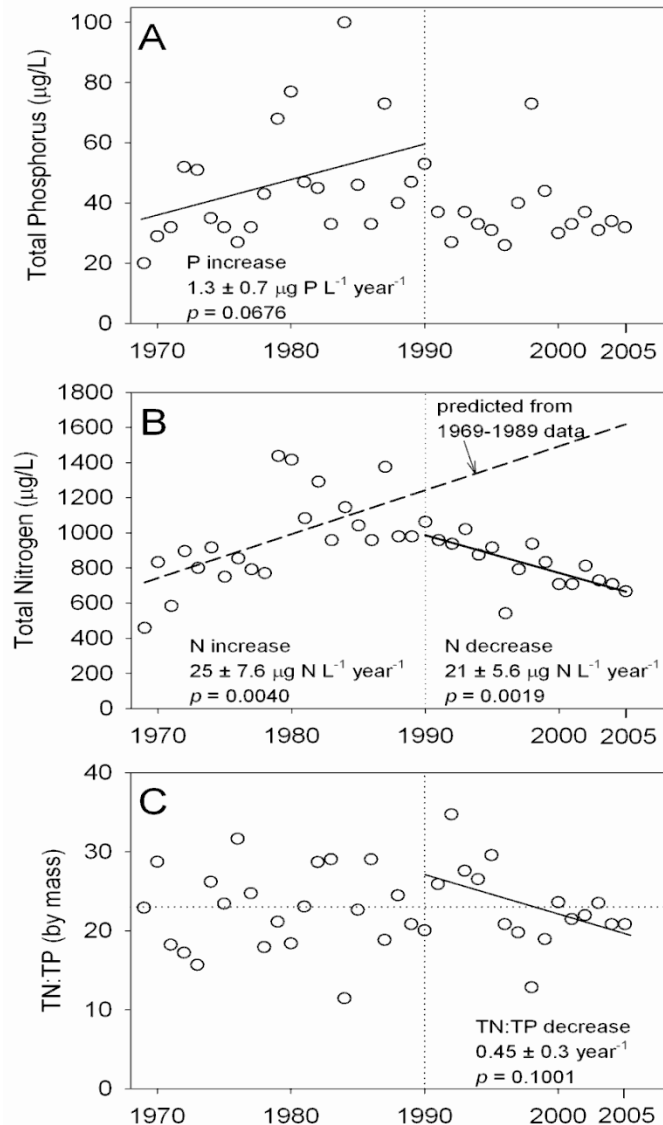
**Lets go back to the ‘P only’
paradigm from whole-lake
experiments, suggesting that P
alone controls algal biomass
(Schindler et al., 2008)**

The Argument:

**If nitrogen is in short supply,
nitrogen fixation by cyanobacteria
will make up the nitrogen deficit:**



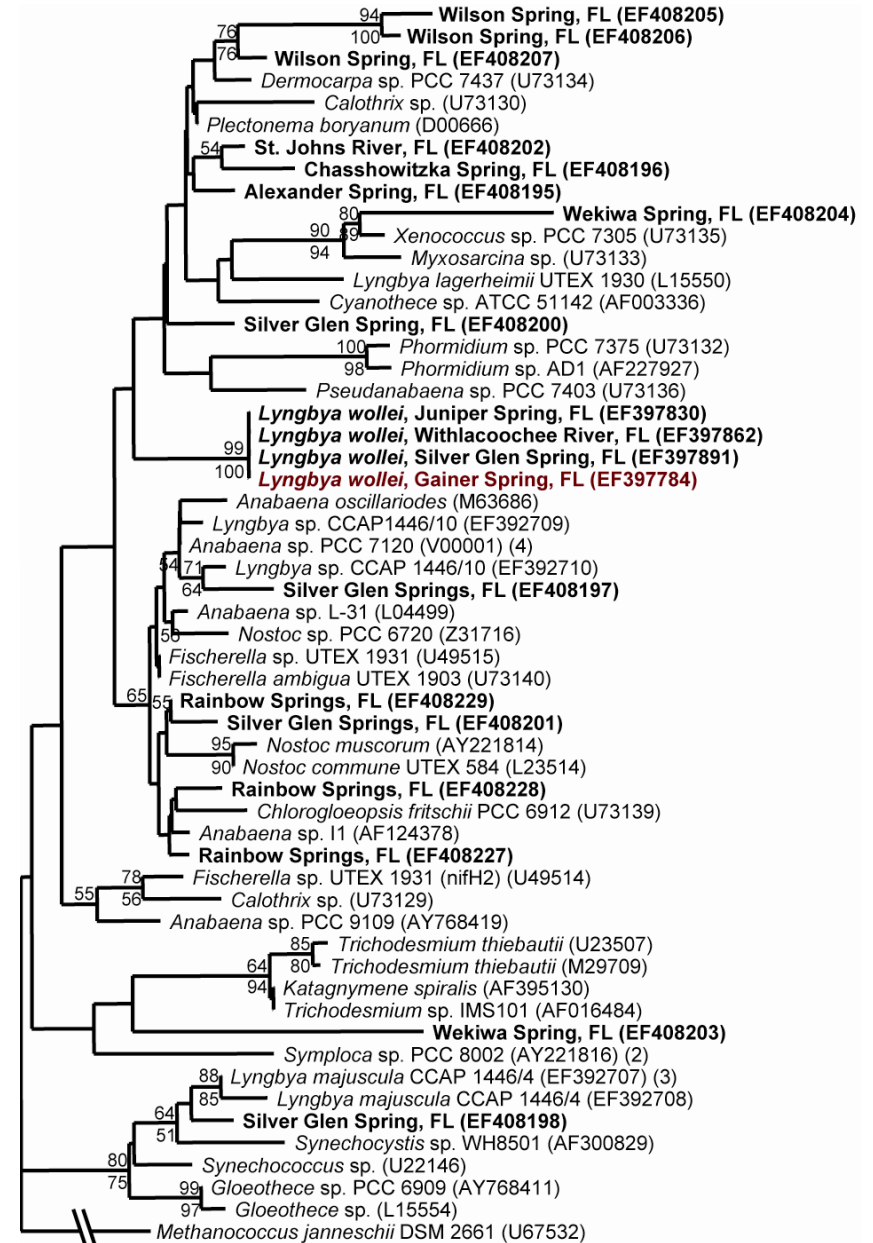
Lets look at the data for lake 227: What happened following N&P fertilization (1968-1989), then only P fertilization (1989 →)?



Following cessation of N fertilization, Total N, TN:TP, and phytoplankton biomass decreased. N_2 fixation could not keep up with ecosystem N demands (Scott & McCarthy L&O 55:1265-1270 (2010))

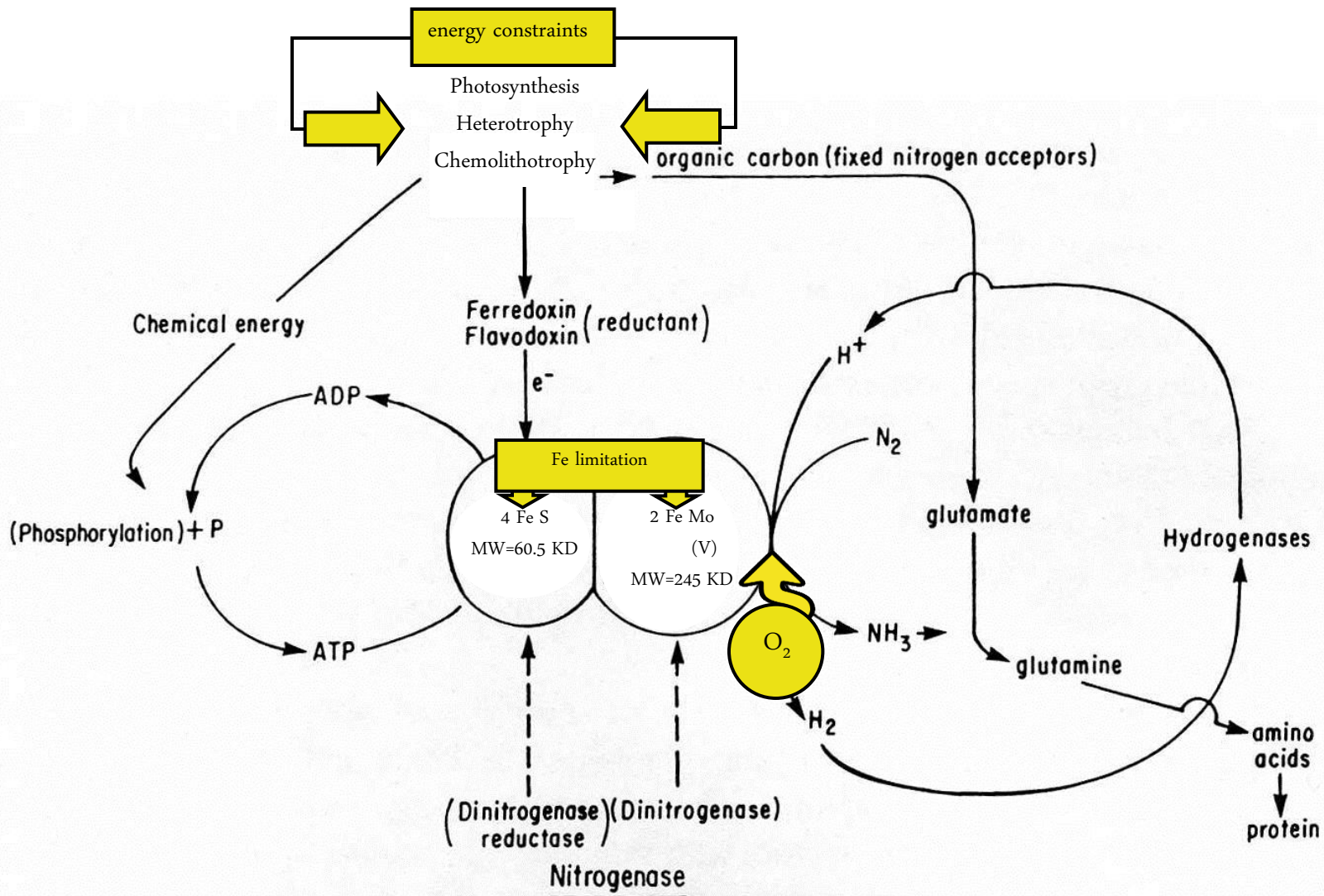
WHY?????

