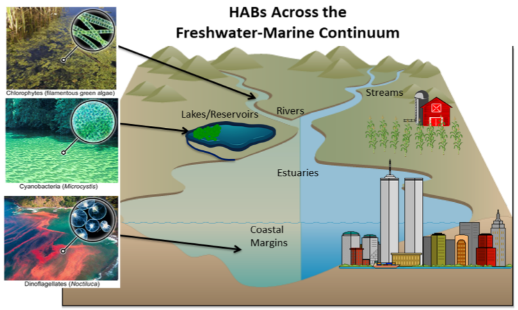
Where do we go from here? Mitigating harmful cyanobacterial blooms in a world facing human nutrient over-enrichment and climate change

Hans Paerl and colleagues,
UNC-Chapel Hill, Institute of Marine Sciences and many other places!










http://paerllab.web.unc.edu/research/

Human and climatic Drivers of Expanding Harmful Cyanobacterial Blooms (CyanoHABs): Established and emerging/evolving issues ?

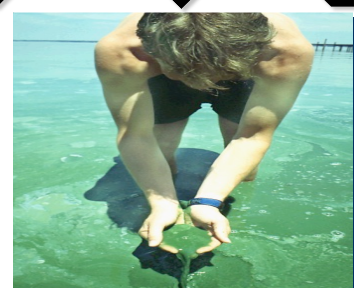
Urban, agricultural and industrial expansion

Increasing nutrient (Nitrogen & Phosphorus) inputs

Water use and hydrologic alterations play key roles

Climate (warming/precip changes) play interactive roles

Blooms are intensifying and spreading

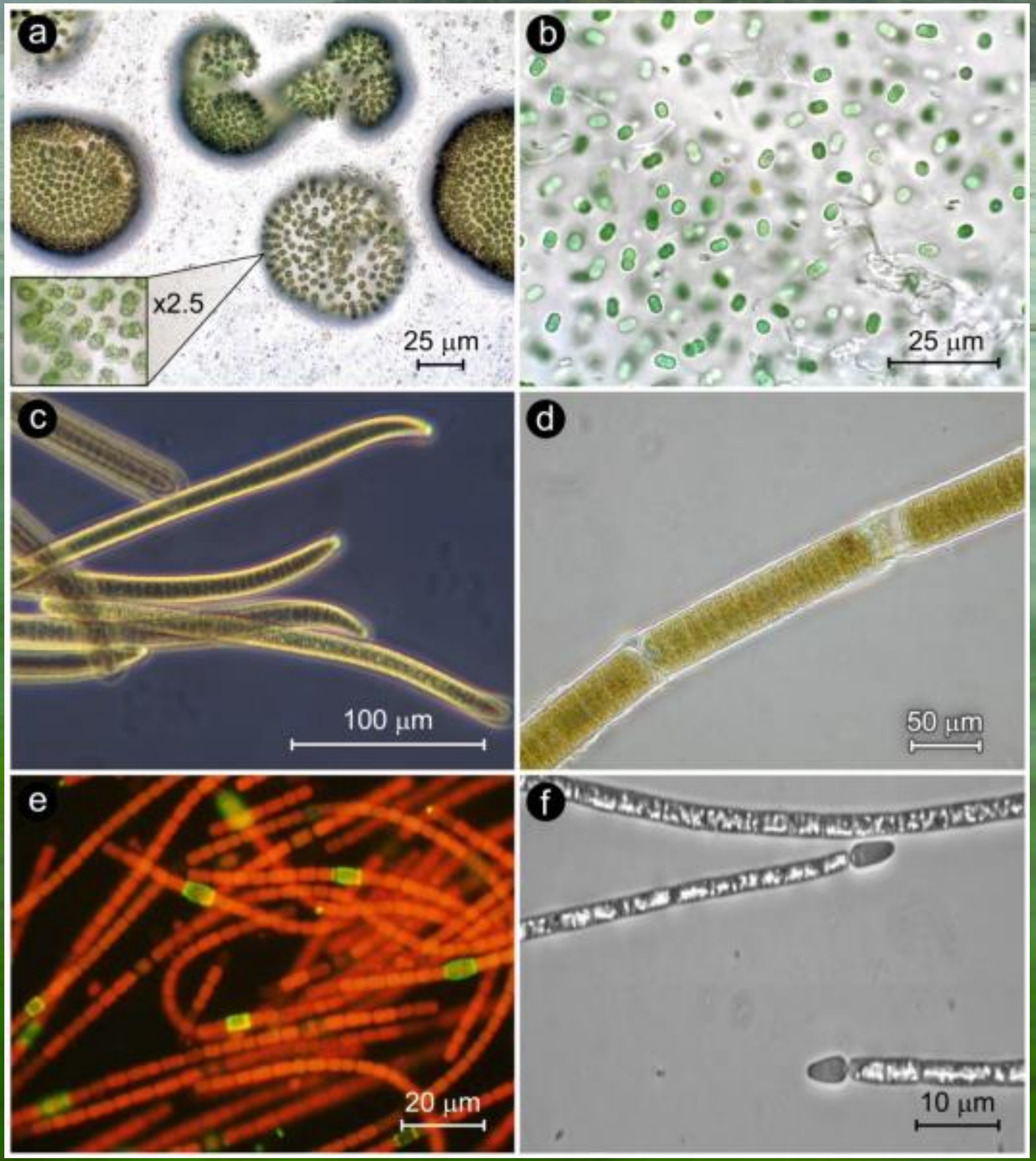


The Planktonic CyanoHAB "Players"

Coccoid, solitary/colonial
(e.g. *Microcystis* & picocyanos).
Most do not fix N_2

Filamentous, non-heterocystous
(e.g. *Lyngbya, Oscillatoria*).
Some species fix N_2

Filamentous, heterocystous
(e.g. *Dolichospermum, Nodularia, Cylindrospermopsis*).
All fix N_2



CyanoHABs: symptomatic of nutrient enrichment along the freshwater to marine continuum

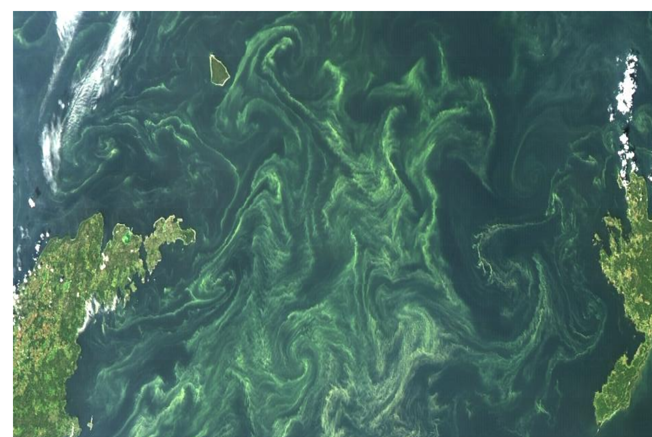


- Freshwater Ecosystems (lakes, reservoirs, rivers)



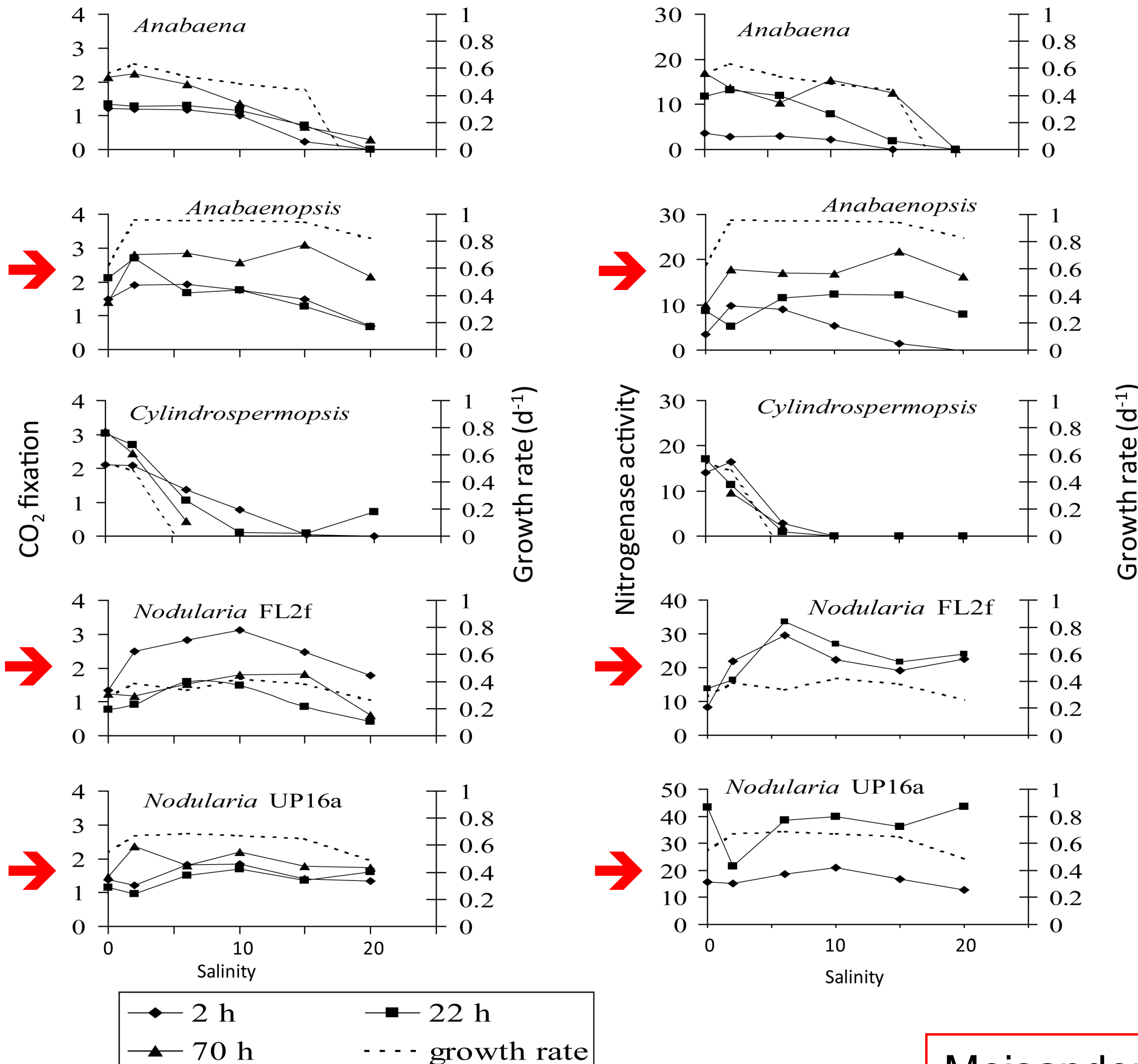
- Estuaries





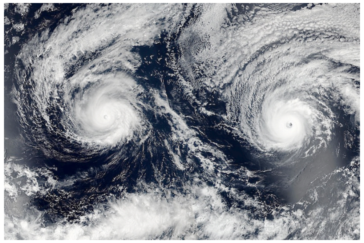
- Coastal waters & seas

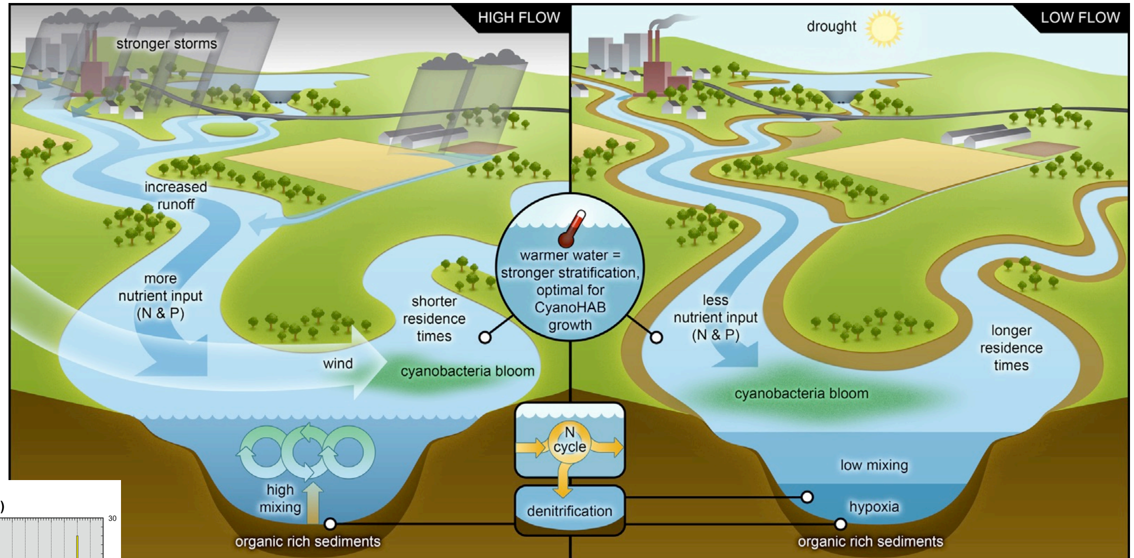
Salinity is <u>not necessarily</u> a barrier to cyanobacterial expansion

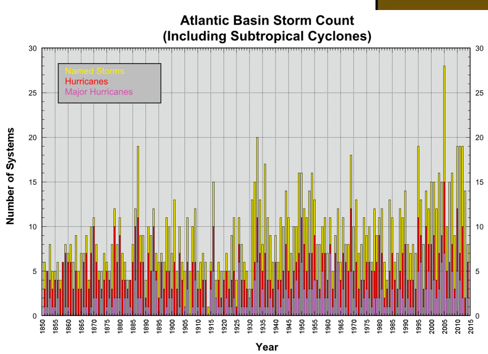


Moisander et al., 2001

CyanoHABs are expanding along the freshwater to marine continuum due to nutrient enrichment, hydrologic variability and warming: Some examples







Environmental Science & Technology

Feature

Cite This: Environ. Sci. Technol. 2018, 52, 5519−5529

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Mitigating the Expansion of Harmful Algal Blooms Across the Freshwater-to-Marine Continuum

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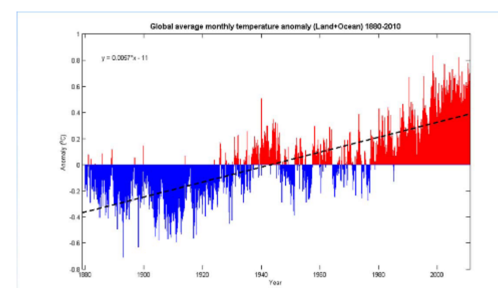
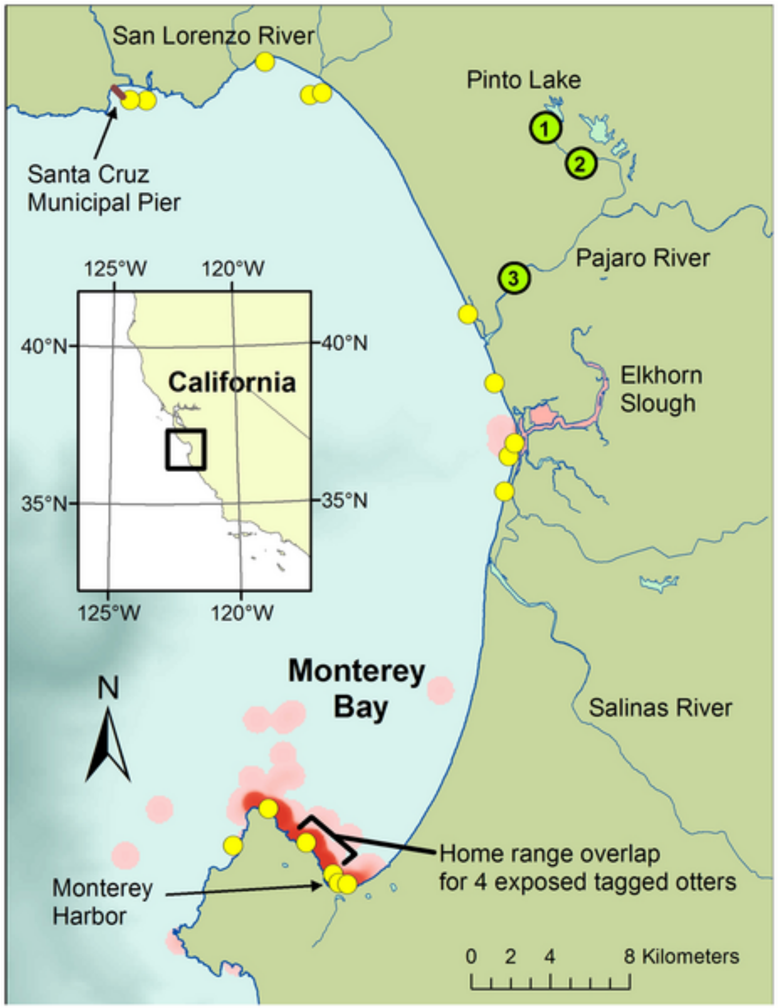
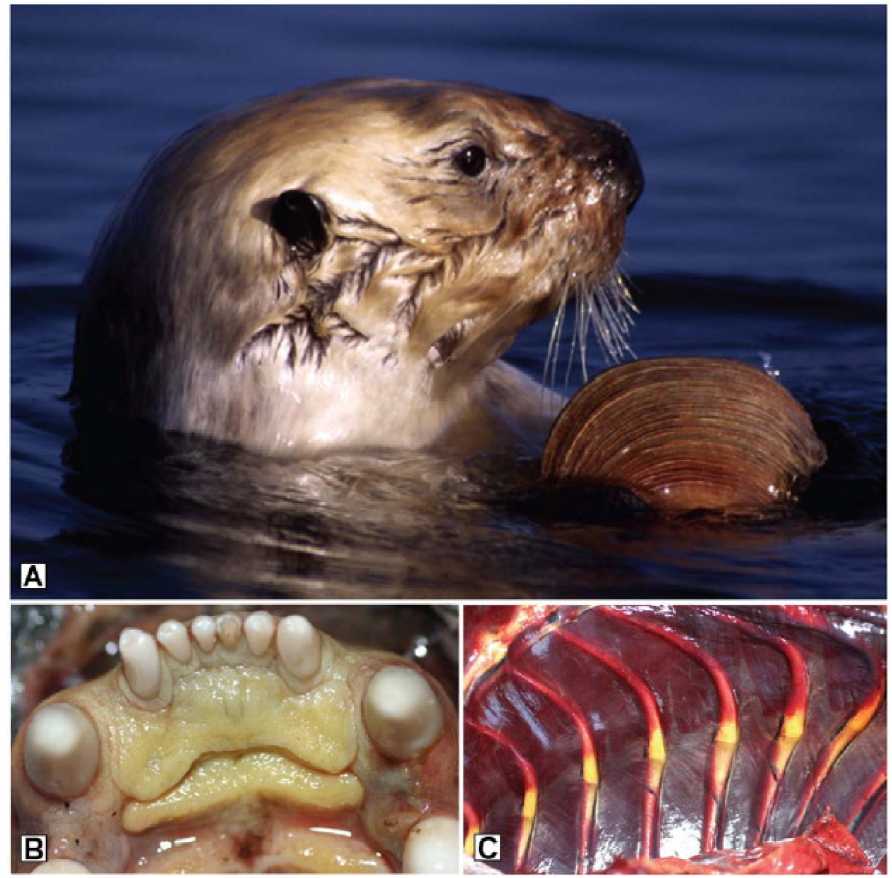
ABSTRACT: Anthropogenic nutrient overenrichment, coupled with rising temperatures, and an increasing frequency of extreme hydrologic events (storms and droughts) are accelerating eutrophication and promoting the expansion of harmful algal blooms (HABs) across the freshwater-to-marine continuum. All HABs—with a focus here on cyanobacterial blooms—pose serious consequences for water supplies, fisheries, recreational uses, tourism, and property values. As nutrient loads grow in watersheds, they begin to compound the effects of legacy stores. This has led to a paradigm shift in our understanding of how nutrients control eutrophication and blooms. Phosphorus (P) reductions have been traditionally prescribed exclusively for freshwater systems, while nitrogen (N) reductions were mainly stressed for brackish and coastal waters. However, because most systems are hydrologically interconnected, single nutrient (e.g., P only) reductions upstream may not necessarily reduce HAB impacts downstream. Reducing both N *and* P inputs is the only viable nutrient management solution for long-term control of HABs along the continuum. This article highlights where paired physical, chemical, or biological controls may improve beneficial uses in the short term, and offers management strategies that should be enacted across watershed scales to combat the global expansion of HABs across geographically broad freshwater-to-marine continua.