It's not because there's a shortage of N₂ fixing taxa



0.1 substitutions per site

Controls on N₂ fixation: Its not just P or N:P...Other controls



Also, N₂ losses from shallow eutrophic systems exceed “new” N inputs via N₂ fixation

Annual estimates of ecosystem N₂ fixation, denitrification, and net ecosystem N₂ flux in lakes.

Location	N ₂ Fixation (g N m ⁻² yr ⁻¹)	Denitrification (g N m ⁻² yr ⁻¹)	Net N ₂ Flux (g N m ⁻² yr ⁻¹) ¹
Lake 227 (ELA) ²	0.5	5-7	-6.5 – -4.5
Lake Mendota ²	1.0	1.2	-0.2
Lake Okeechobee ²	0.8 – 3.5	0.3 – 3.0	-2.2 – 0.5
Lake Erken ²	0.5	1.2	-0.7
Lake Elmdale	10.4 ³	18 ⁴	-7.6
Lake Fayetteville	10.6 ³	23 ⁴	-12.4
Lake Wedington	7.0 ³	12 ⁴	-5.0

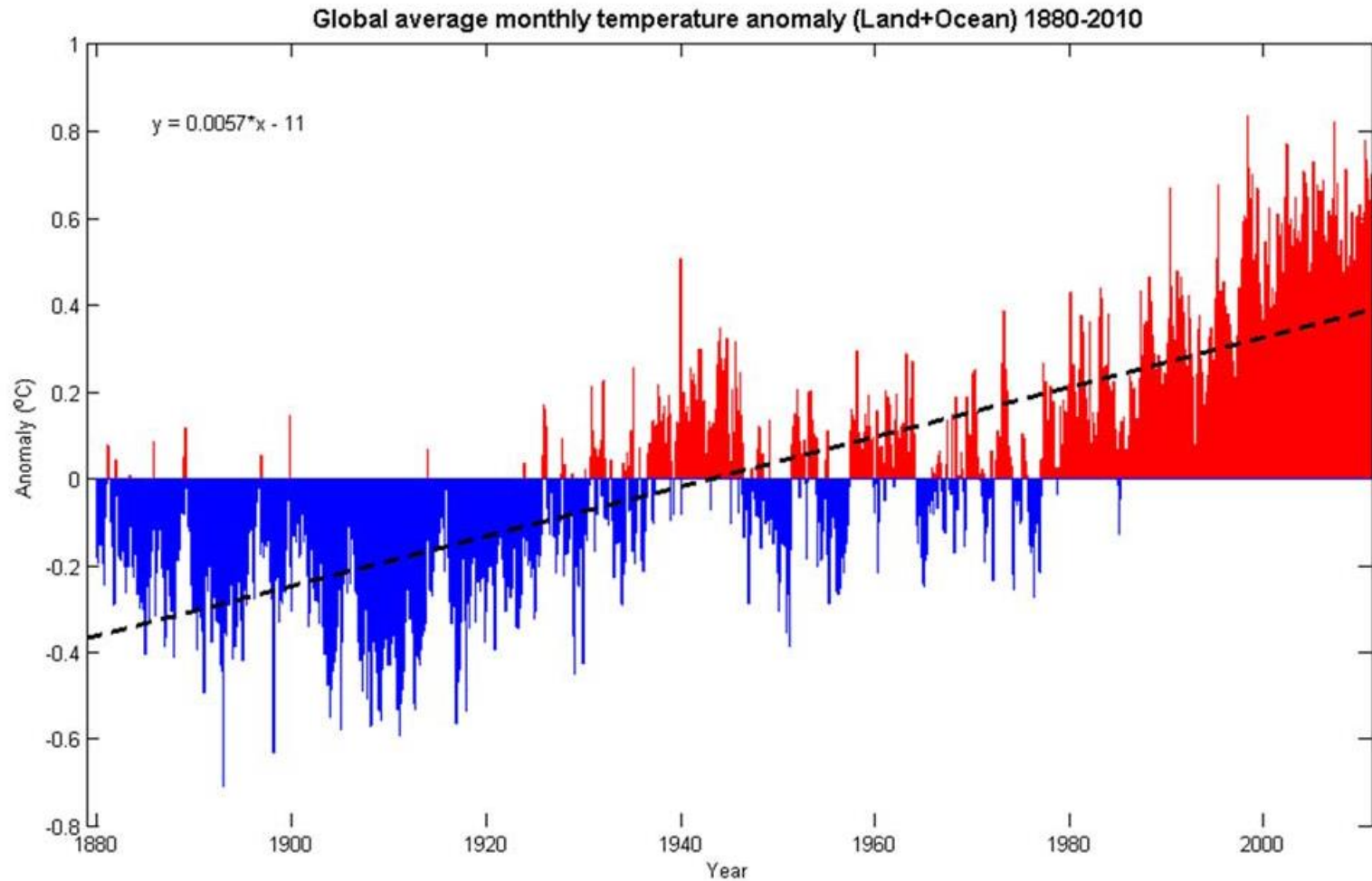
¹Net negative N₂ flux represents reactive N loss, positive represents gain; ²Paerl and Scott (2010); ³J.T. Scott (unpublished data); ⁴Grantz et al. (2012)

Conclusions: 1. N₂ fixation does NOT meet ecosystem N demands

2. More N inputs will accelerate eutrophication

3. We Gotta get serious about controlling N!!

Confounding Impacts of Climate Change: Its Getting Warmer



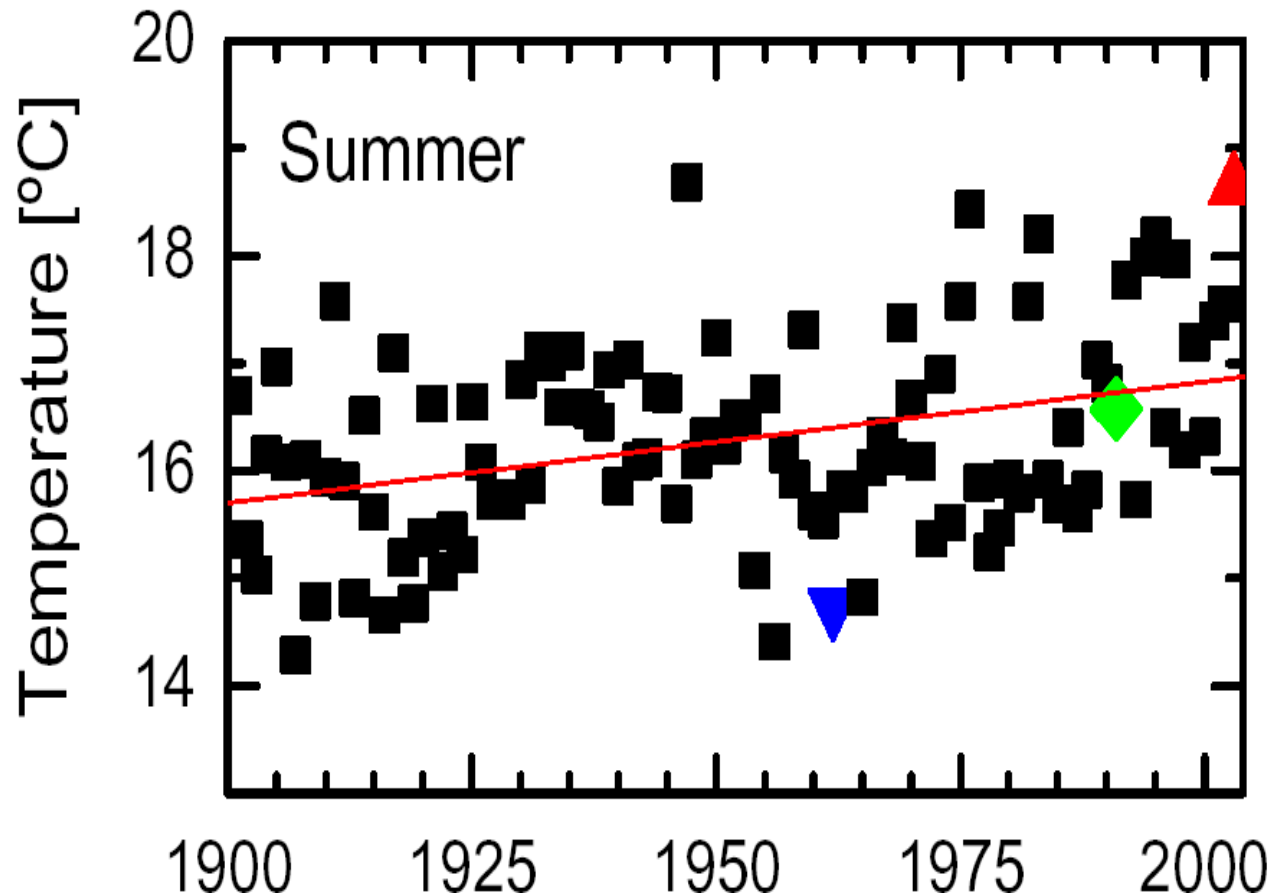
Positive proof of global warming.



Additional Evidence

2003 was the hottest summer in 500 years in Europe!
2005, 2009, 2012 were the hottest years ever in N. America
2010 hottest year in central Asia

Below is the mean summer surface water temperature in a range of Dutch lakes

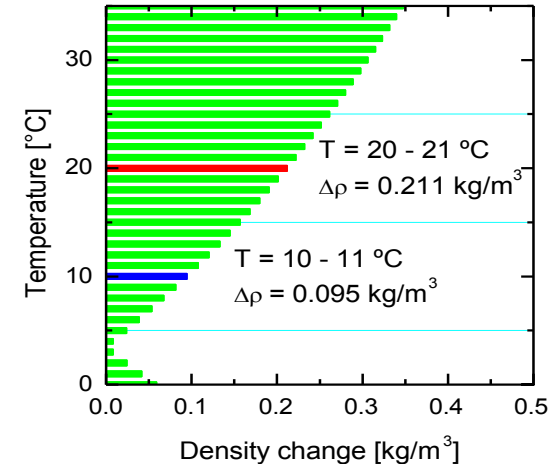
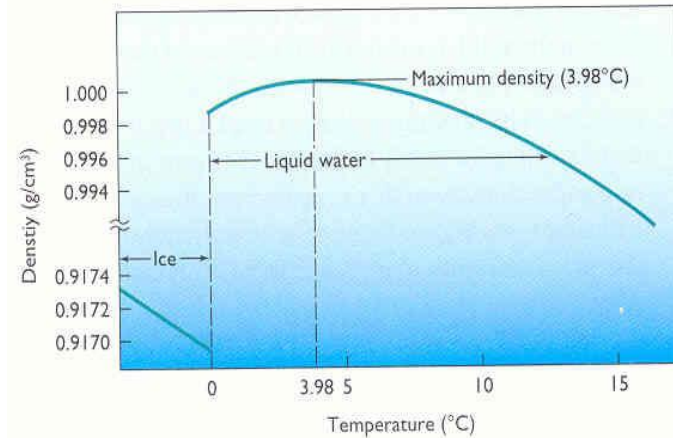


Huisman et al. 2006; KNMI, De Bilt, the Netherlands

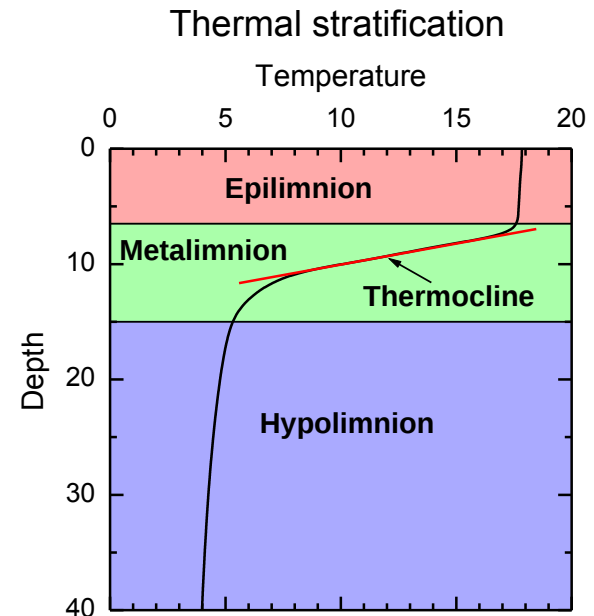
Temperature affects stratification

density profile of water

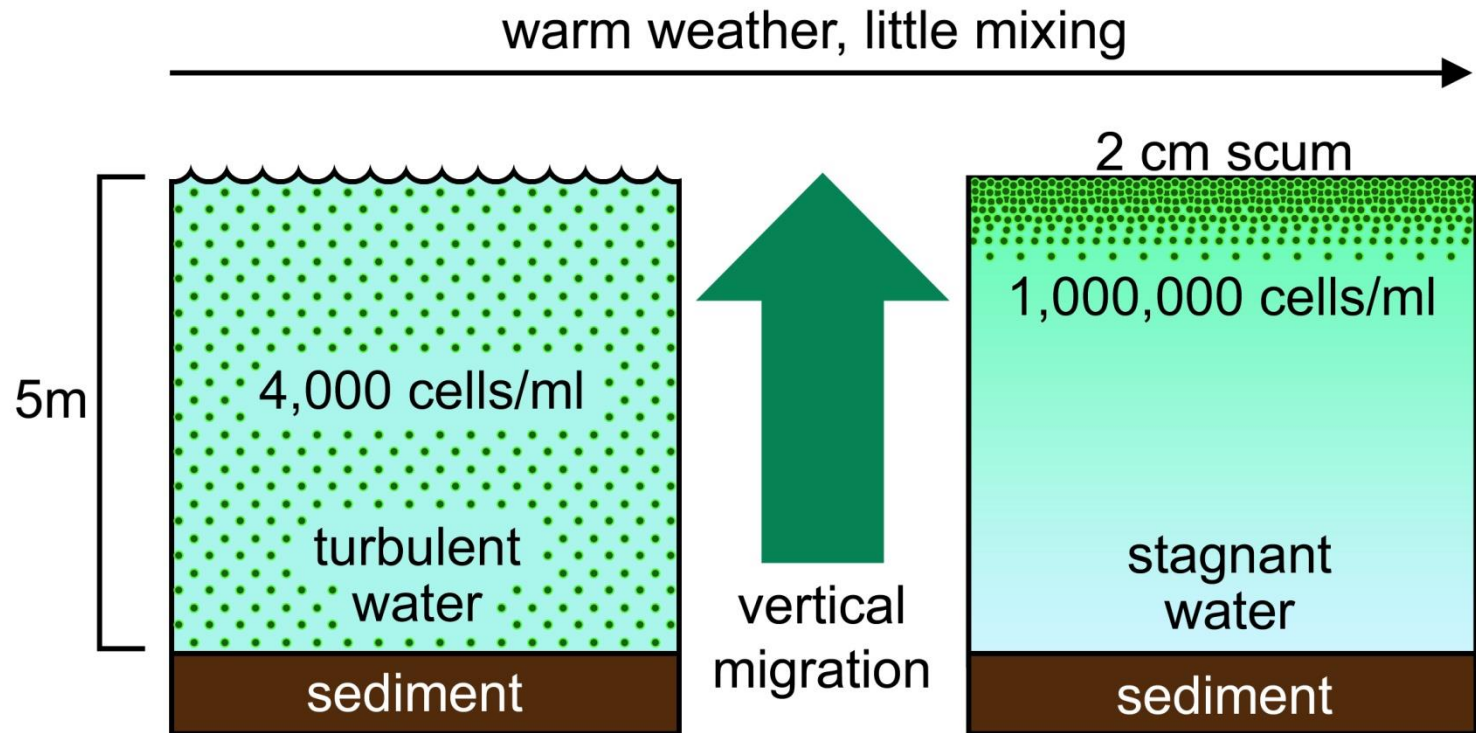
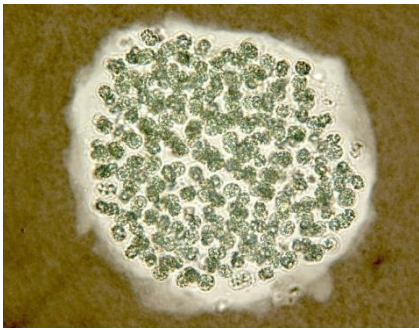
→ density change per 1 °C



→ At higher temperature, stratification is stronger !



Buoyant Cyanos favored by Stronger Stratification

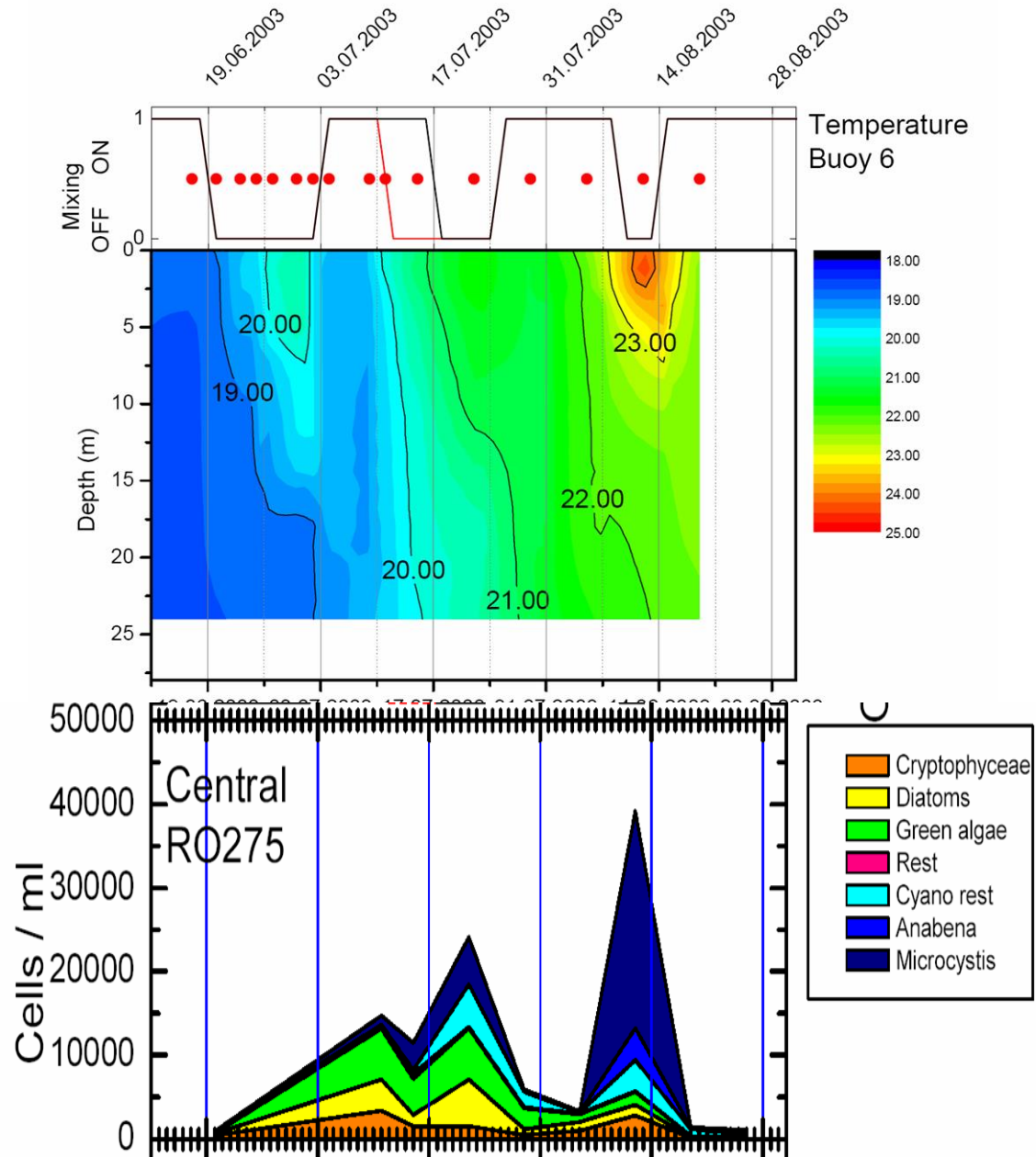


Mid August 2003:

Nieuwe Meer, Holland

Heatwave & little mixing

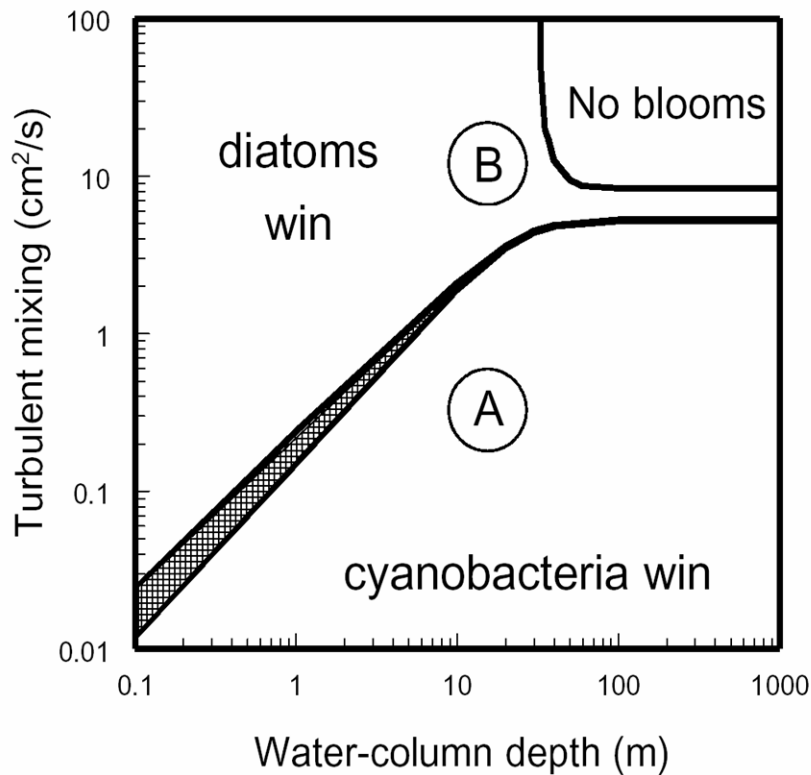
Microcystis benefits!



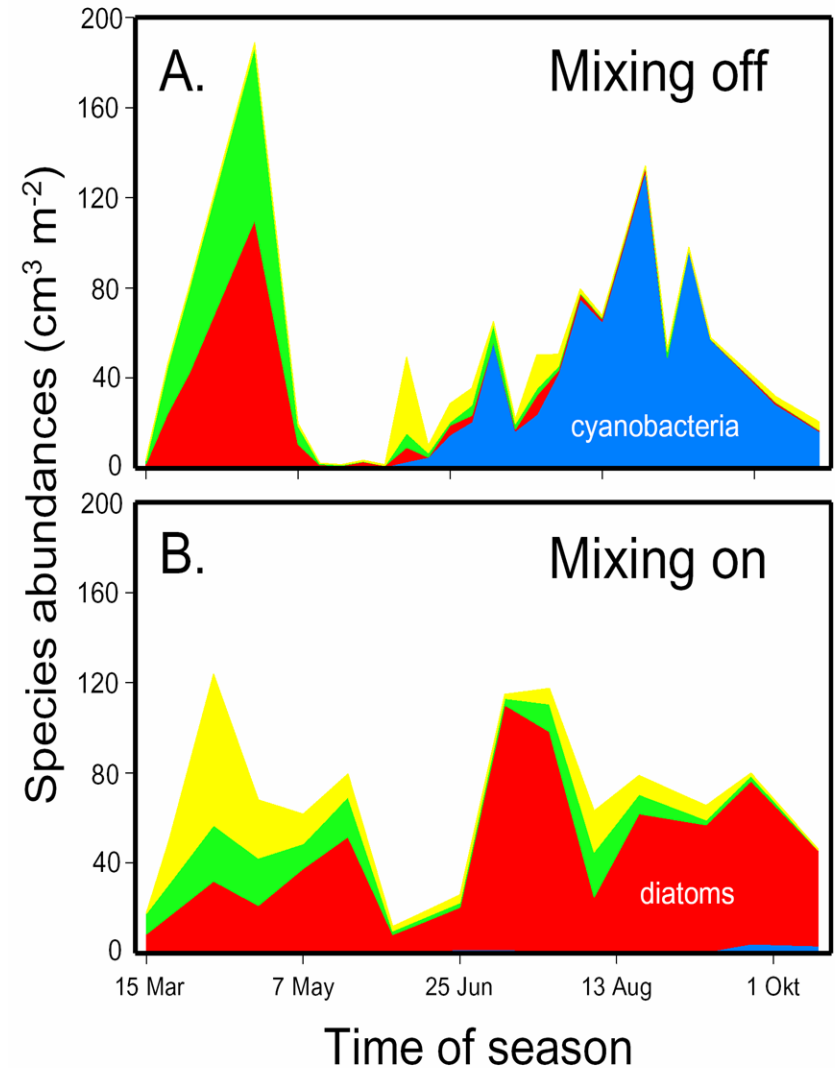
Jöhnk et al., 2008

Testing the Model

Theory



Lake data



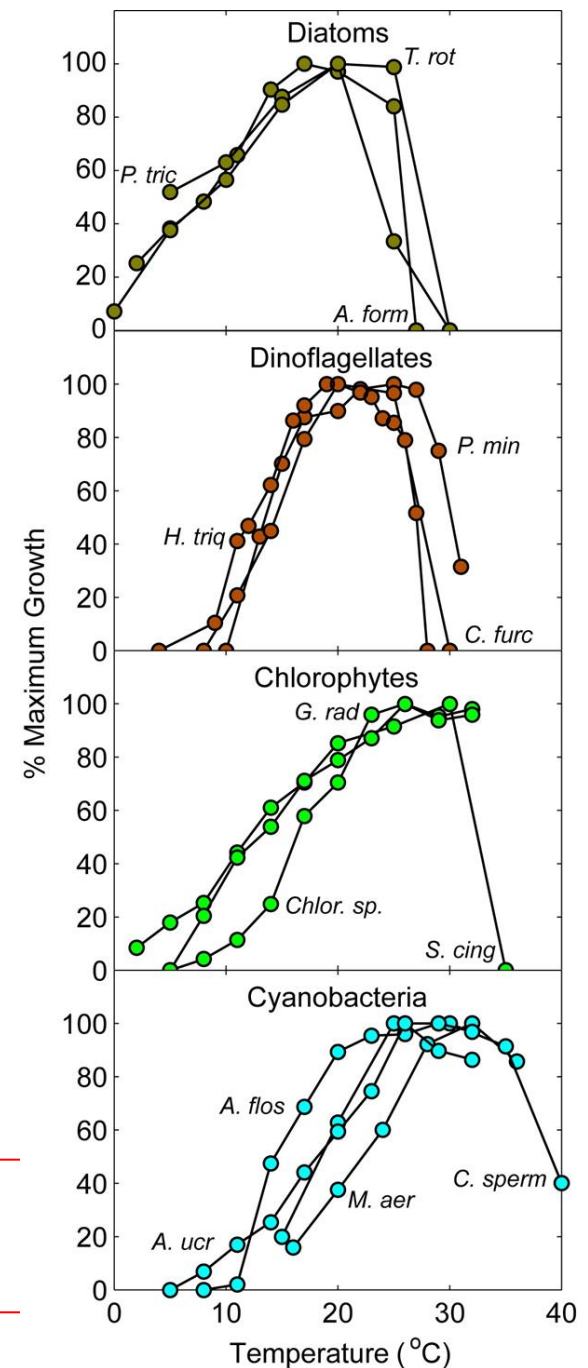
Huisman et al., 2004

The link to CyanoHABs.....