CyanoHAB and microcystin transfer form Pinto Lake to Monterey Bay, CA



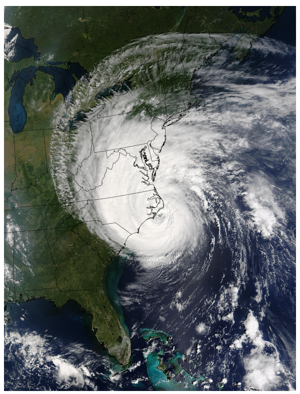
Miller et al. PLOS ONE 2010

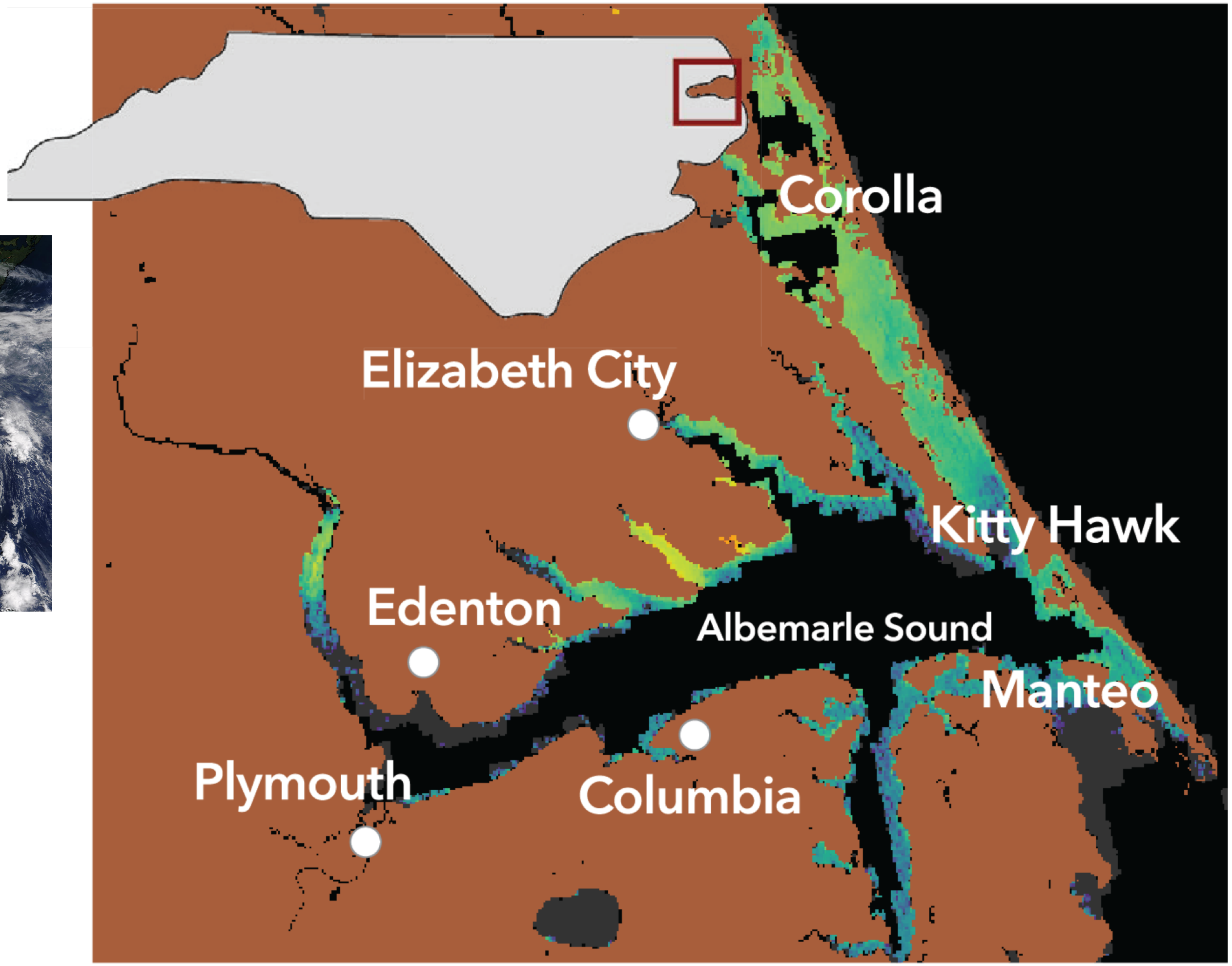


32 otters identified as suffering from microcystin poisoning.

CyanoHAB expansion into North Carolina's brackish Albemarle Sound

driven by more flashy and frequent storms and nutrients





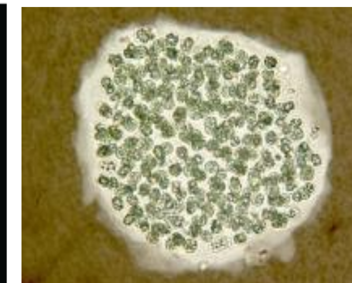
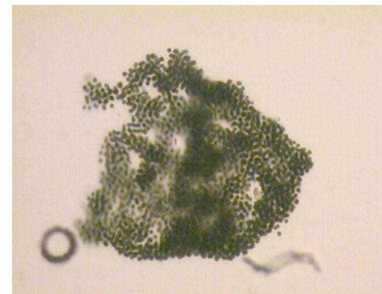
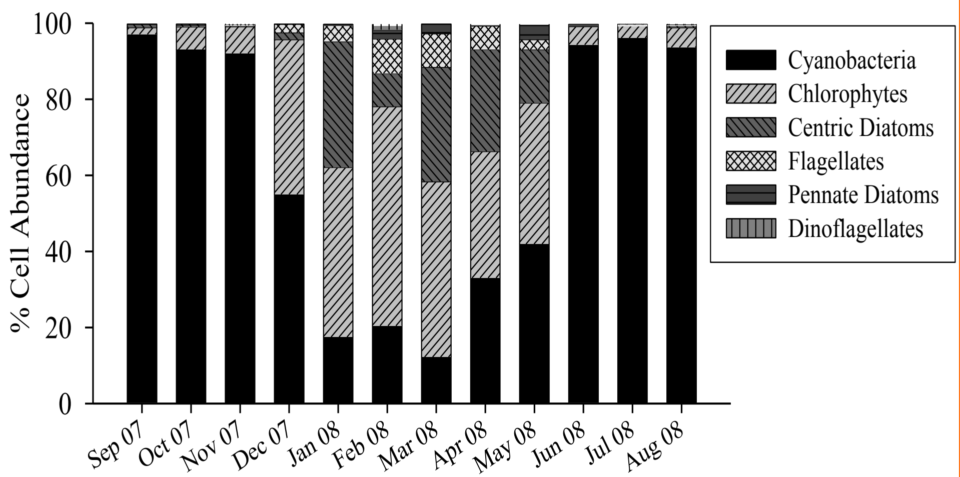


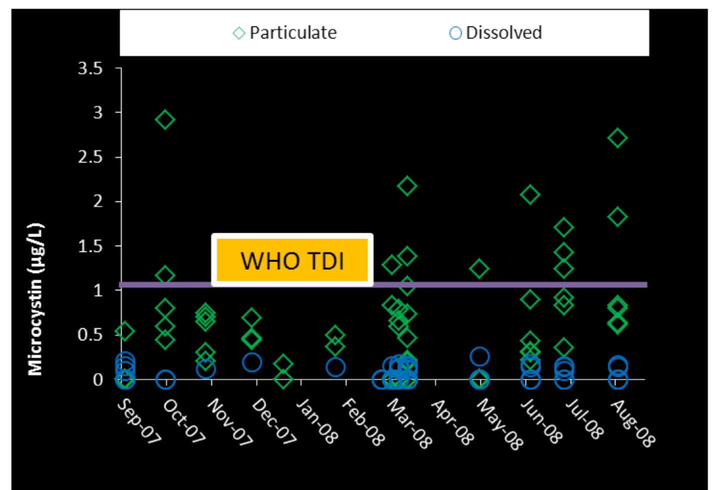
Image from Cyanobacteria Assessment Network: EPA/NASA/NOAA/USGS
(epa.gov/cyanoproject)

CyanoHAB Transfer from Caernarvon Diversion into Breton Sound Estuary, LA



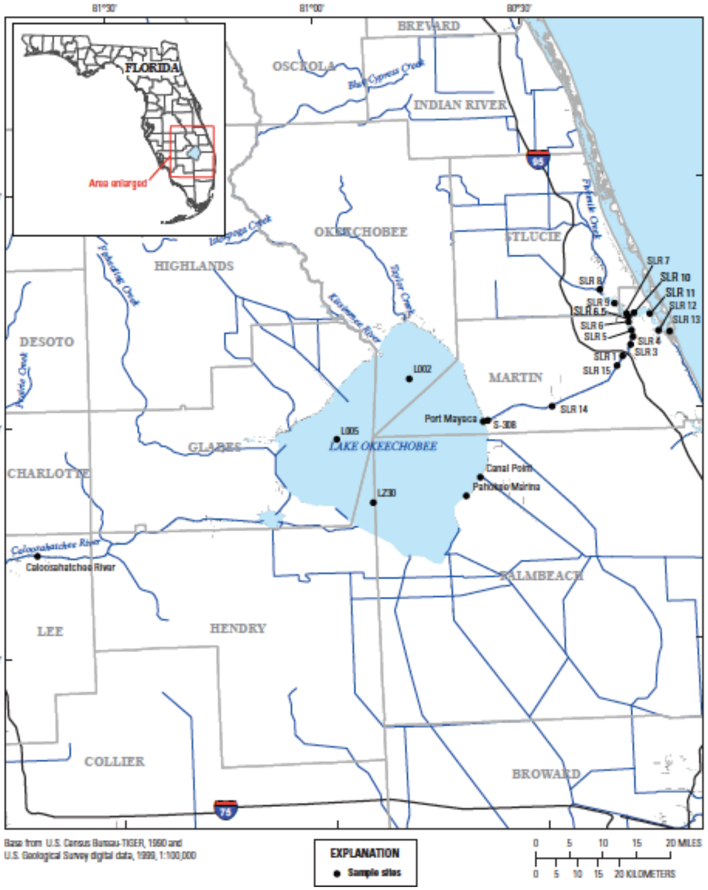
Phytoplankton Community Composition

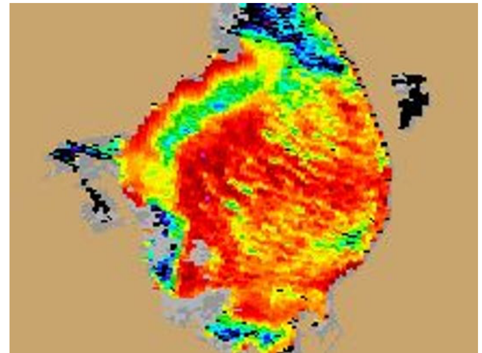


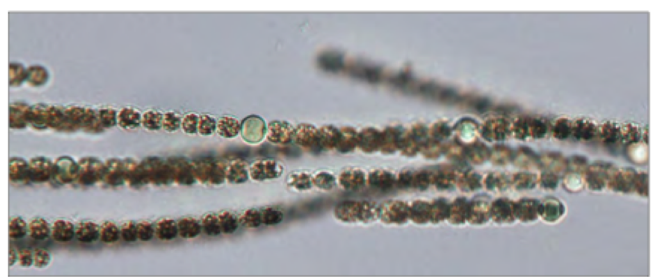


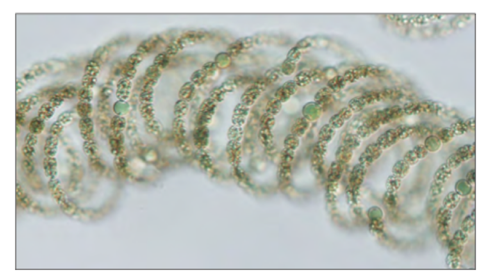
Riekenberg et al. 2015, Estuaries and Coasts

CyanoHABs on the move: Lake Okeechobee to Florida's East and West Coasts (2016)





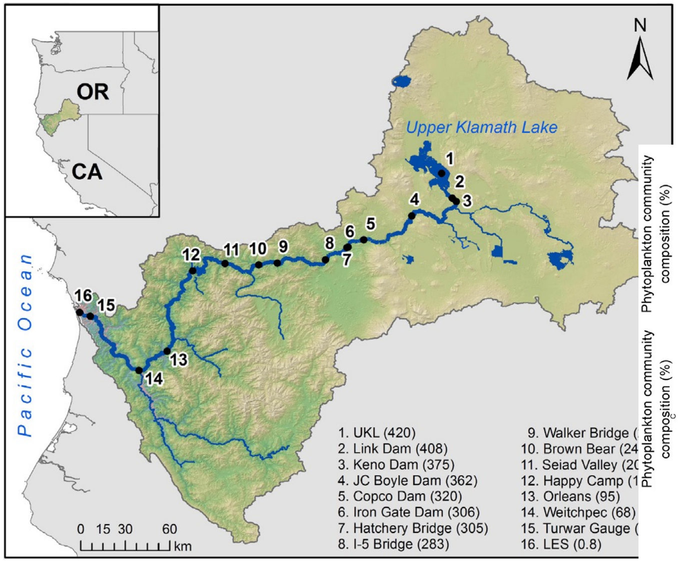


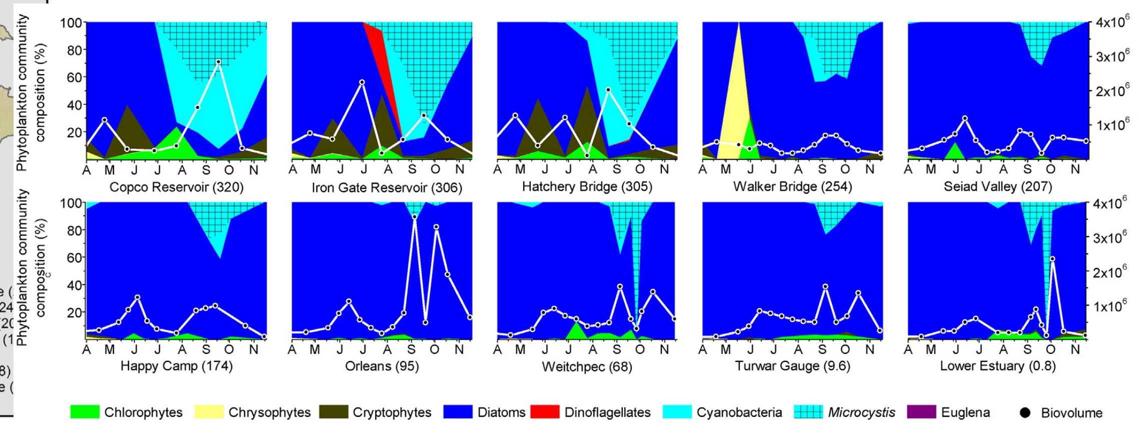


Rosen et al., 2017: Cyanobacteria of the 2016 Lake Okeechobee and Okeechobee Waterway harmful algal bloom