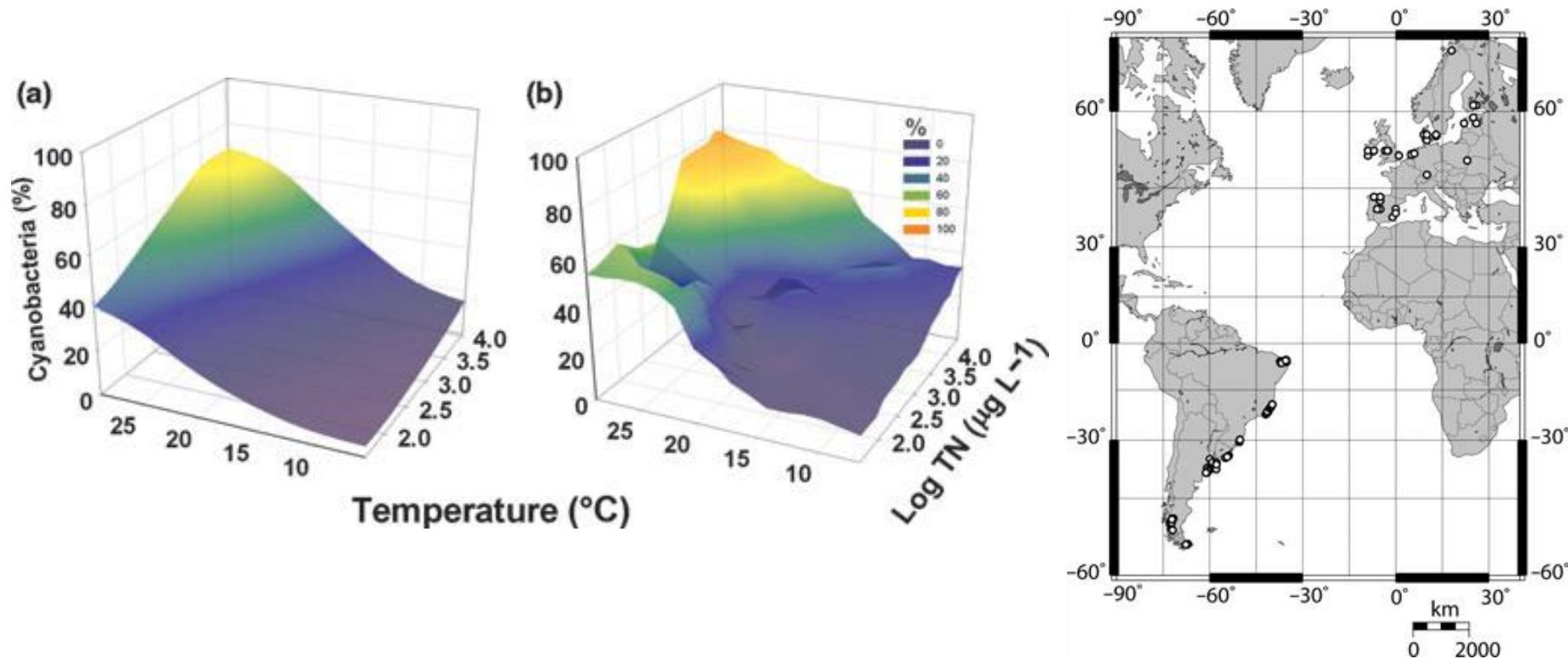
Temperature affects growth rates



References: Kraweik 1982, Grzebyk & Berland 1996; Kudo et al., 2000, Litaker et al., 2002, Briand et al., 2004, Butterwick et al., 2005, Yamamoto & Nakahara 2005, Reynolds 2006



Cyanobacterial dominance along temperature & nutrient gradients in 143 lakes



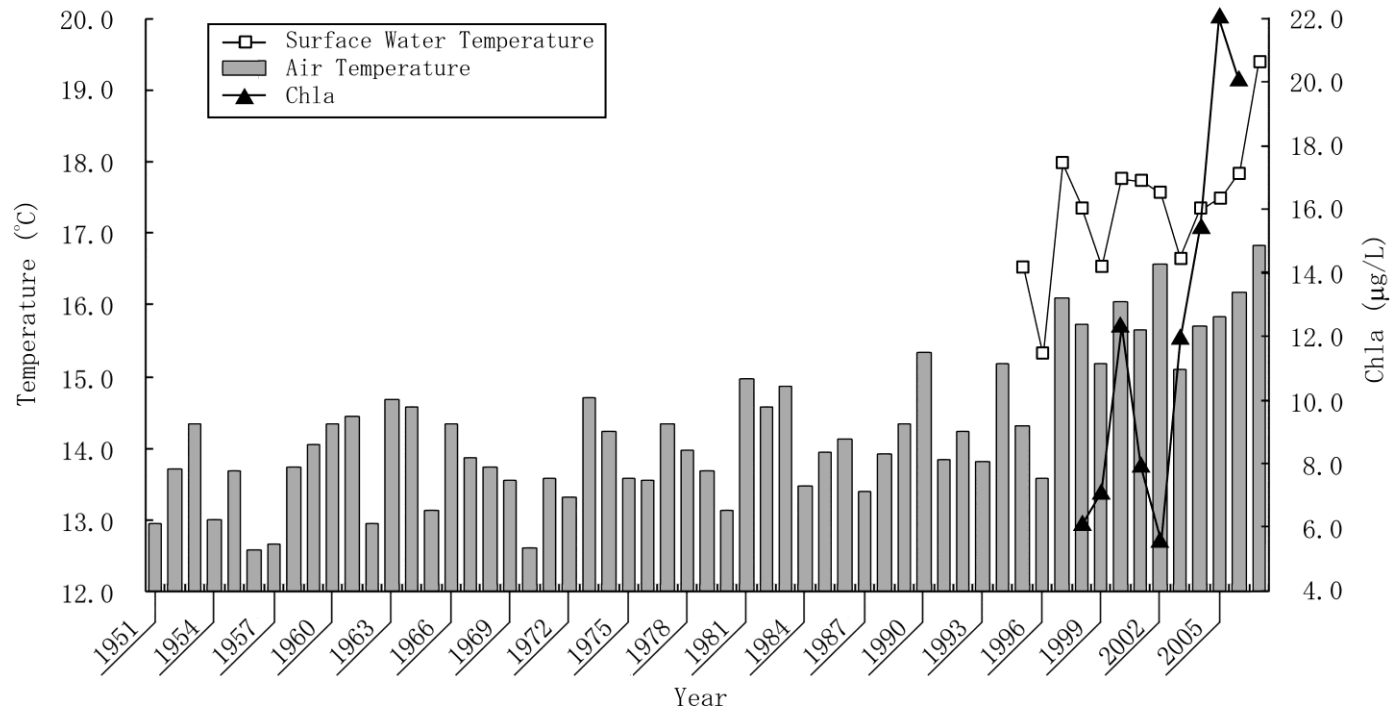
Percentage of cyanobacterial biovolume in phytoplankton communities as a function of water temperature and nutrients in 143 lakes along a climatic gradient in Europe and South America.

(a) Combined effects of temperature and nutrients as captured by a logistic regression model

(b) Response surface obtained from interpolation of the raw data using inverse distance weighting.

From Kosten et al. (2012). *Global Change Biology*

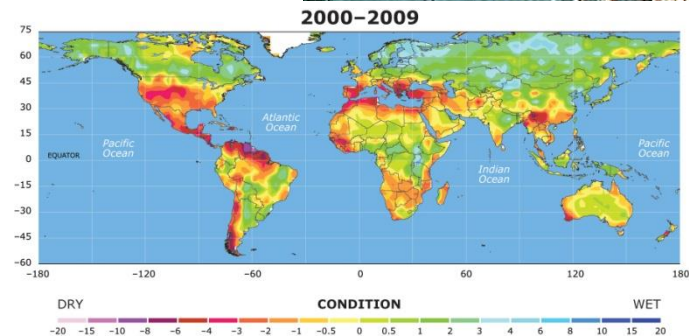
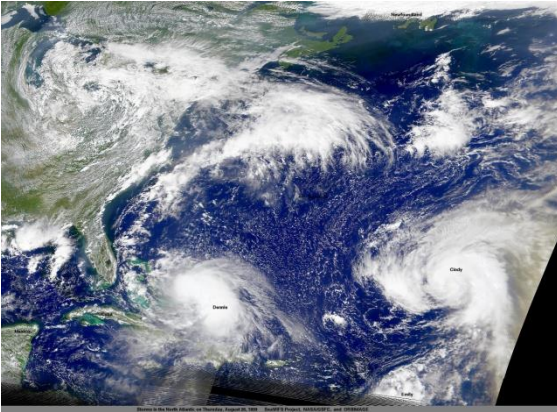
Temperature increases and longer-lasting, more intense cyanobacterial blooms in Taihu. Is warming changing CyanoHAB thresholds?



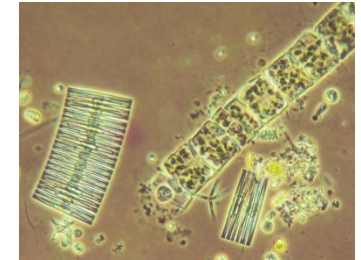
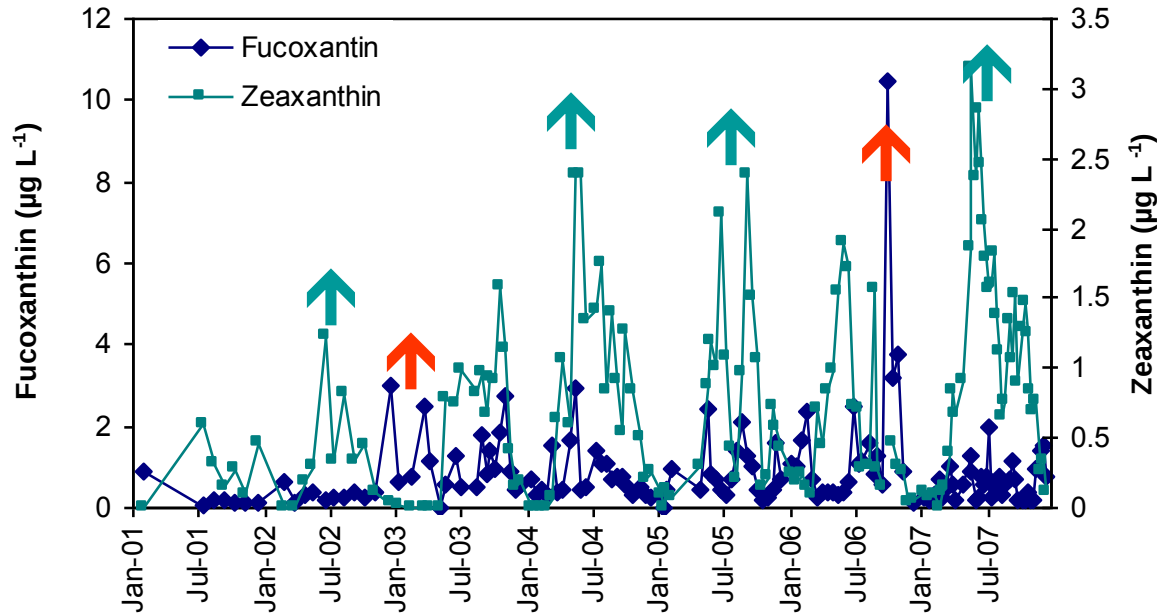
Hydrologically: Things are getting more extreme

- Storms, droughts more intense, extensive & frequent

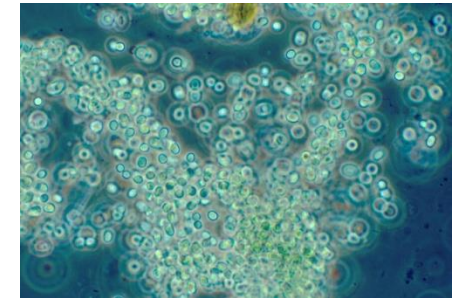
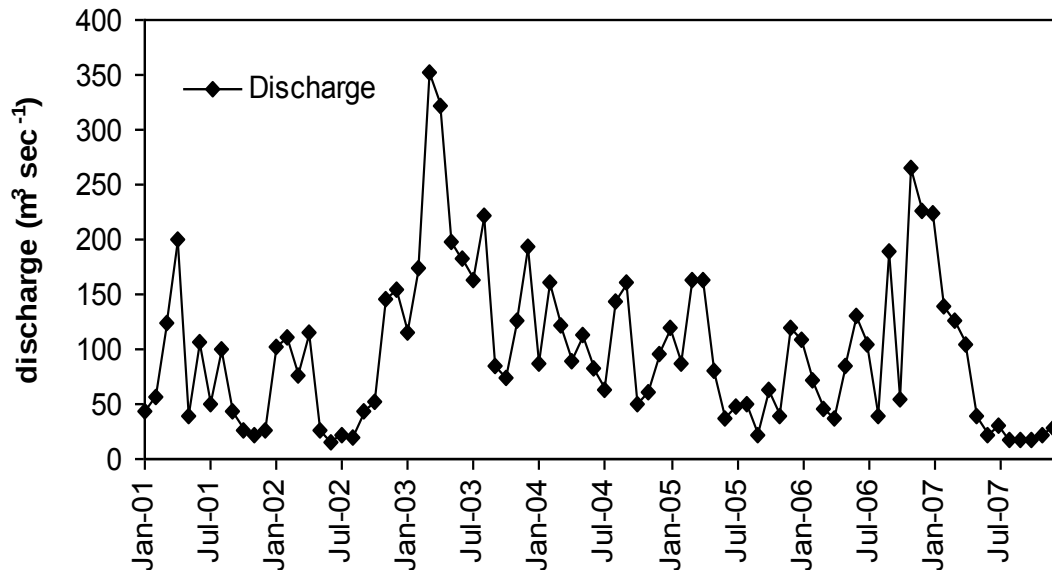
Melillo et al., 2014. 3rd National Climate Assessment, US Global Change Research Program



Hydrology (flushing) interacts with temperature to determine diatom (fucoxanthin) and cyanobacterial (zeaxanthin) dominance in Neuse R. Estuary



**Diatoms like it cool
& fast**



**Cyano like it hot
& slow**

Paerl et al. 2009

What's being done to "fix" Taihu?

- Need for dual nutrient reduction strategy recognized
- Wastewater collection and treatment
- Creating buffer zones
- Dredging sediments
- Diversion of Yangtze R. water (to enhance flushing)
- Algal Collection techniques
- Precipitation/flocculation

Since 2007, Wuxi has built 68 new wastewater plants, treating 1,513,000 ton/day, upgraded all wastewater treatment levels for BOD, starting P but not (yet) N removal.



建成覆盖所有城镇的**68座**污水处理厂，
日处理能力达到**151.3万吨**。
投资**7.8亿元**对现有污水处理厂全面进行
提标改造。



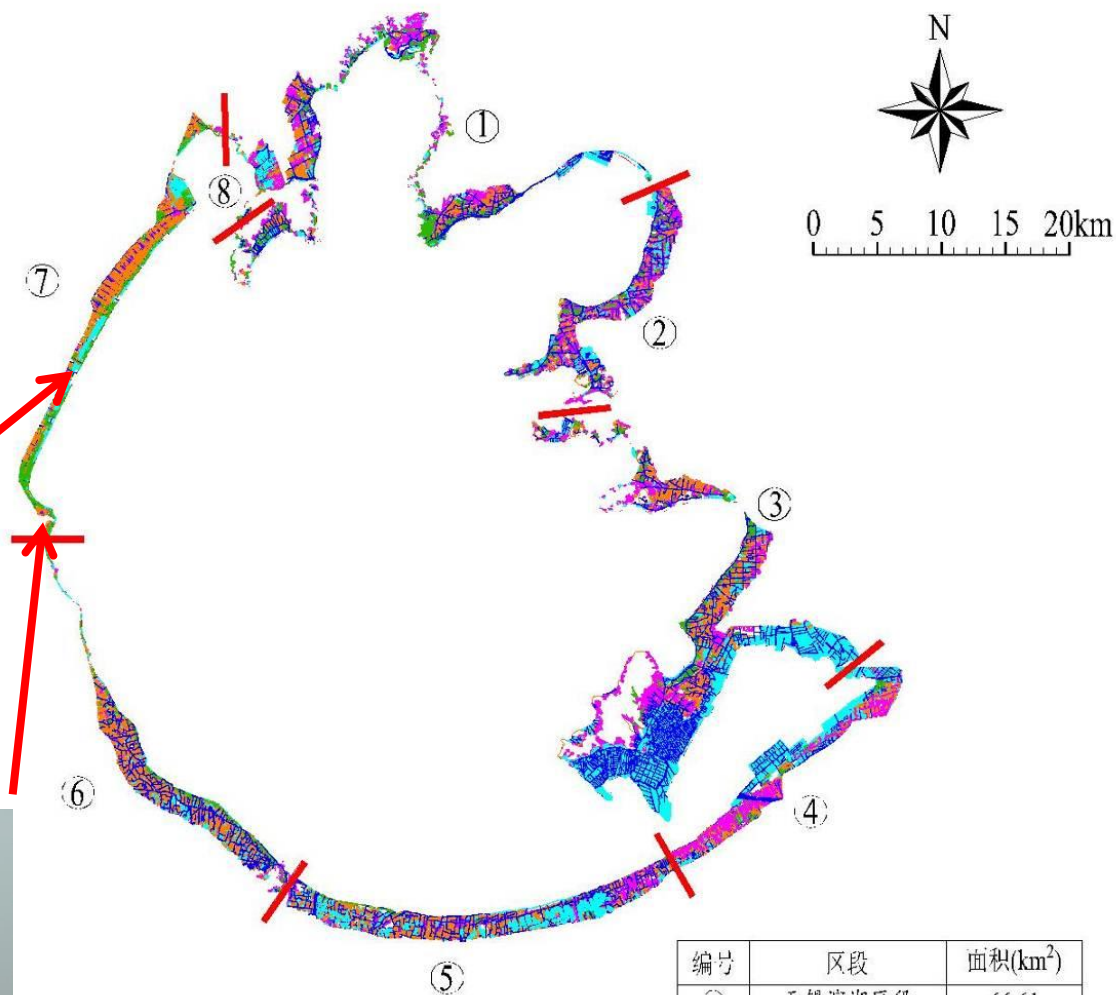
(无锡市太湖办顾刚提供)

Using vegetative buffers to retain storm water nutrients



(Qin et al., 2012)

Construction of buffer zones and wetlands around the lake



图例	土地利用	面积(km ²)
	城镇农村及工交建设用地	72.98
	林地、果园	42.26
	农田	192.61
	河流沟渠	29.68
	水库、坑塘	114.78

编号	区段	面积(km ²)
①	无锡滨湖区段	66.61
②	苏州高新区段	44.39
③	苏州吴中区段	142.55
④	苏州吴江市段	44.68
⑤	湖州吴兴区段	60.81
⑥	湖州长兴县段	44.50
⑦	无锡宜兴市段	41.38
⑧	常州武进区段	7.39
合计		452.31

(叶春提供)



Pump station

Entrance

Exit

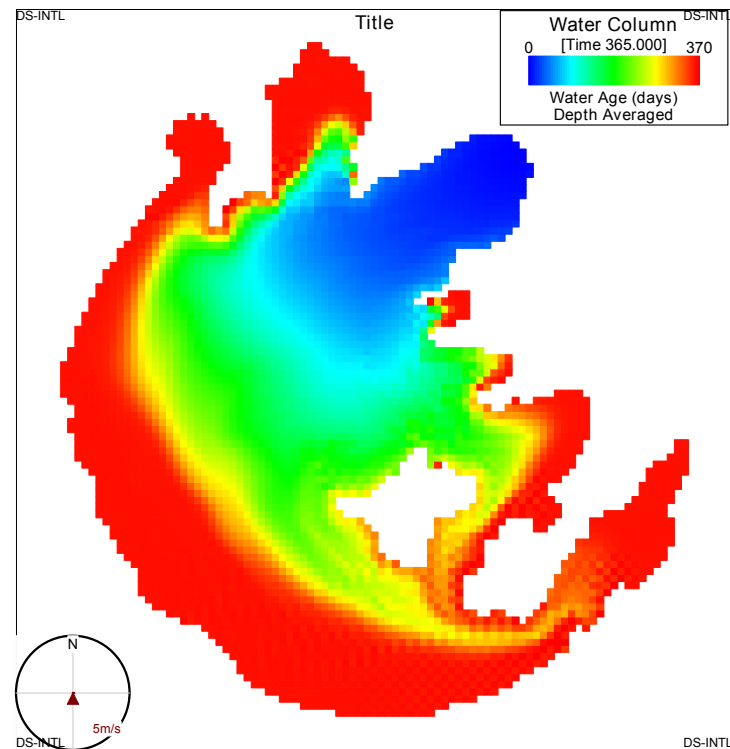
Water diversions in Lake Taihu

Yangtze River water diversion through Taihu: Cure or Curse?