USGS Open-File Report 2017-1054

Klamath Reservoir to Klamath River to the Pacific Ocean





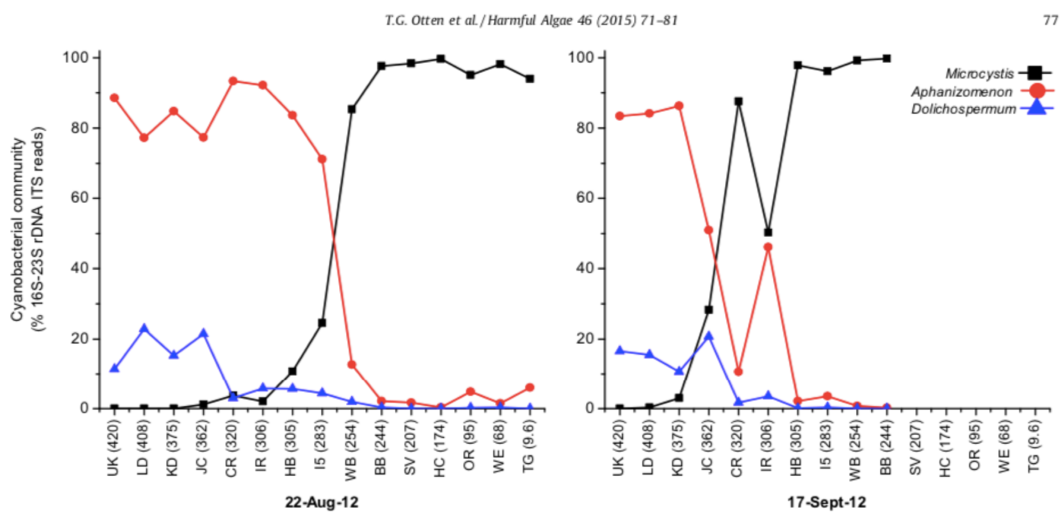
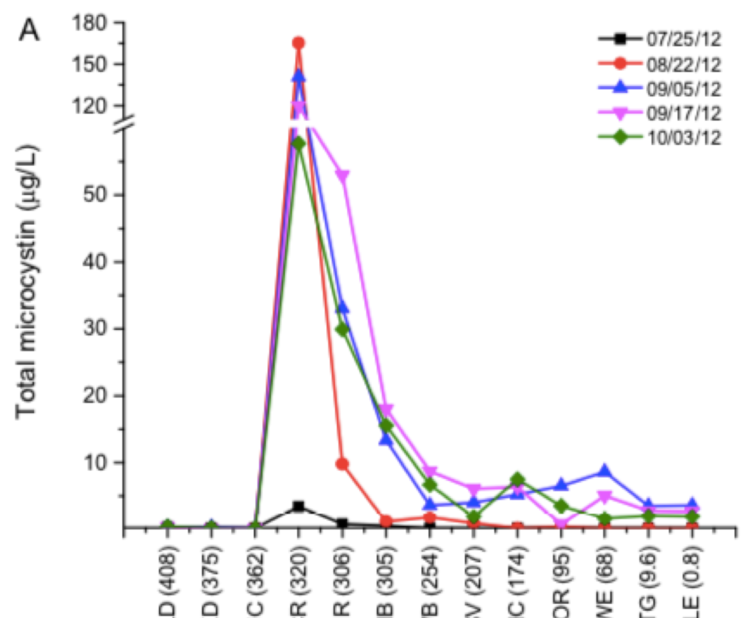
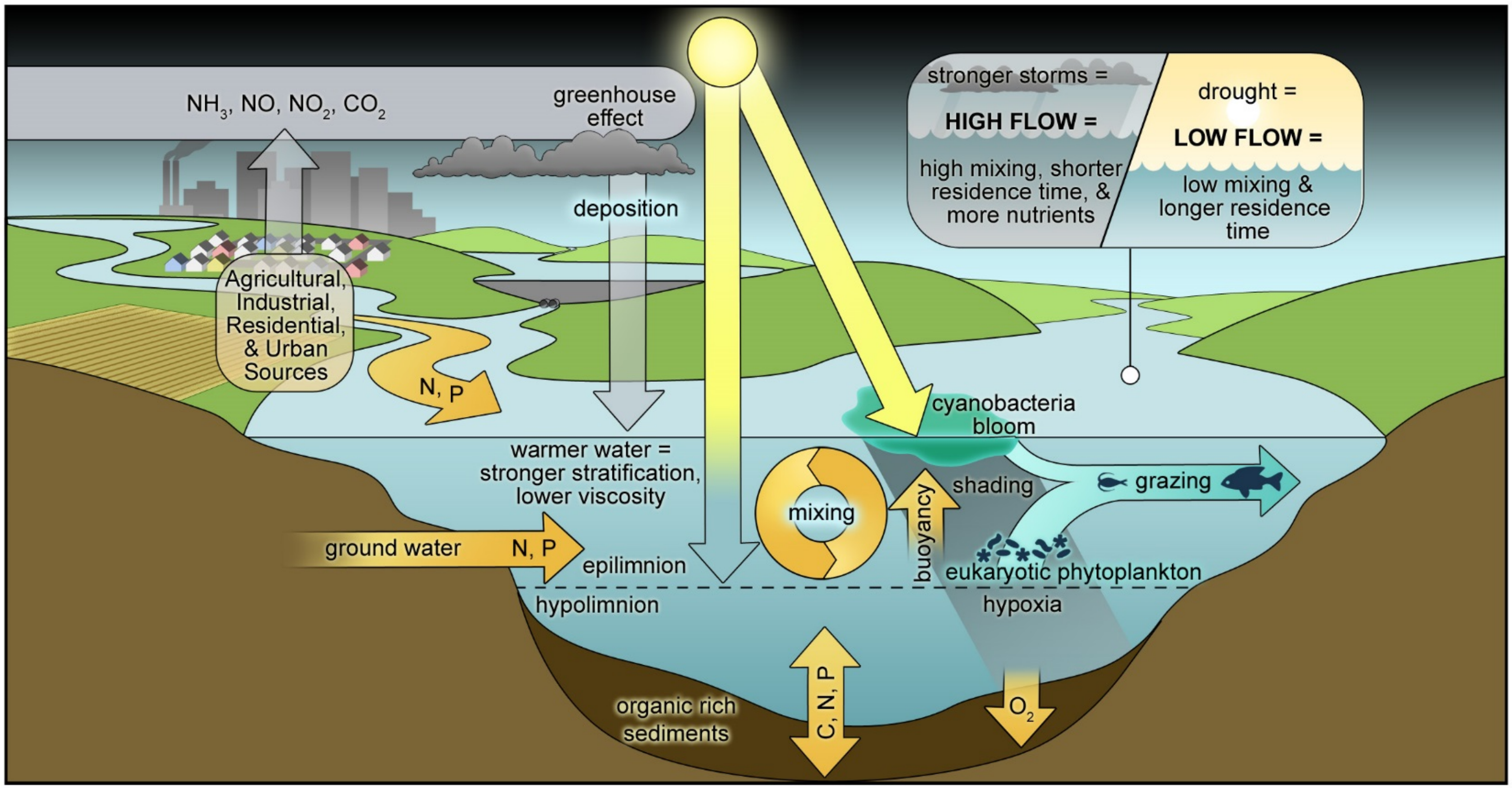


Fig. 6. Cyanobacteria community structure across the Klamath system during peak bloom as assessed by the relative proportion of 454 sequencing reads of the 16-23S rDNA internal transcribed spacer region (average of 835 reads/sample).



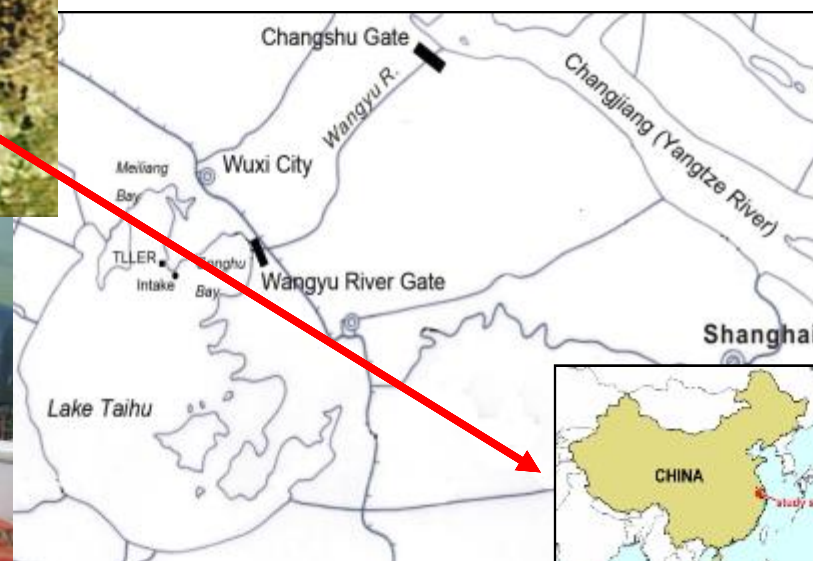
Otten et al., 2015, Harmful Algae

Drivers of CHABs: Interactive physical, chemical and biotic factors

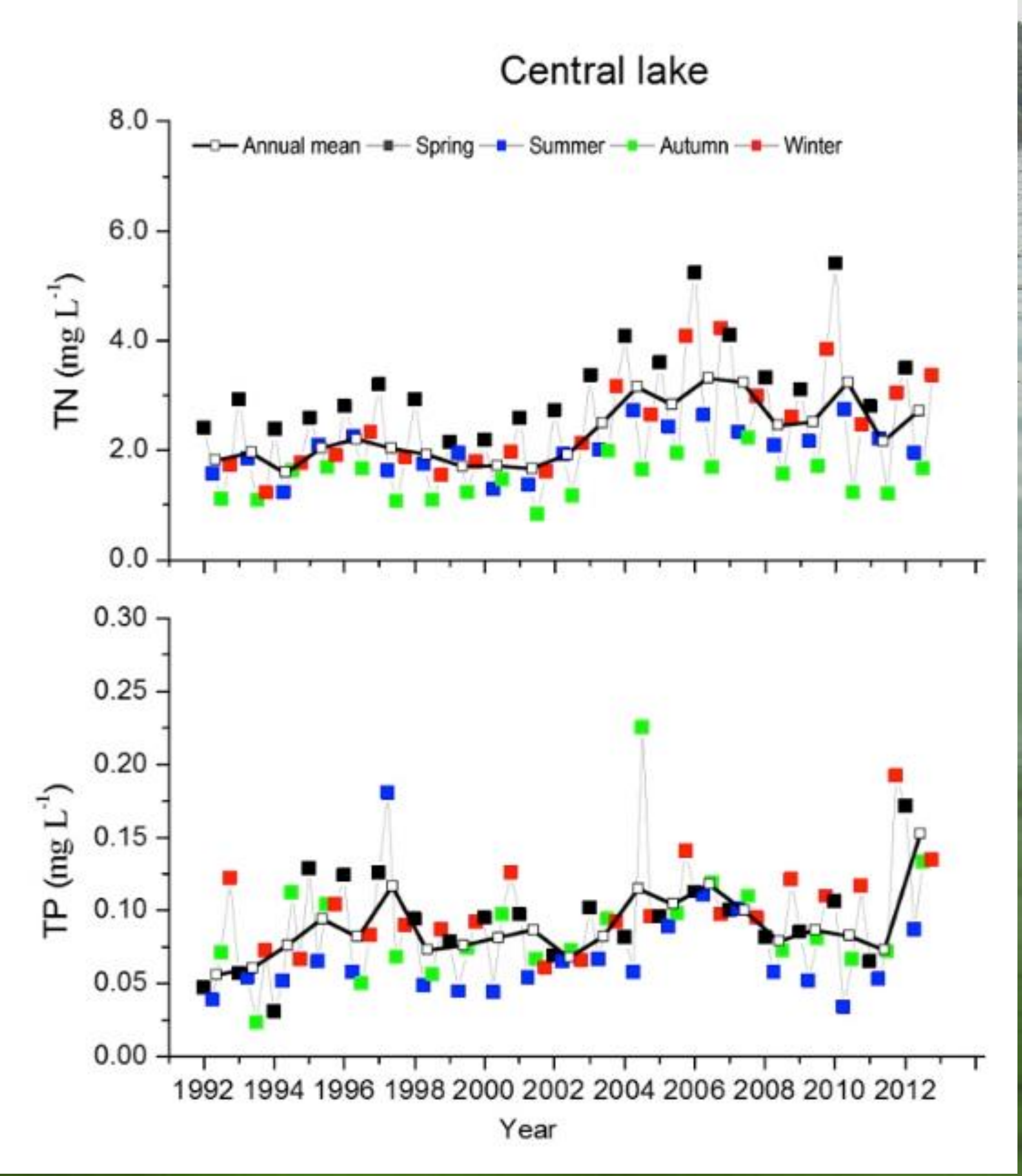


The CyanoHAB "poster child", Lake Taihu, 3rd largest lake in China

<u>Nutrient over-enrichment</u> associated with unprecedented human development in the Taihu Basin over past 3 decades. Taihu has experienced a "state change"



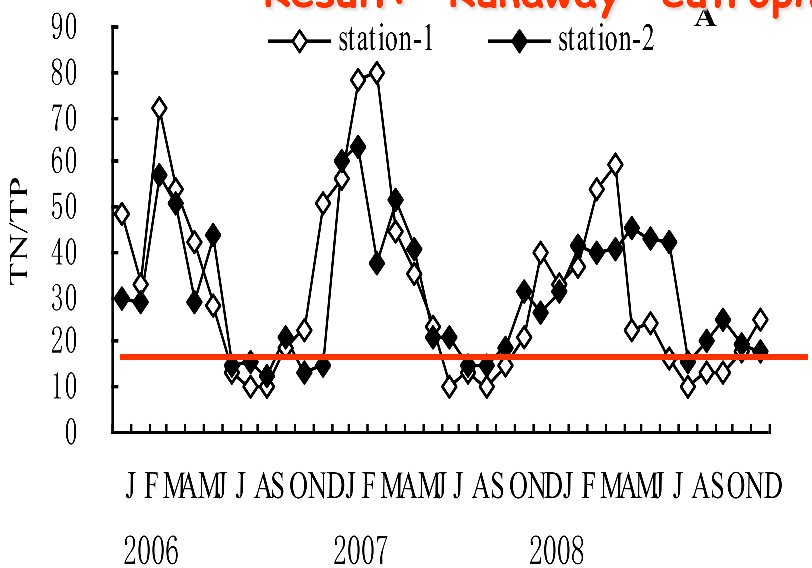
Recent history of nutrient (TN, TP) increases in Lake Taihu 1992-2012

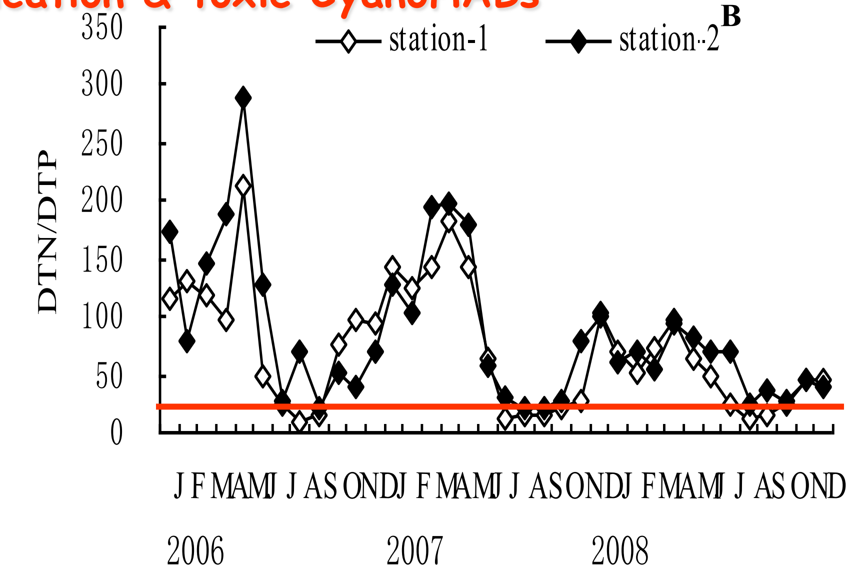


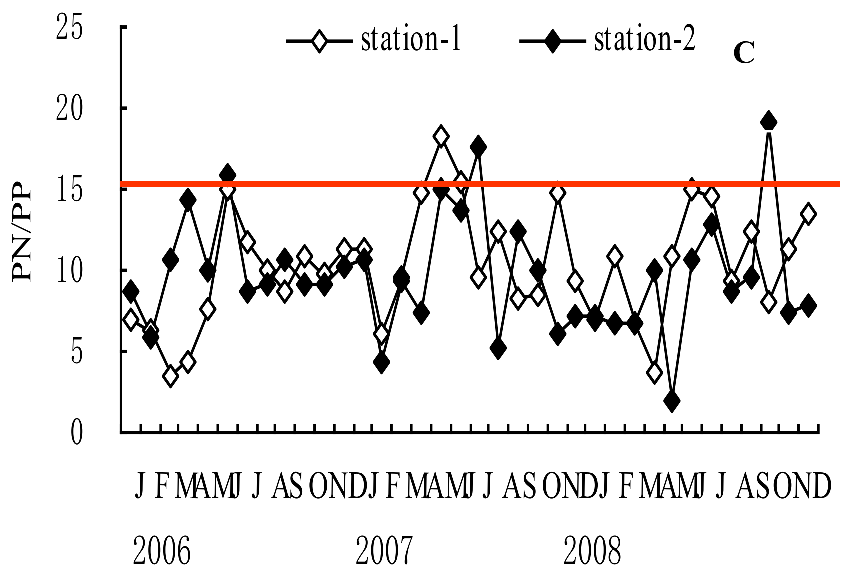
Qin et al., 2010
Xu et al., 2015

The "nutrient problem" in Taihu

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

Xu et al. 2010; Paerl et al. 2011, 2014

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

Using nutrient dilution bioassay experiments to determine N&P reductions needed to control blooms