➤ The heavily polluted lake regions (i.e. Meiliang Bay, Zhushan Bay and west littoral) are not remedied by the water transfer route and volume.

➤ Water residence time is reduced from ~ 320 days to ~ 220 days at best. This has no significant impact on reducing bloom potentials.

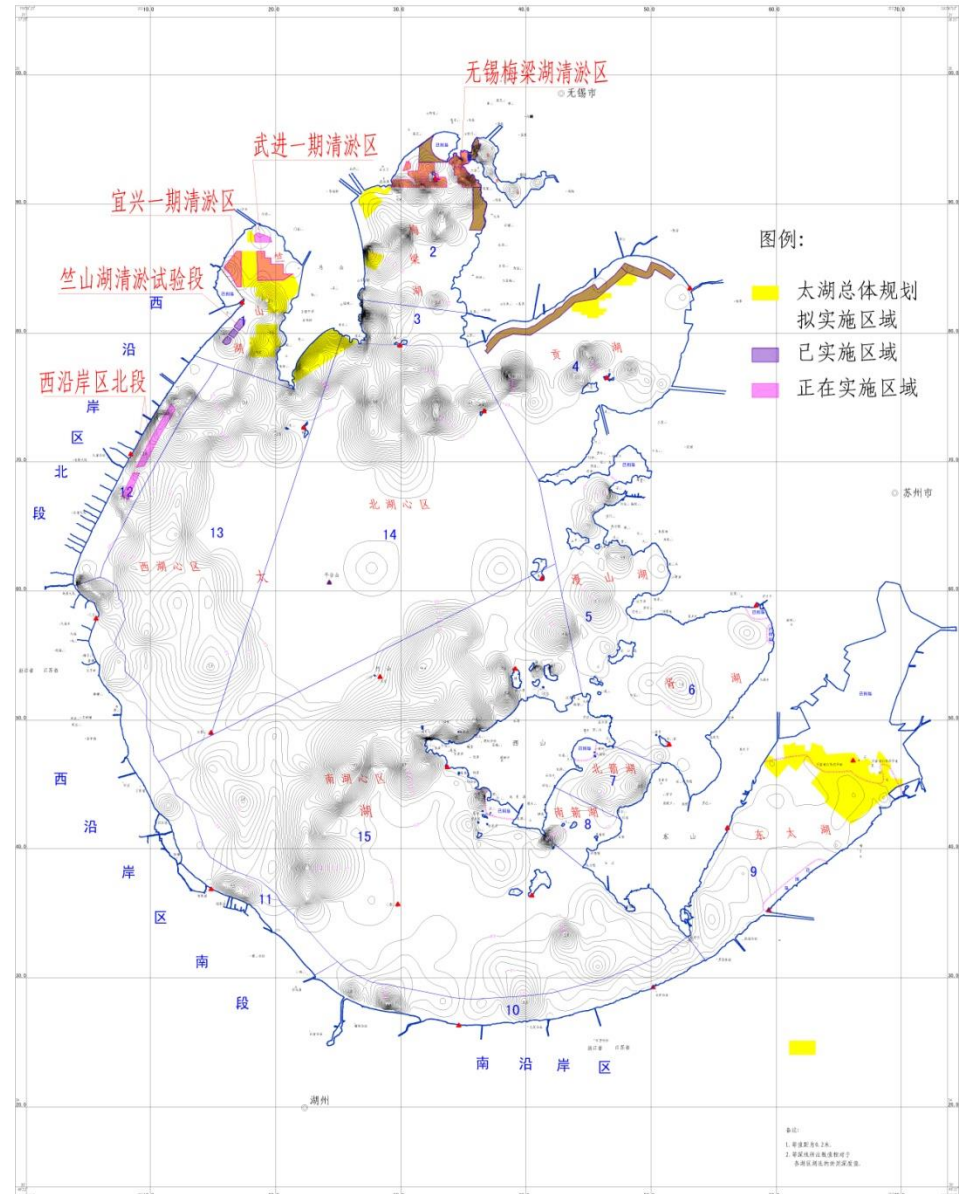
➤ The diversion may makes things worse...input from the heavily polluted Yangtze River adds ~15% to the N and P loads to the lake, potentially exacerbating eutrophication and blooms.



Polluted sediment dredging

✓ 40 km² in north-western area and 1200 cubic meters (Lake area 2,300 km²). This has actually made the situation worse by releasing a legacy of nutrients and other pollutants, AND dredged sediments are deposited in catchments surrounding the lake Basin

(省水利厅提供)



CyanoHAB collection and removal

❖ Between 2007 and 2012, 3500,000 tons of algal scum had been removed. However, this is <1% of what was produced!!



Flocculation and precipitation of CyanoHABs

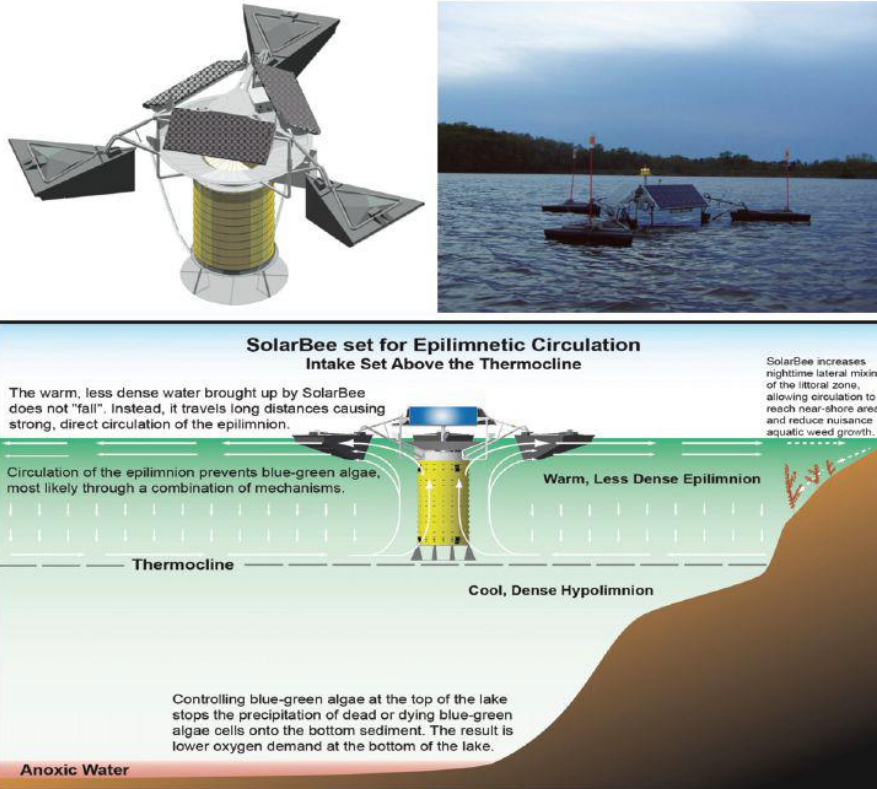
❖ Trials indicate that sediment resuspension overwhelms “sediment capping” (i.e., can't hide the problem). ❖ Costs prohibitive. ❖ Doesn't solve the excess nutrient problem

Bottom Line: Need to reduce BOTH N and P inputs, no matter what other “fixes” are proposed

Other physical-chemical approaches

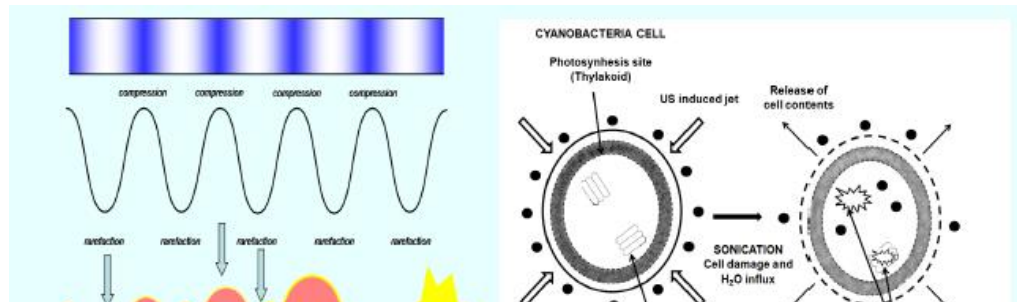
Altering circulation

Solar-Powered, Long-Distance Circulation



- May discourage formation of some buoyant cyanoHABs in confined waters
- May also increase primary production (by obviating light limitation)
- Nutrient transport and circulation??