Sampling

Distribution

Nutrient addition

Incubation

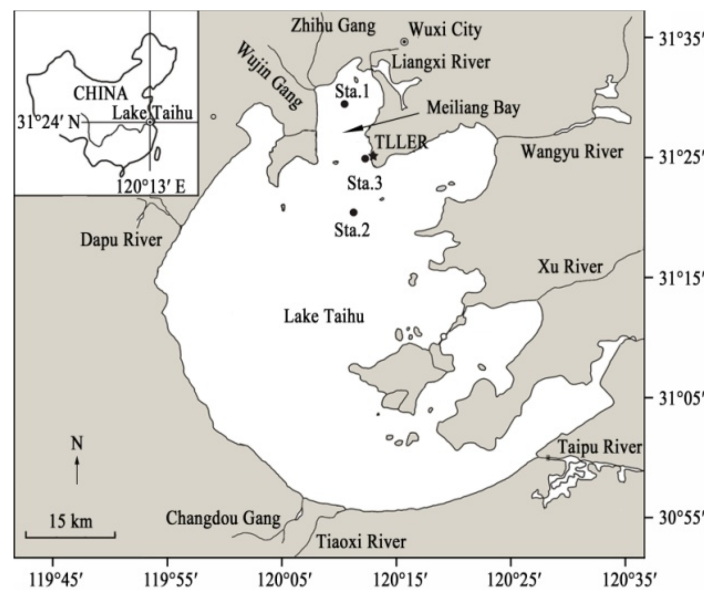
Six nutrient dilution bioassays were conducted:

1. 0% (lake water, no dilution)
2. 30% dilution
3. 50% dilution
4. 70% dilution

N was added as KNO_3, and P was added as $K_2HPO_4 \cdot 3H_2O$.

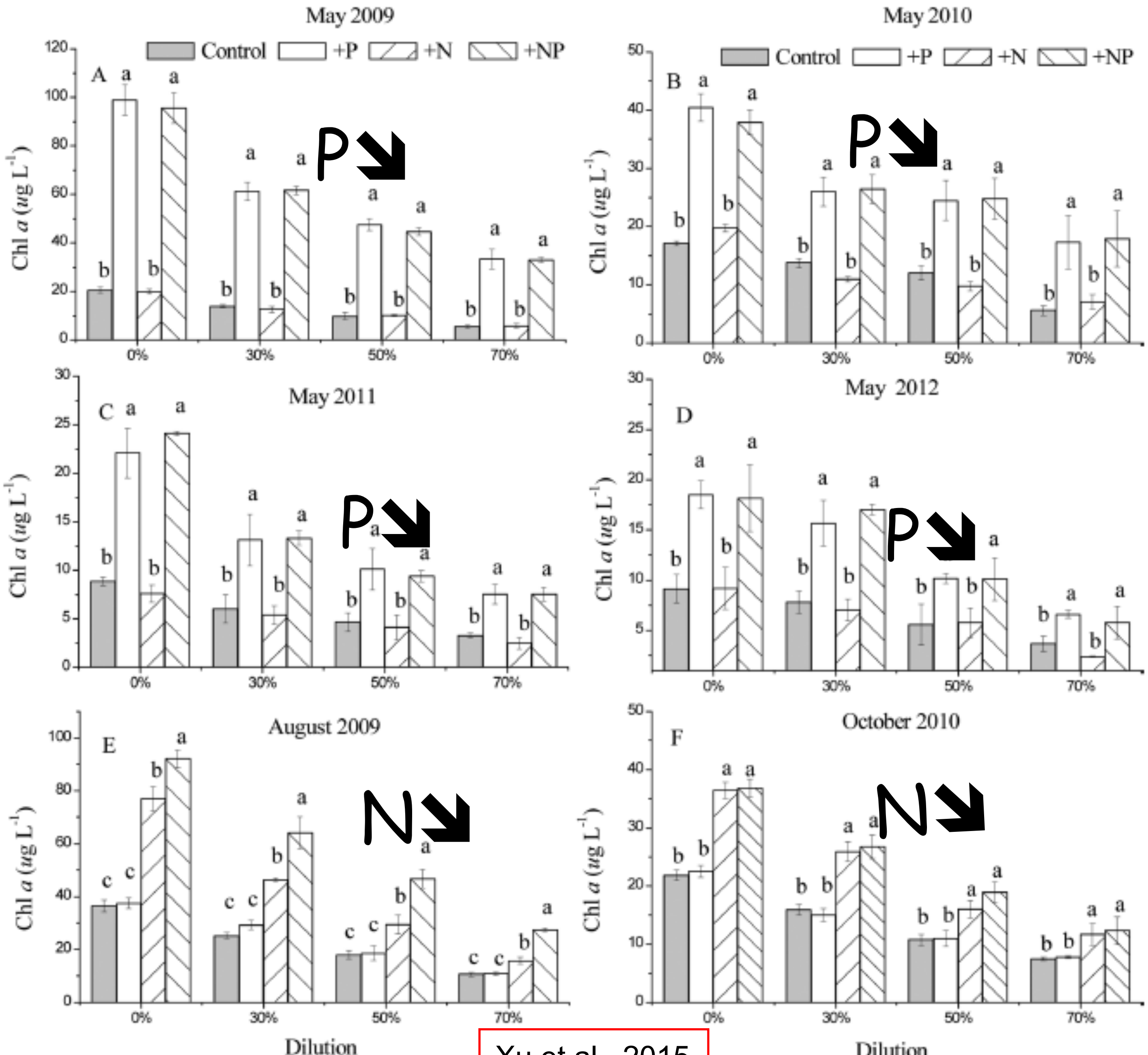
Containers were incubated in the surface water to maintain ambient conditions.

Testing fast response of phytoplankton to the change in ambient conditions



Xu et al., 2015

Nutrient Dilution Bioassays: How much N & P reduction is needed to control blooms?

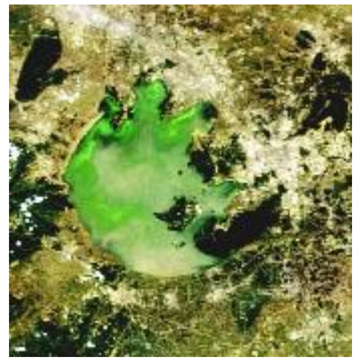


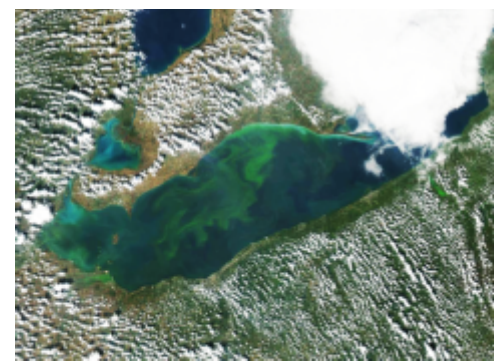
30-50% for P

50-70% for N

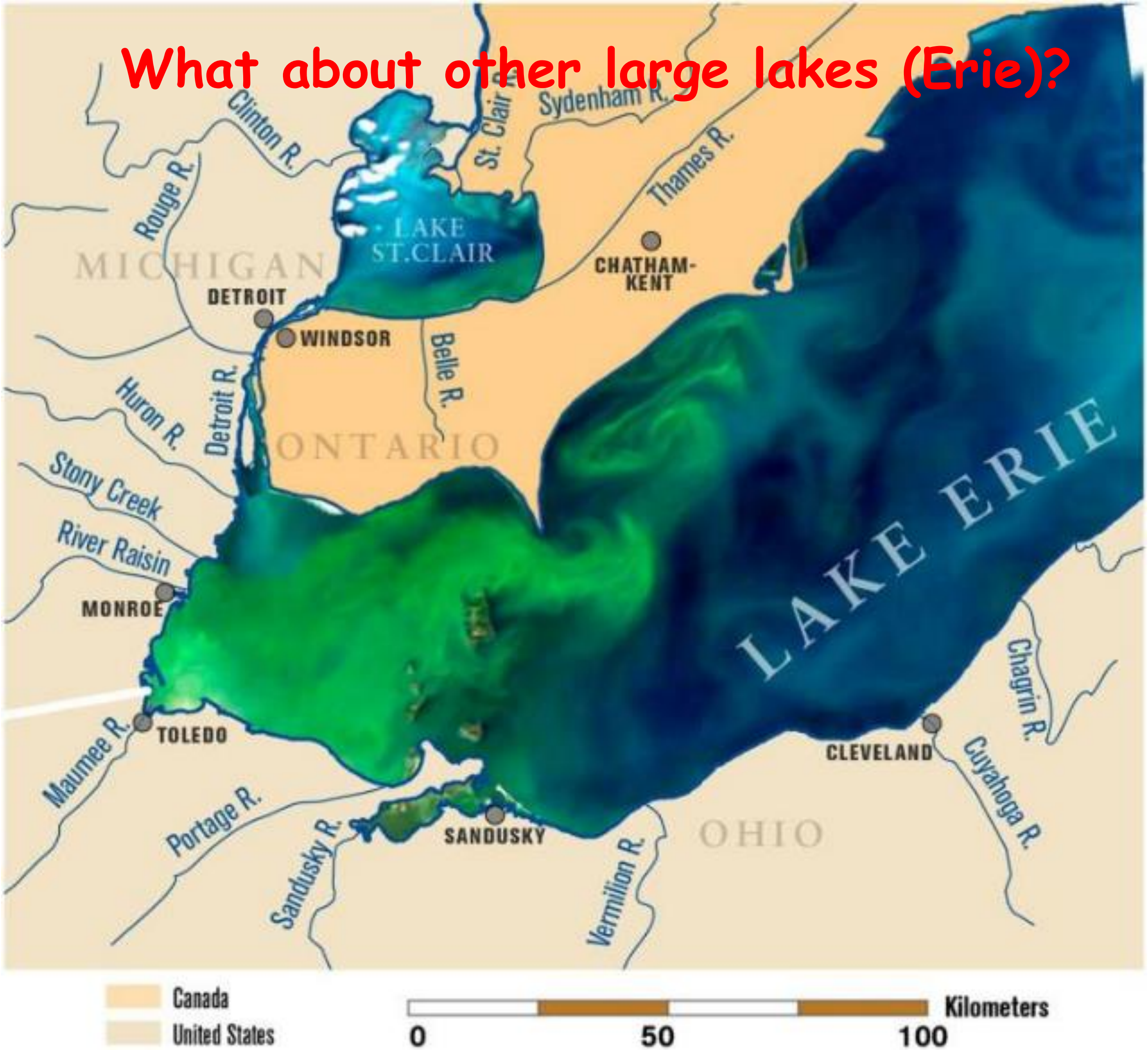
Xu et al., 2015

Taihu: a "looking glass" for eutrophying aquatic ecosystems worldwide?





What about other large lakes (Erie)?



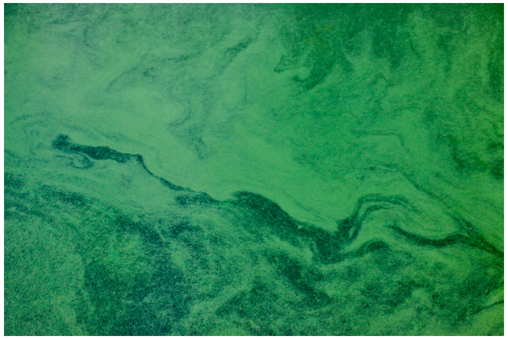
Looking beyond "P only"

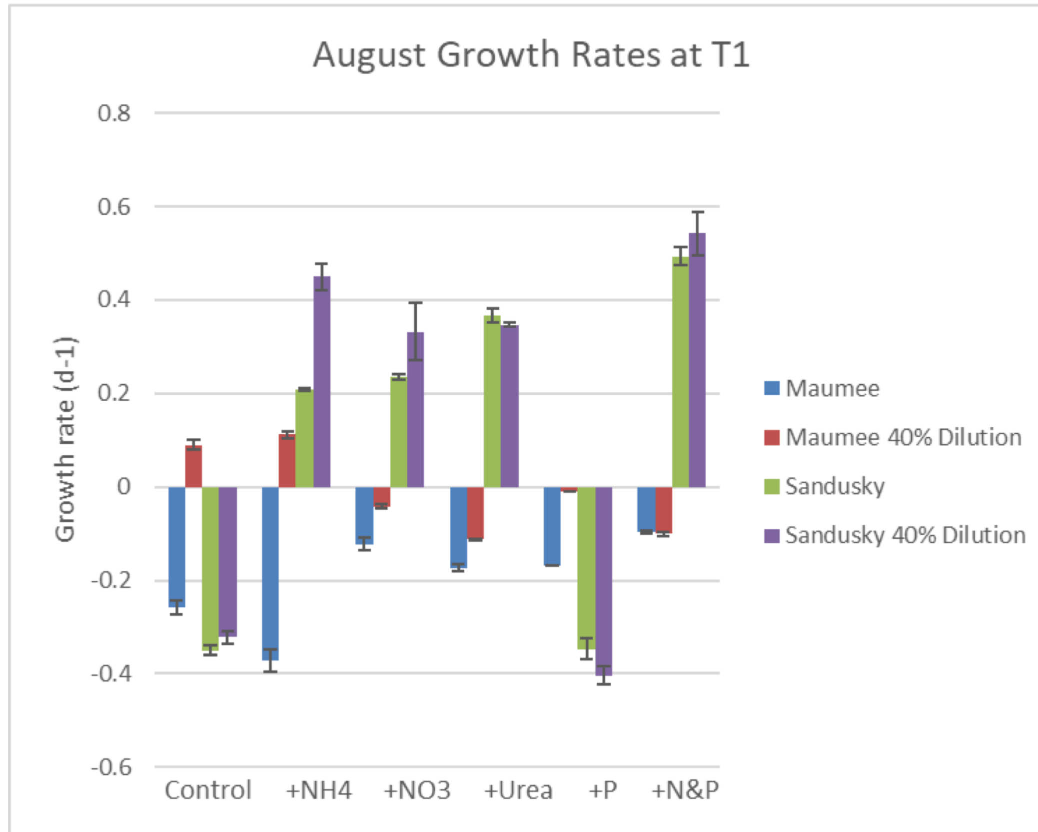
Davis et al. (2009). The effects of temperature and nutrients on the growth and dynamics of toxic and non-toxic strains of *Microcystis* during cyanobacteria blooms. *Harmful Algae* 2009, *8*, 715-725.

Chaffin et al., (2013) Nitrogen Constrains the Growth of Late Summer Cyanobacterial Blooms in Lake Erie. *Advances in Microbiology* 3, 16-26.

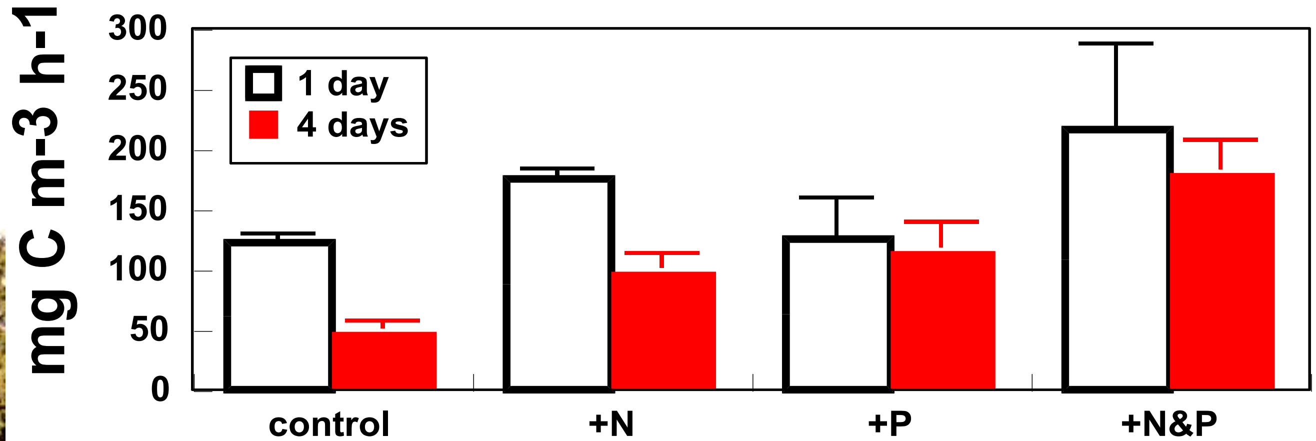
Gobler et al., (2016) The dual role of nitrogen supply in controlling the growth and toxicity of cyanobacterial blooms. *Harmful Algae* 54:87-97.

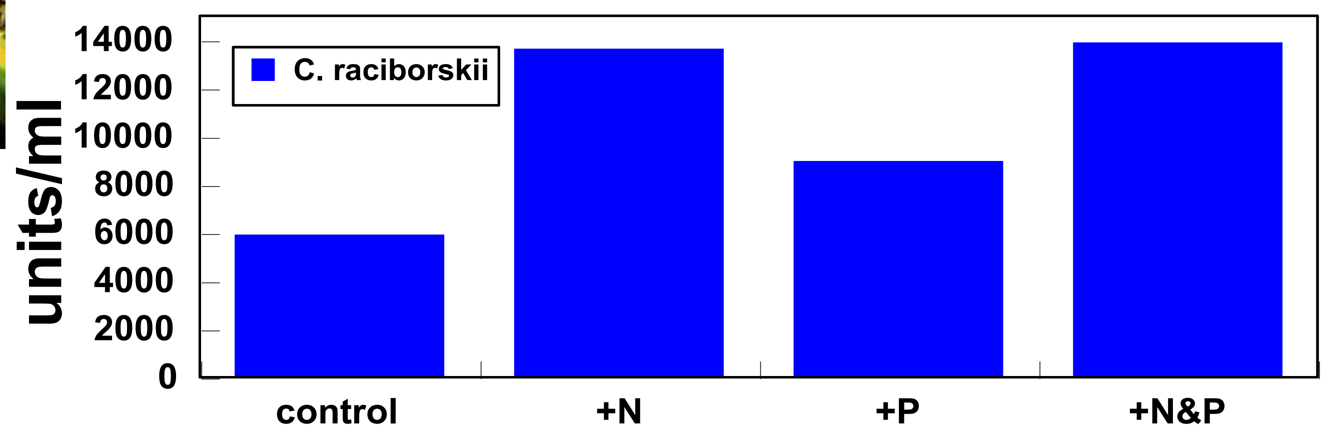
Western Lake Erie, August 2019: Algal growth rates compared to control (no additions)





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

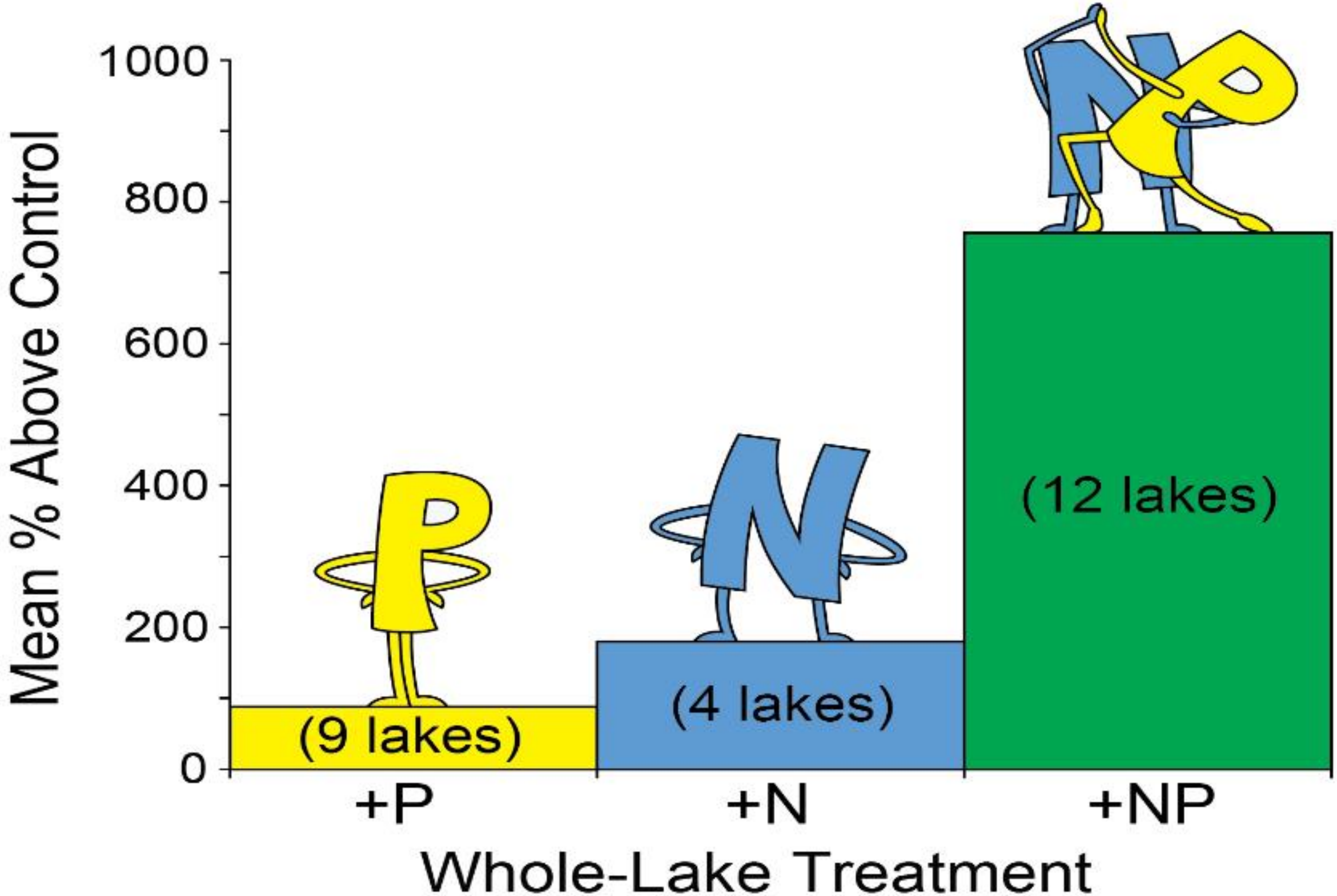




Take home message: *Cylindrospermopsis raciborskii* is opportunistic
Dual N & P input constraints will likely be needed to control it

Piehler et al, 2009

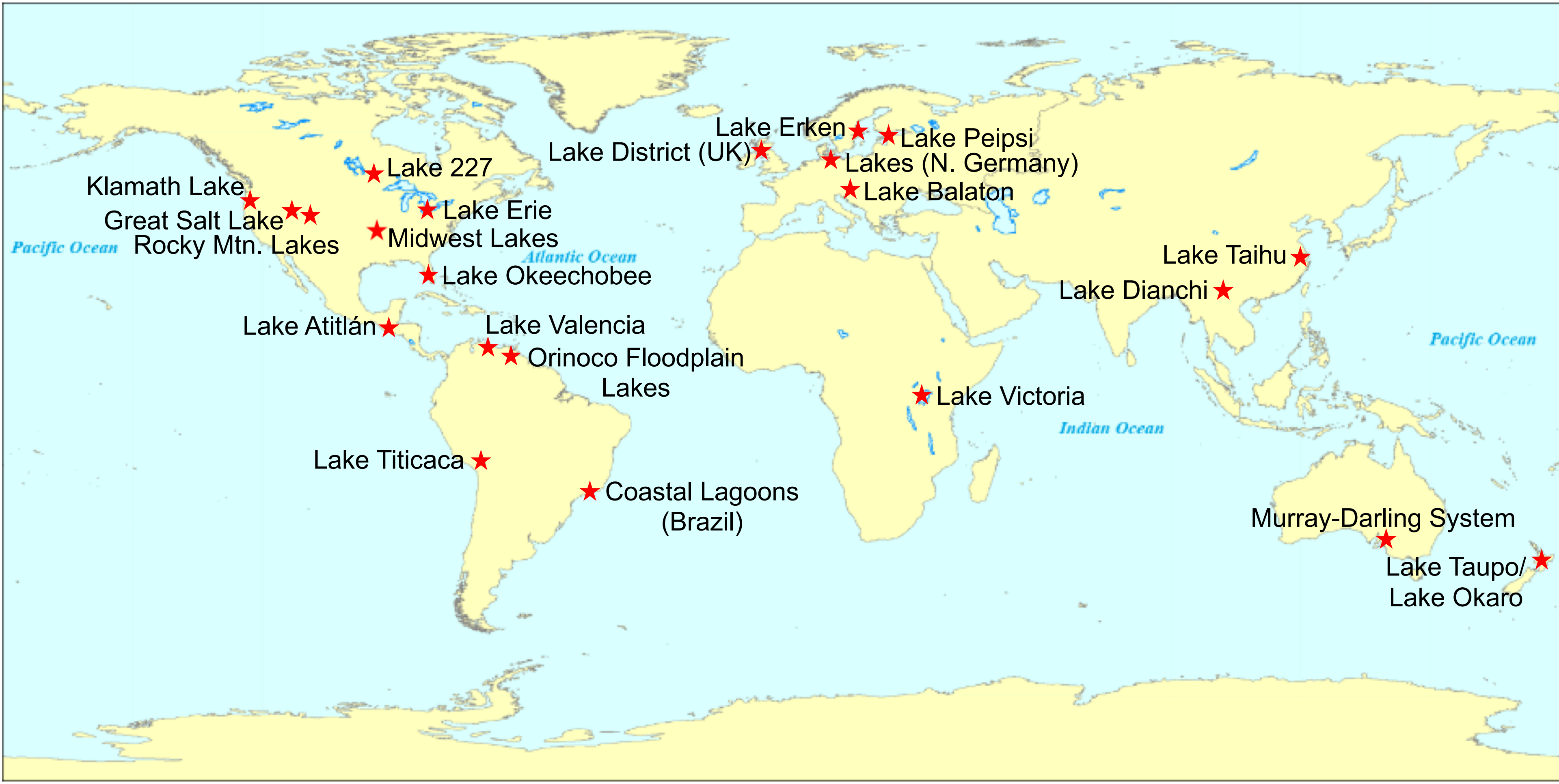
Lets ask other eutrophying lakes? Whole-Lake Fertilization



Co-Limitation Dominant

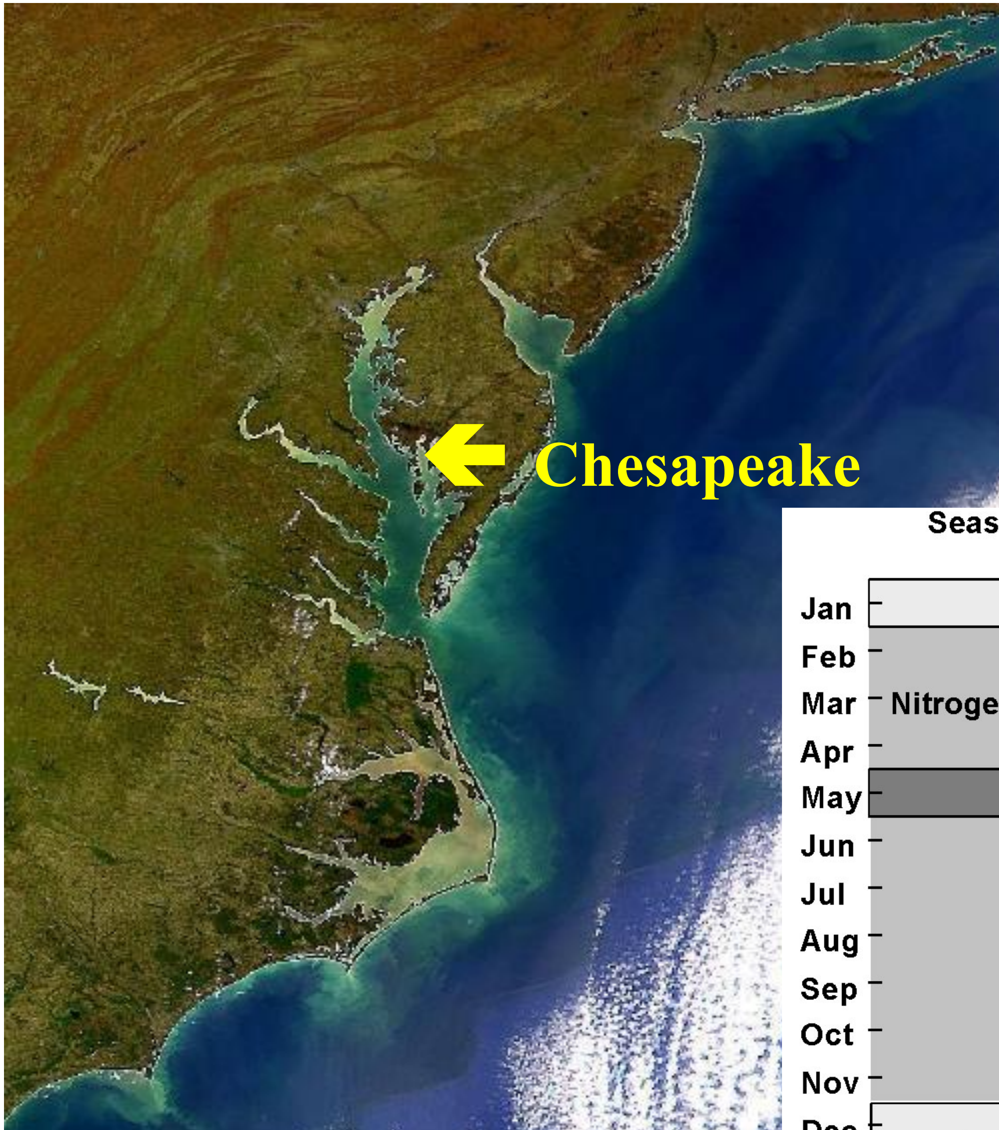
Lewis et al., 2011; Wurtsbaugh et al., 2012; Paerl et al., 2016

Large lakes and reservoirs in which algal blooms (mostly cyanobacteria) have been shown to be N & P stimulated

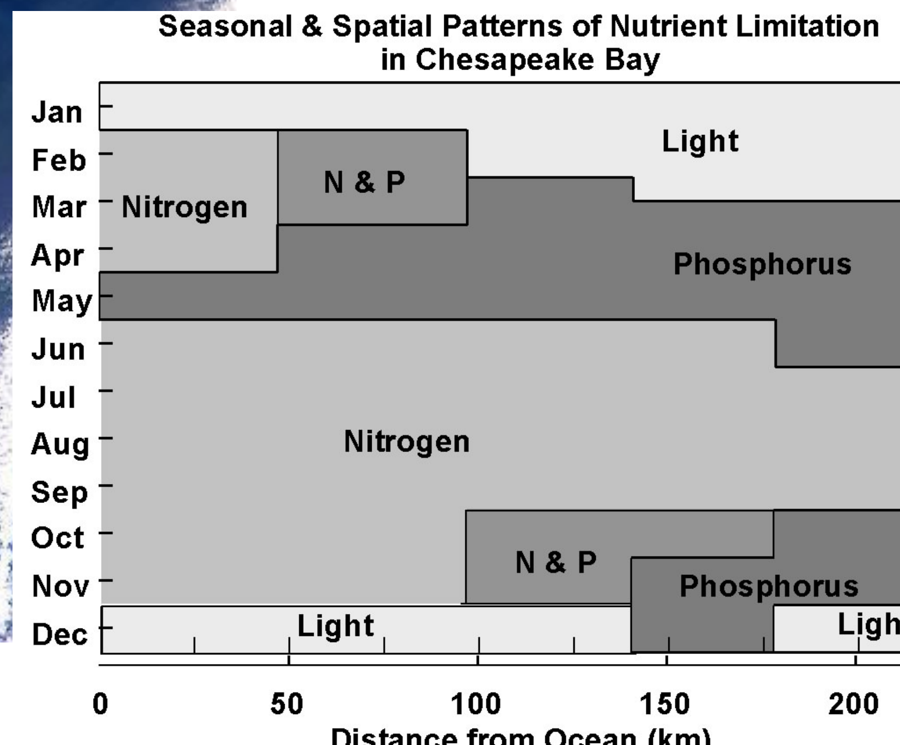


Sources: Havens et al., 2003; Elser et al. 2007; North et al., 2007; Lewis & Wurtsbaugh 2008; Conley et al., 2009; Moisander et al., 2009; Lewis et al. 2011; Abell et al., 2011; Özkundakci et al., 2011; Paerl et al., 2014; and many others.