Effects of ultrasound on cyanobacterial biomass



Note: cell content leaks out upon lysis

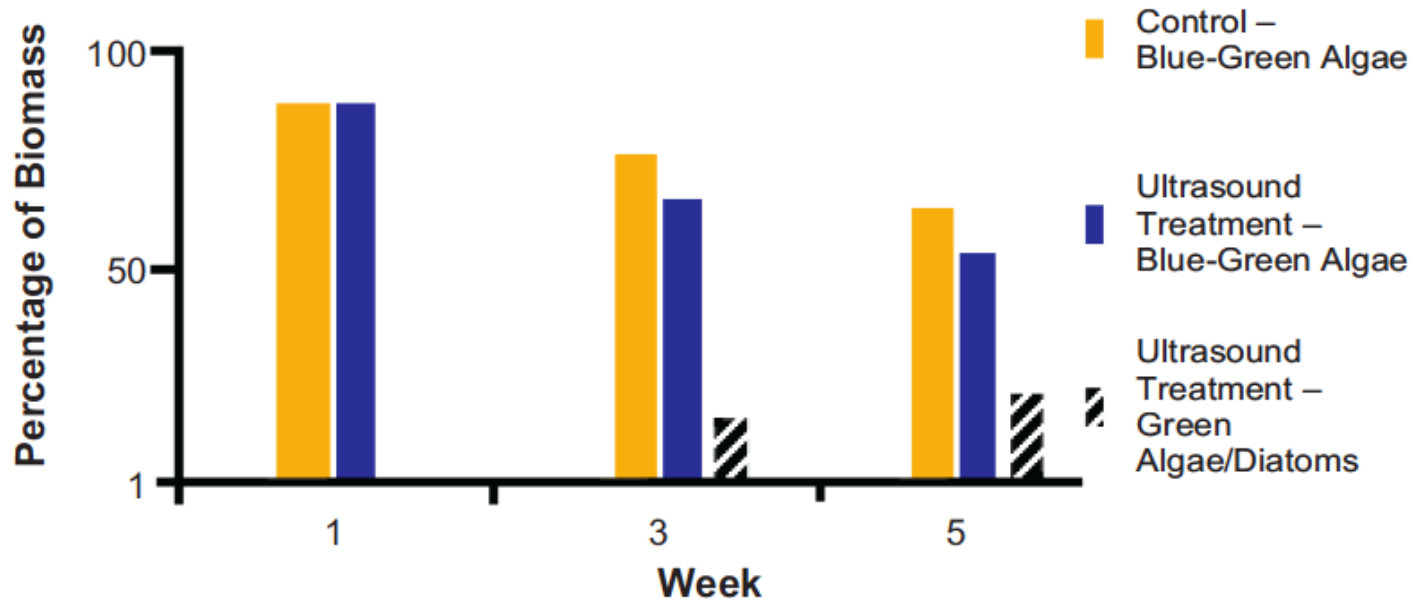
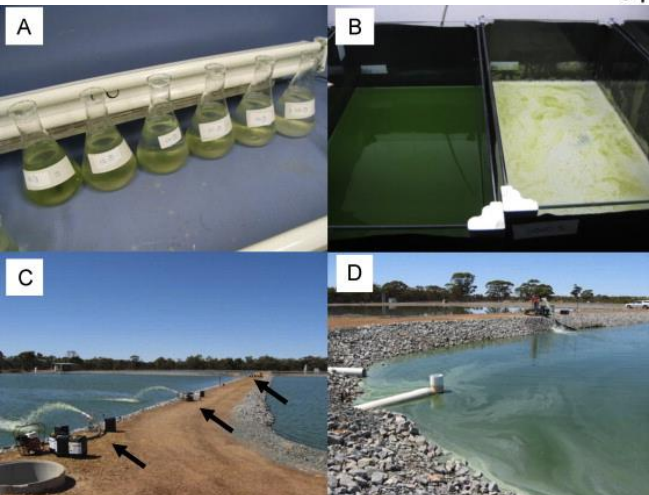
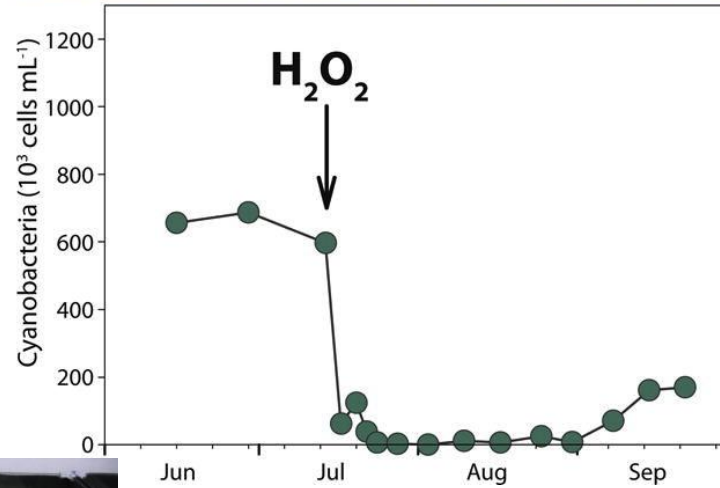


Figure 2. Changes in algal composition in control and ultrasound-treated ponds.

Hydrogen Peroxide Treatment

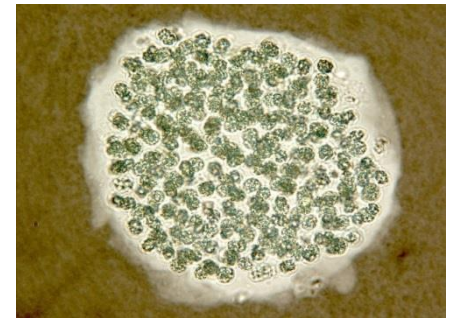
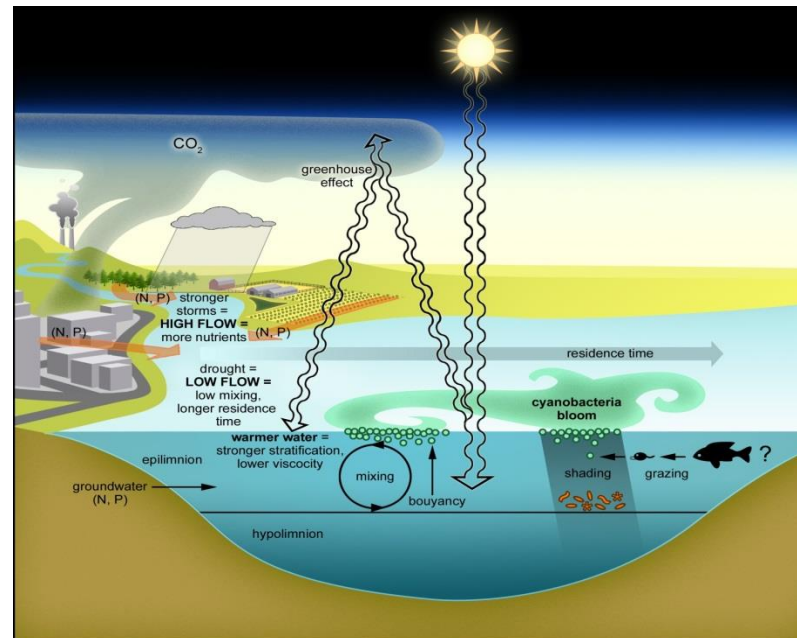


Kills cells (in confined systems) but releases toxins

Matthijs et al., 2012; Barrington et al., 2013

Management ramifications

- In most cases, both N & P reductions are needed (no matter what other physical/chemical approaches are used)
- Nutrient-bloom threshold are system-specific
- Nutrient-bloom thresholds may be changing
 - May need to reduce N and P inputs even more in a warmer world
- Nutrient input restrictions year-round
 - Cyanos are favored by higher temperatures, longer warm seasons



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www.unc.edu/ims/paerllab/research/cyanohabs/

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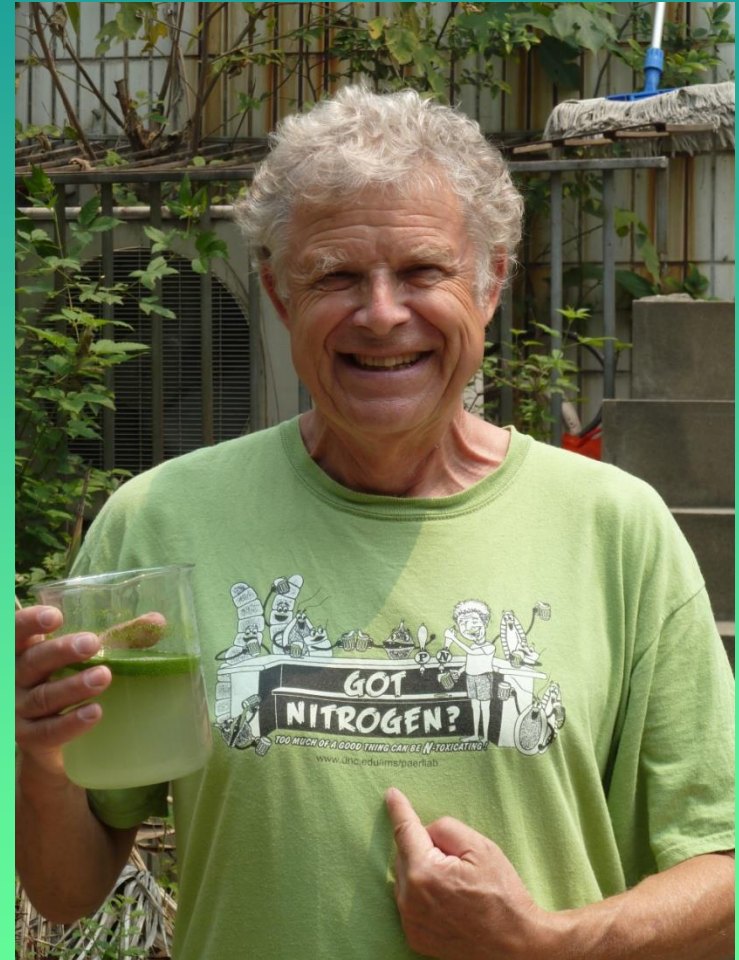
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