Nutrient limitation dynamics in estuaries: Chesapeake Bay

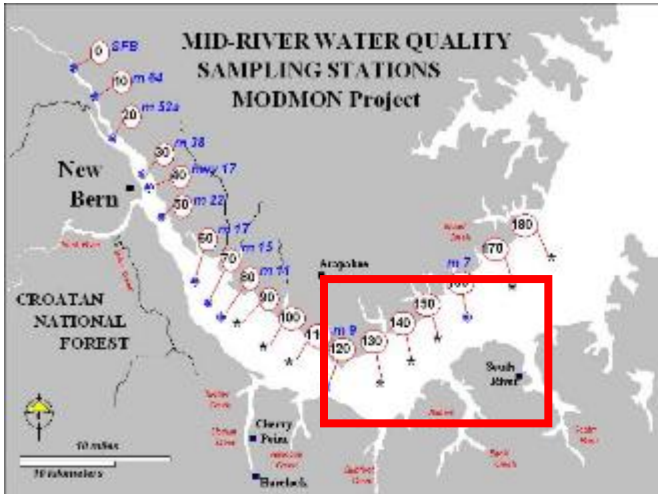


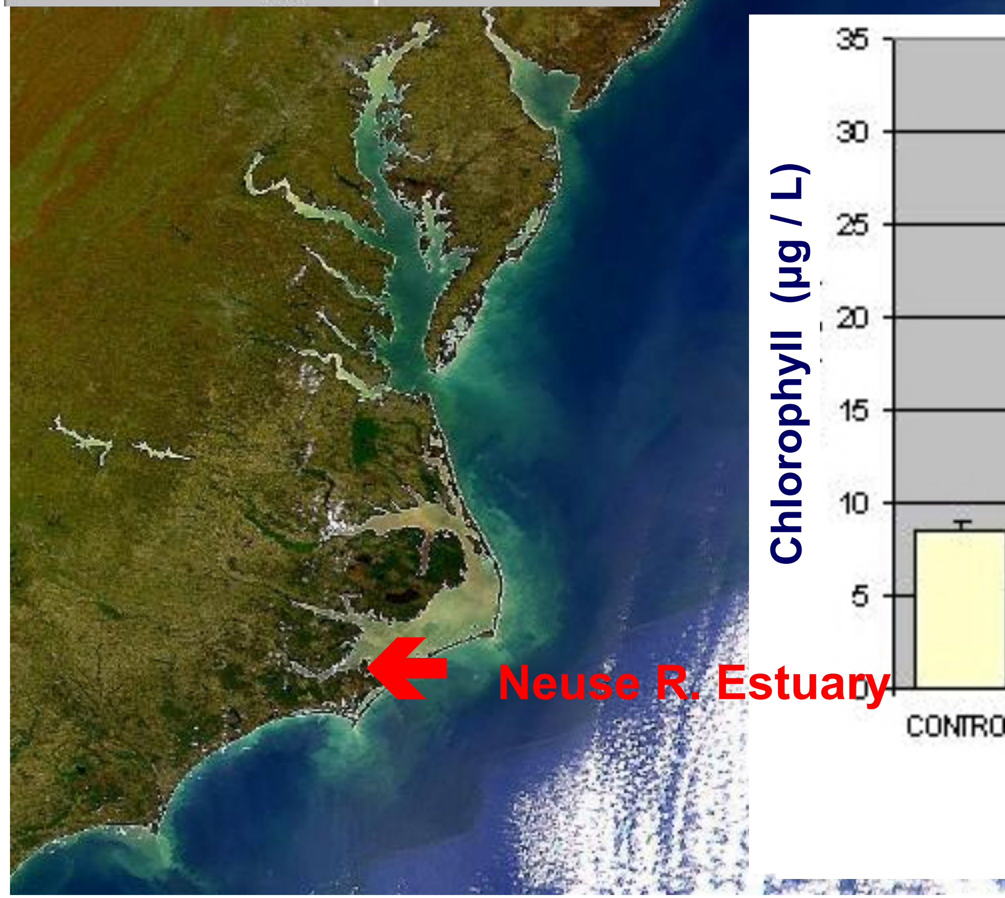
Fisher et al. 1998

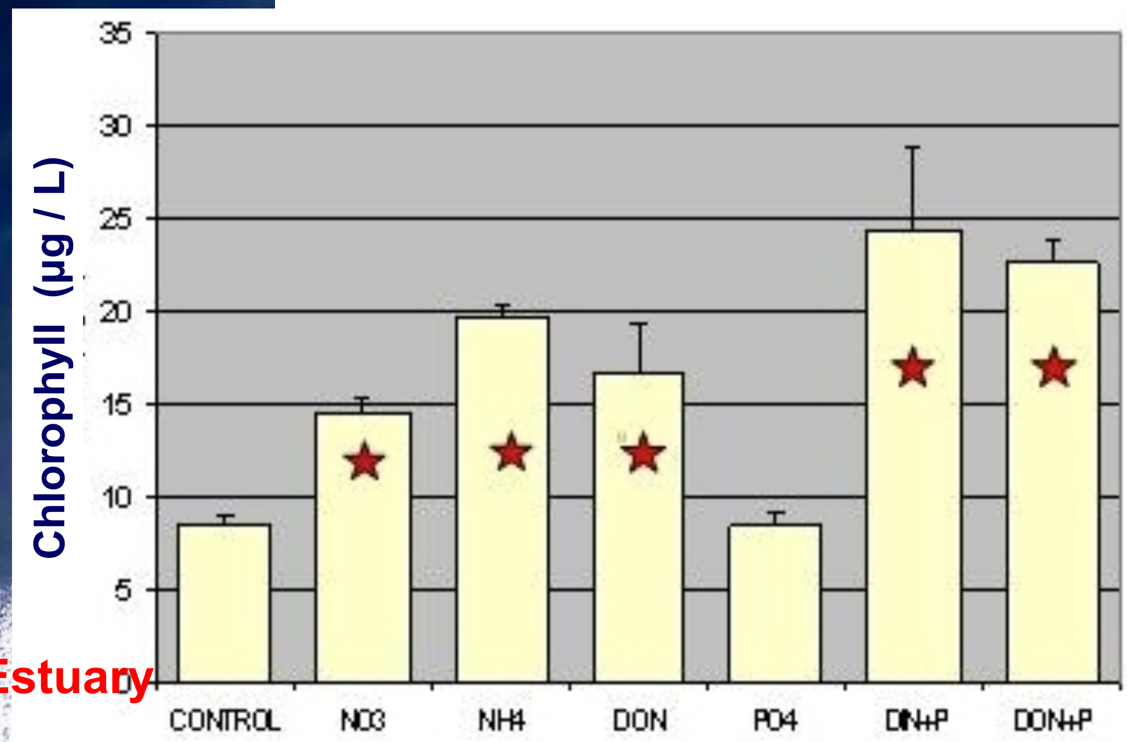


(Fisher et al. 1998)

Nutrient limitation in the Neuse River Estuary, NC



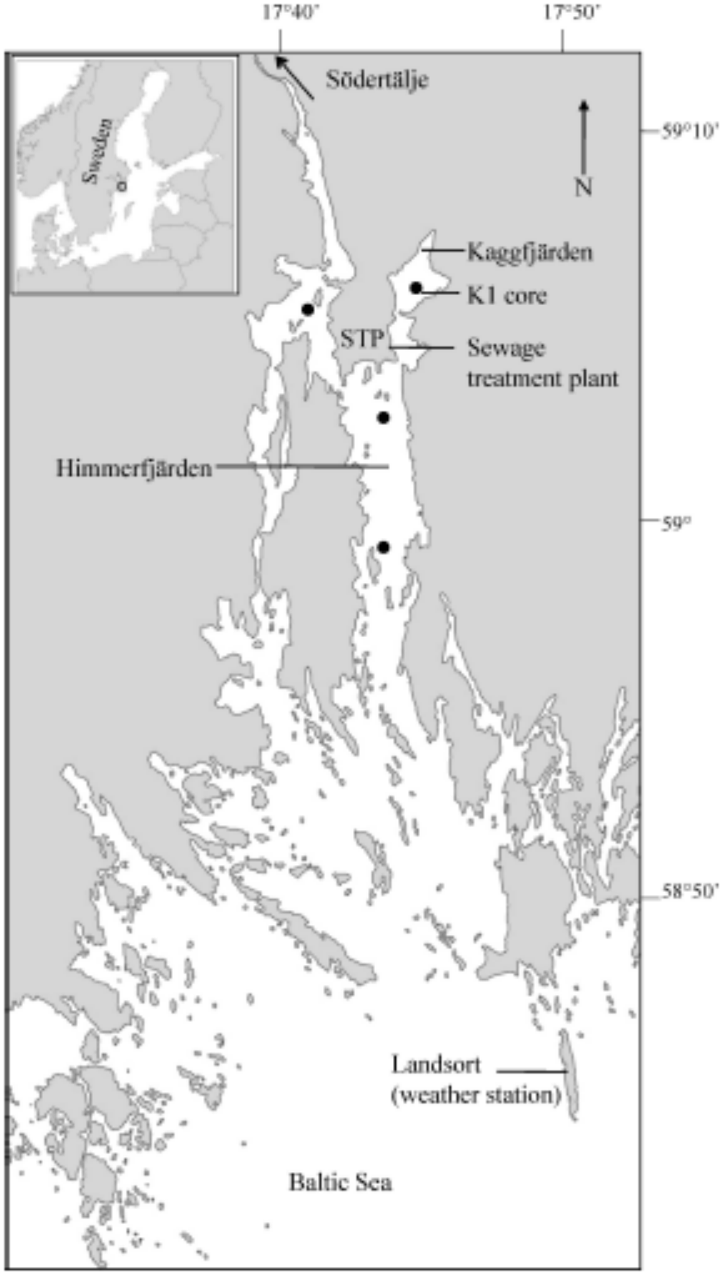




Paerl et al., 1995; Gallo 2006

Reducing nutrient loads to control CyanoHABs. It works if there's a will: The Himmerfjärden, Sweden, case.

Courtesy: Ulf Larsson & Ragnar Elmgren
Stockholm University



The Himmerfjärden case: **Baltic coastal area with large Sewage treatment plant,**

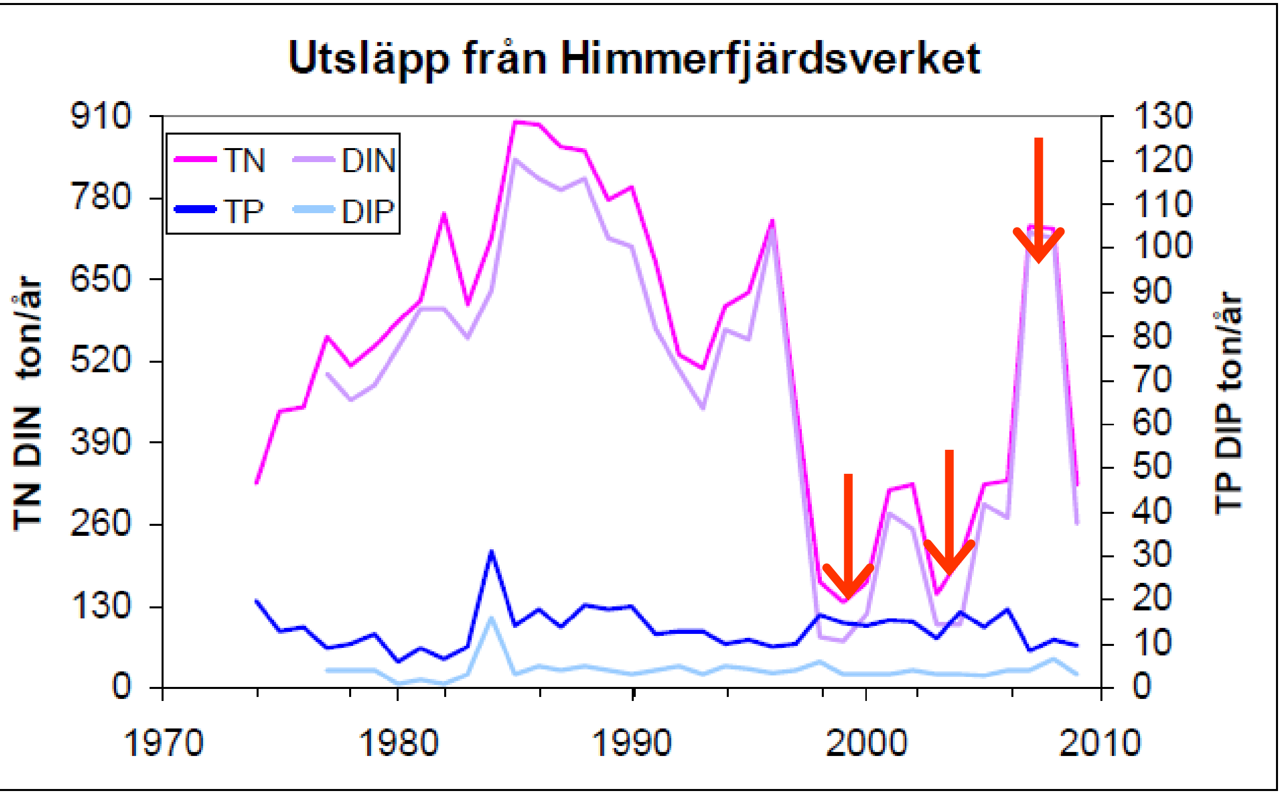
P removal since 1976

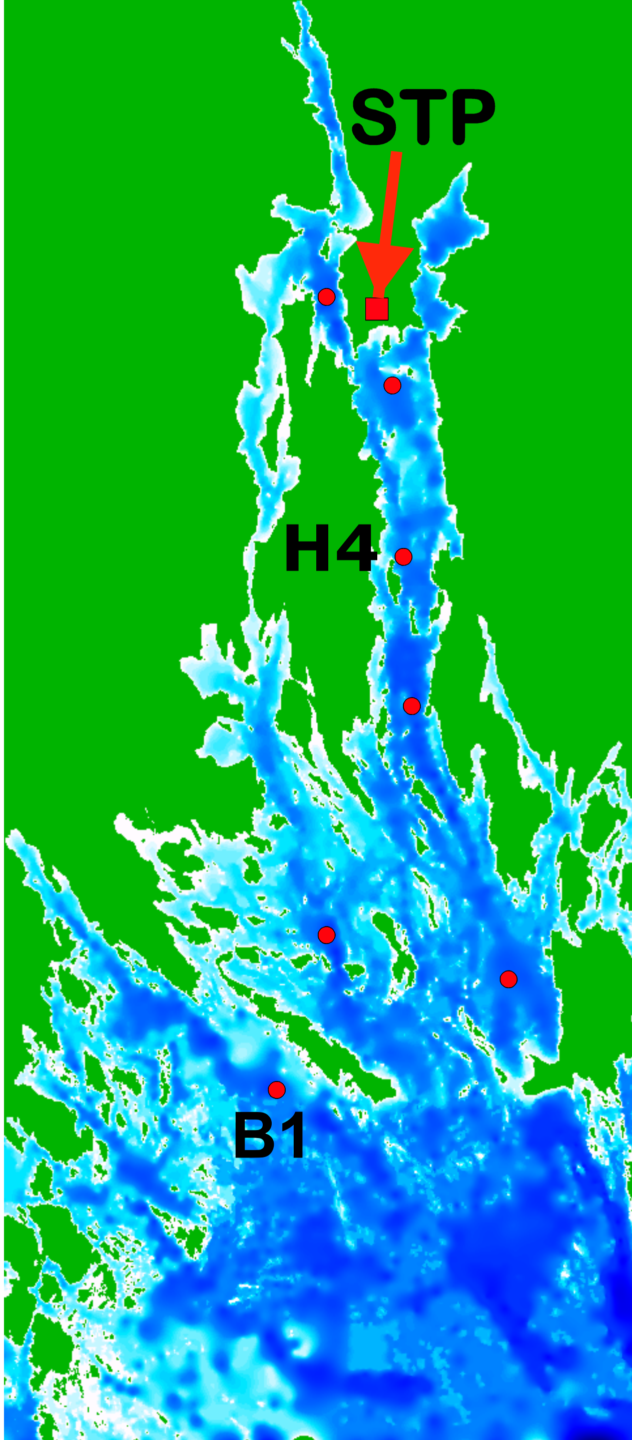
N removal started in 1993 (50%) & 2000 (80%).

No N removal 2004-2008

EFFECTS ON PHYTOPLANKTON (Chl a)?

Plant loads , tonnes/ year

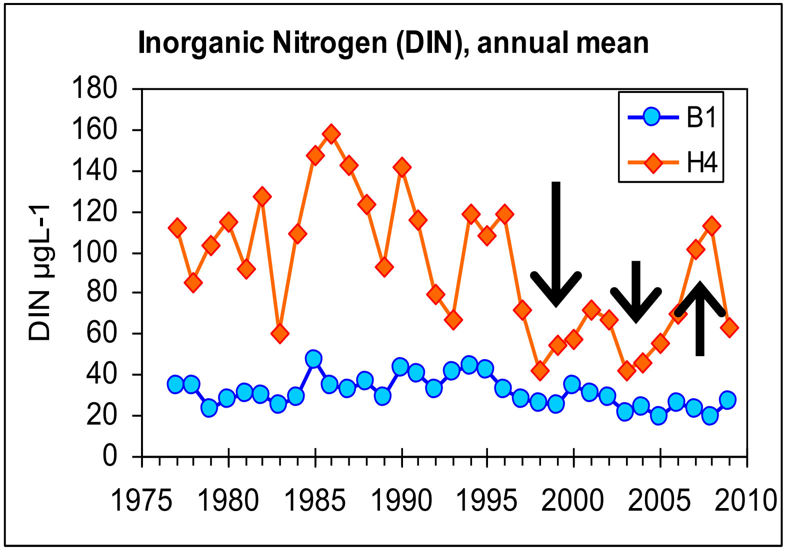


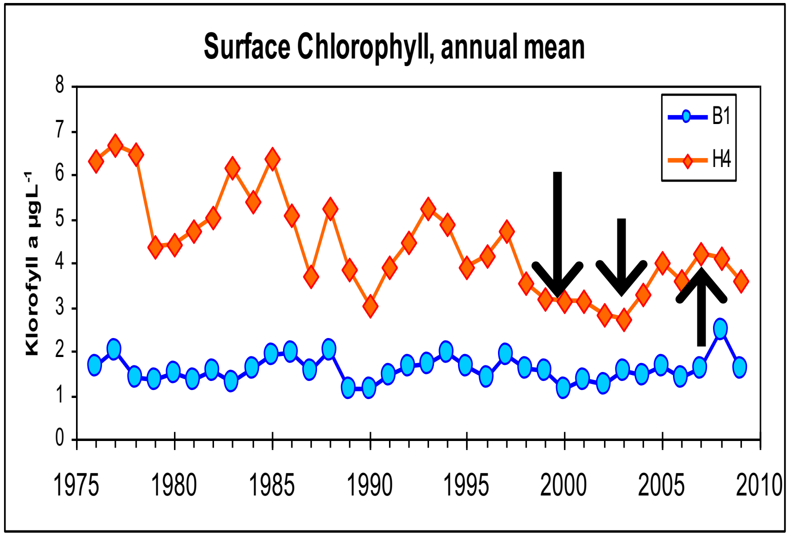


H4 =Eutrophicated station

B1= Reference station

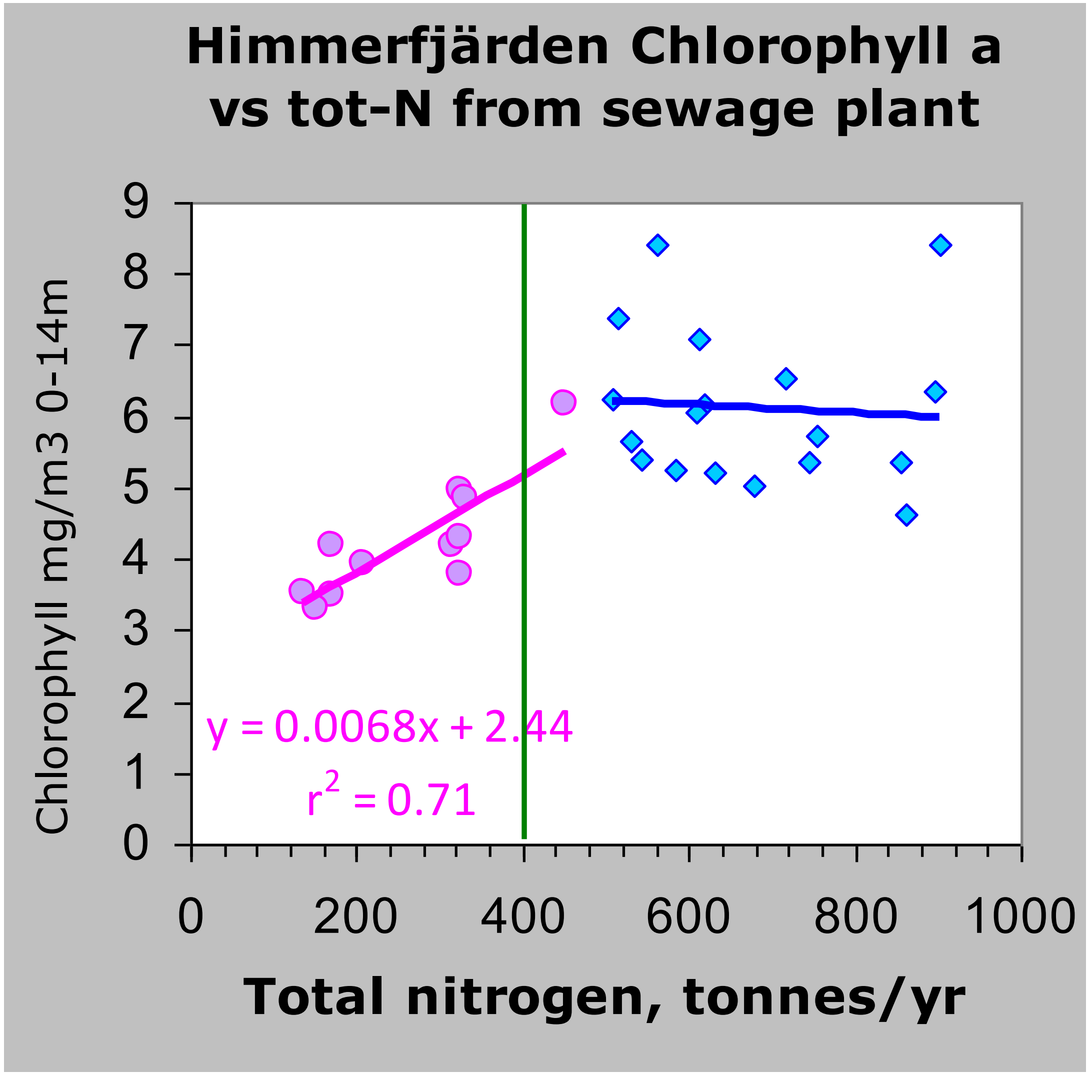
The results: Reducing DIN inputs reduced Chl a and controlled CyanoHABs





Larsson and Elmgren, 2016

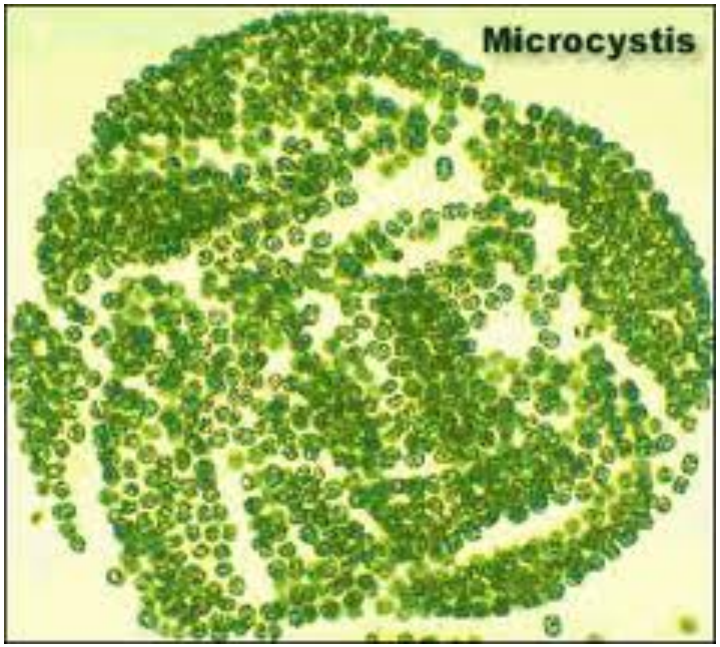
Developing a N loading-bloom threshold



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

Source:
Ulf Larsson, pers.comm.

Will there be a shift of cyanobacteria communities to N_2 fixers upon N reduction?



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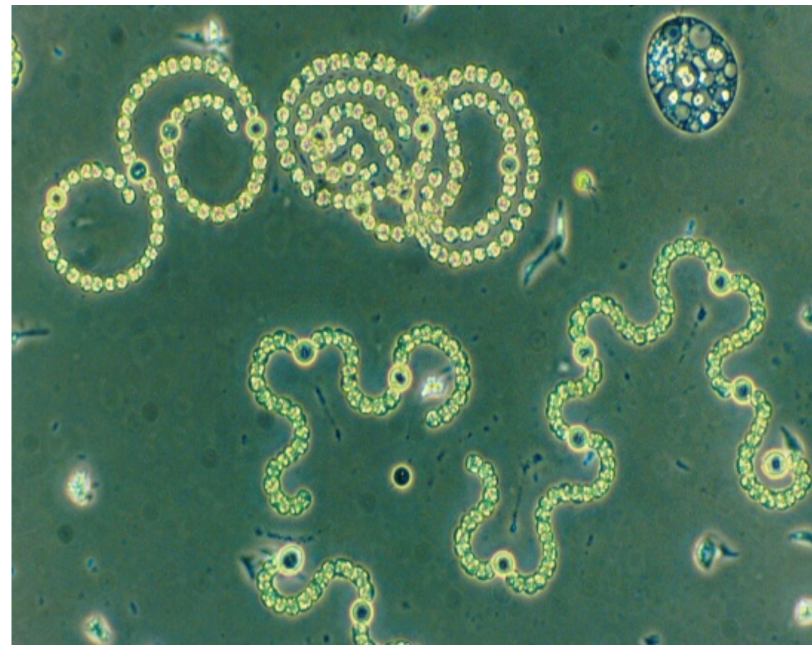
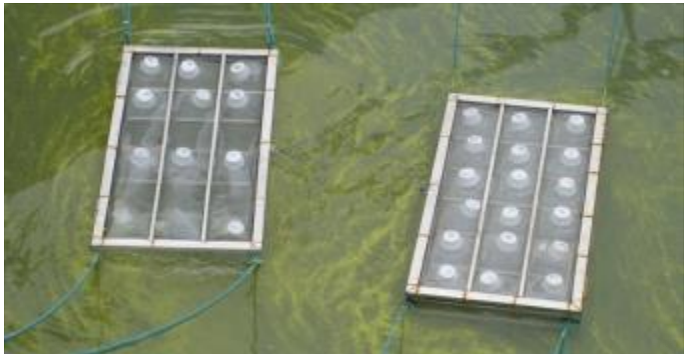
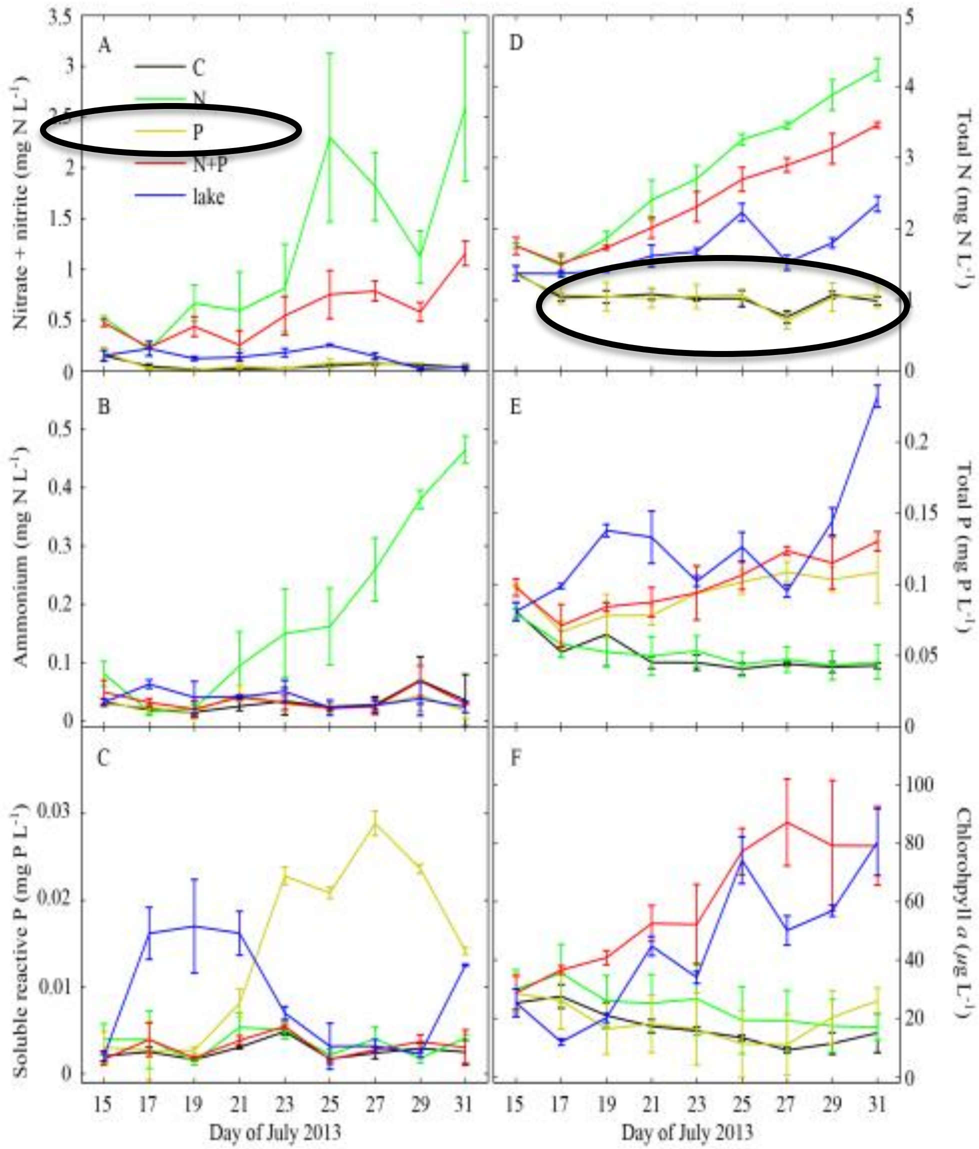


Microcystis spp.

Anabaena (Dolichospermum) spp.

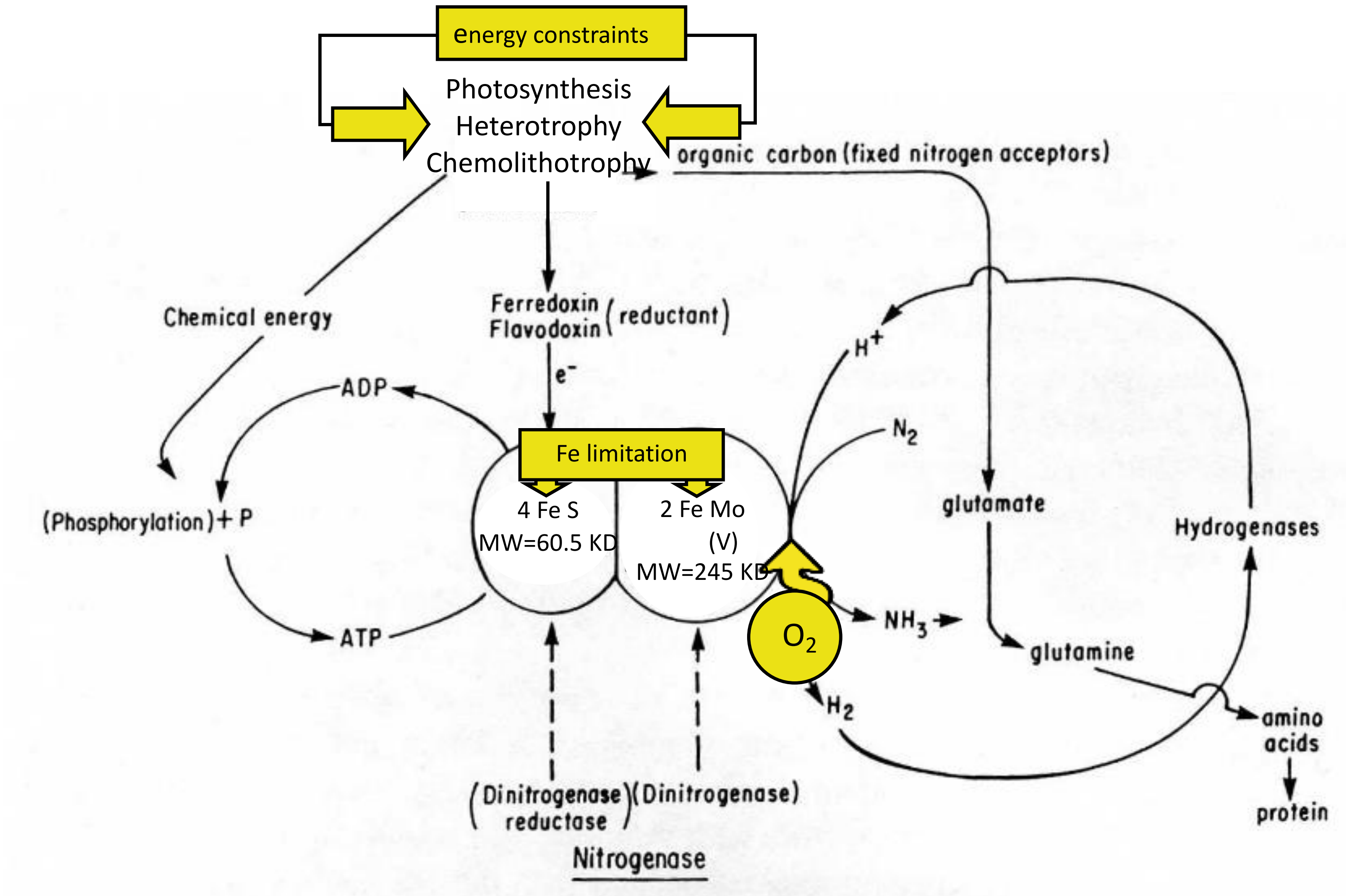
In situ Bioassays in Lake Taihu indicate N_2 fixation does not "catch up" with N demands and N losses. Most likely, the bloom is sustained by high internal N loading, and Cyanos effectively use regenerated N



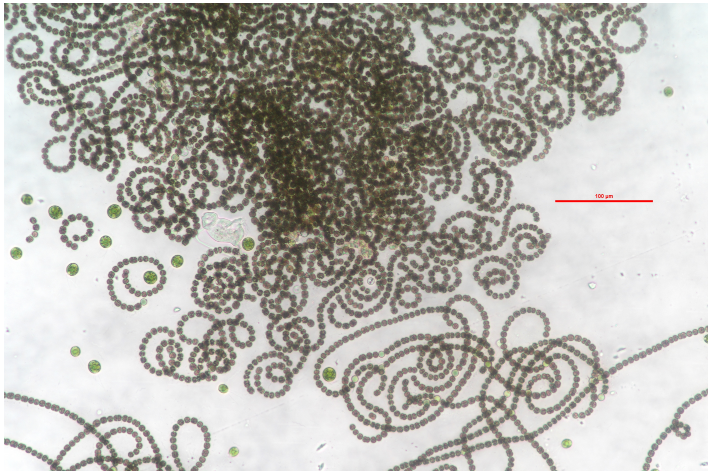


Paerl et al., 2014

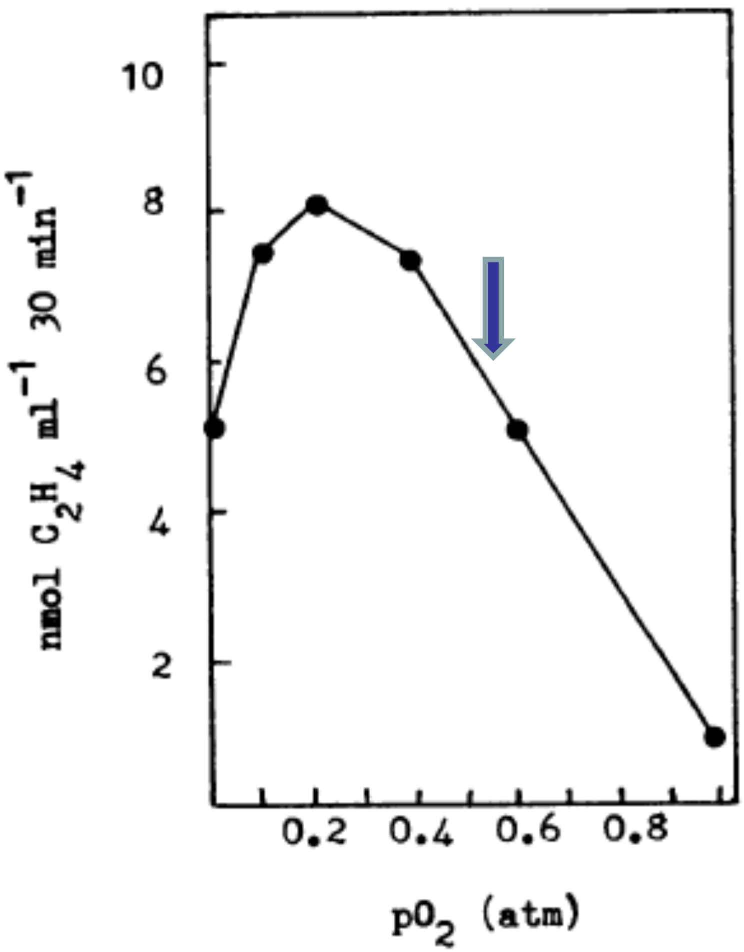
Why doesn't N_2 fixation provide N needed to ecosystem demands? Controls on N_2 fixation: Its not just P



The "oxygen problem": During blooms, O_2 supersaturated (< 0.4 Atm) conditions exists, which are inhibitory to N_2 fixation, even in heterocystous cyanobacteria (e.g., *Anabaena sp.*)



Taihu, 10 August, 2018



Fay 1992

Overall, N_2 losses from eutrophic systems by denitrification exceed "new" N inputs via N_2 fixation

Annual estimates of ecosystem N_2 fixation, denitrification, and net ecosystem N_2 flux in eutrophic lakes with CyanoHABs.

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

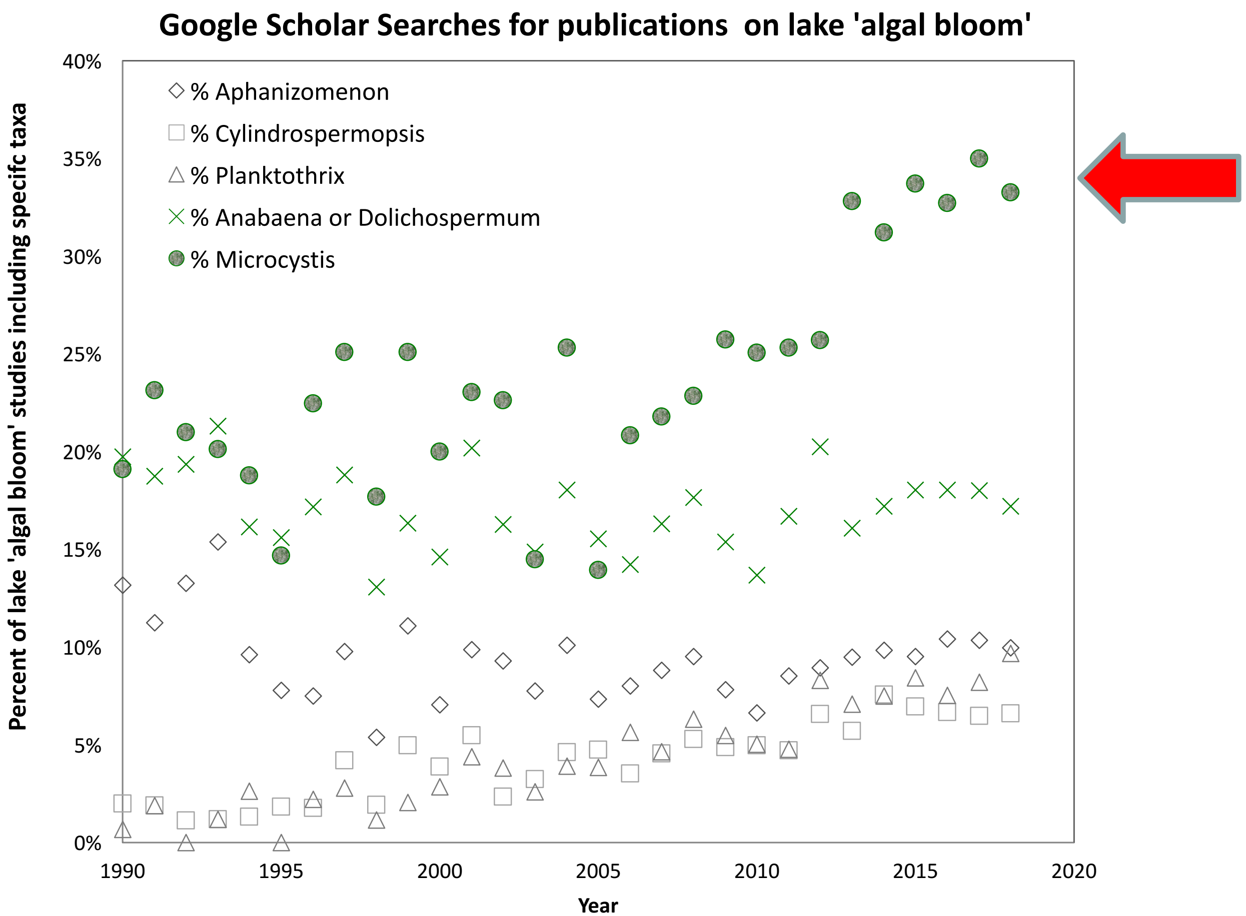
[1]Net negative N_2 flux represents reactive N loss, positive represents gain; [2]Paerl and Scott (2010); [3]J.T. Scott (unpublished data); [4]Grantz et al. (2012); Paerl et al., in review

Conclusions: 1. N_2 fixation does NOT meet ecosystem N demands

2. More N inputs will accelerate eutrophication

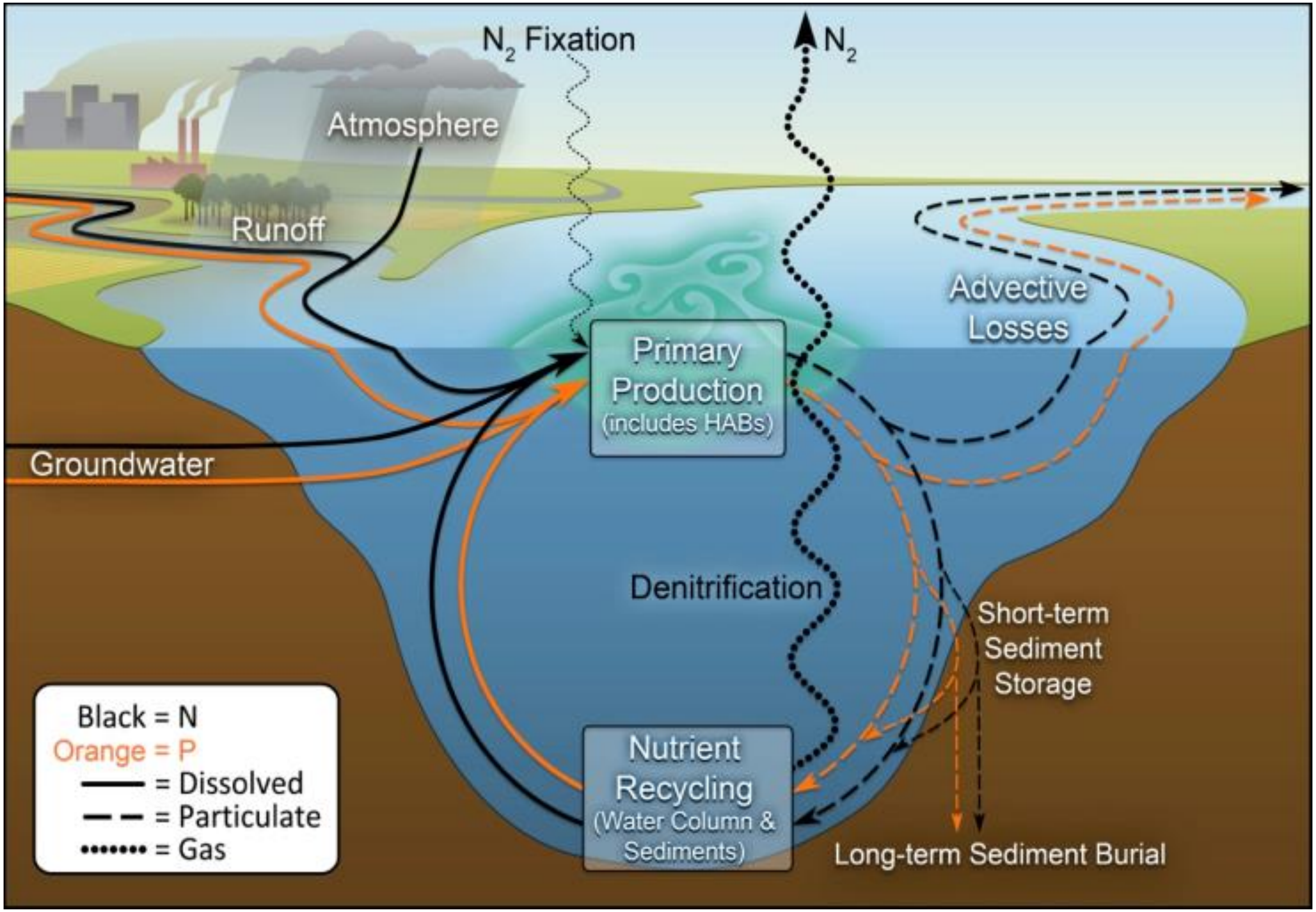
3. We Gotta get serious about controlling N (as well as P) !!

One final indicator that N enrichment is important: The non N_2-fixier, *Microcystis* is "on the march" worldwide



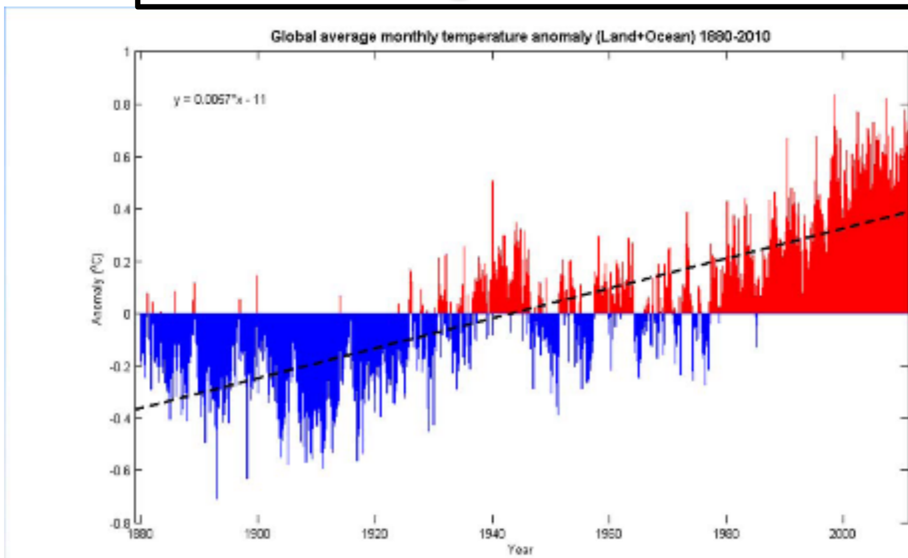
Paerl et al., 2019

Conclusion: N limitation is pervasive in aquatic ecosystems, even ones receiving anthropogenic N enrichment



Bottom line: Need to reduce N along with P to control PP and bloom formation

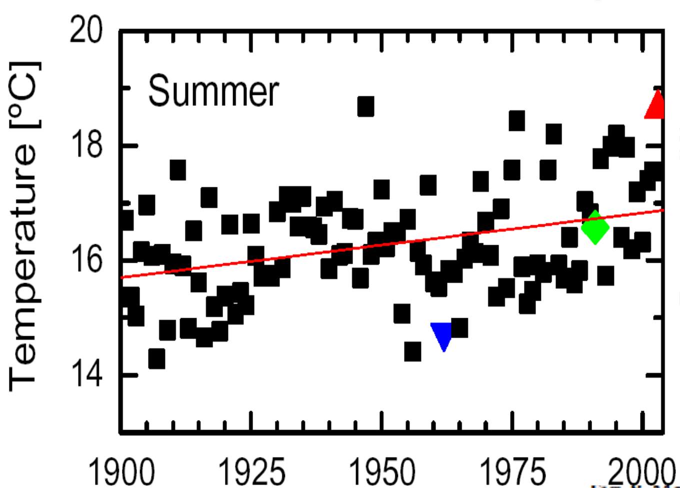
Its Getting Warmer, and CyanoHAB's like it hot



2003 was the hottest summer in 500 years in Europe! Since then, record heat waves

2005, 2009, 2014, 2016, 2018 were the hottest years ever in N. America

2010, 2017 hottest year in central Asia



Huisman et al. 2006

Mean epilimnetic Temp.In Dutch lakes

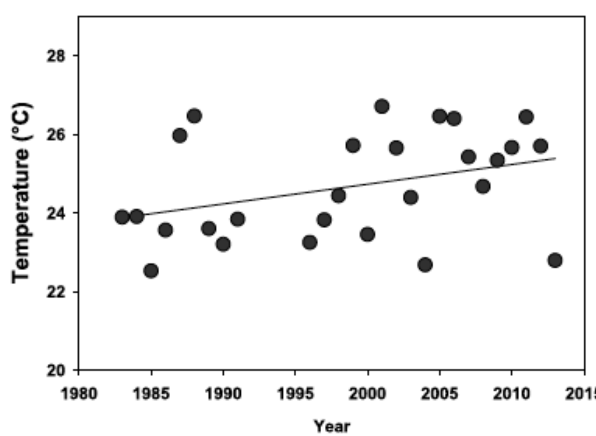
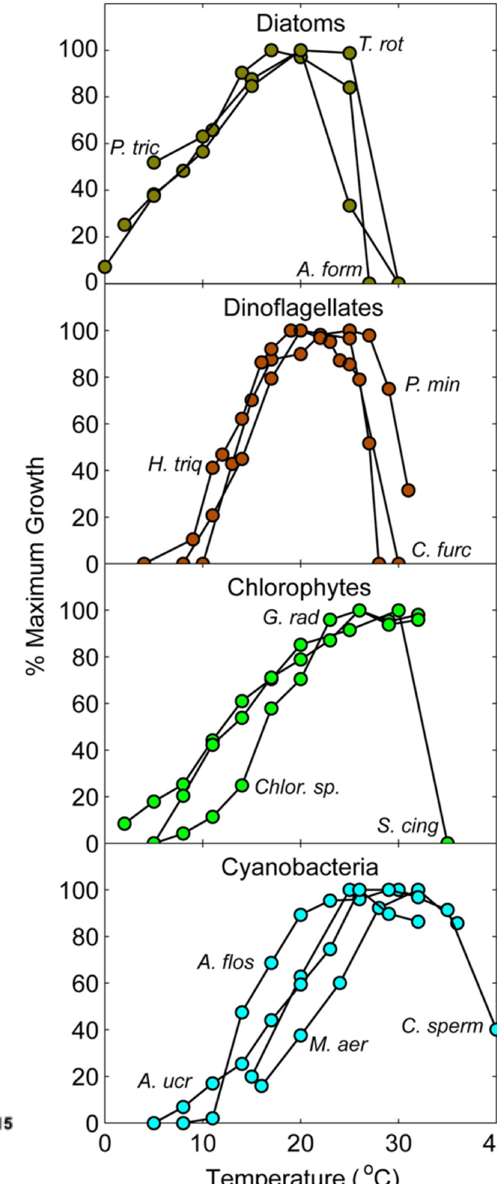
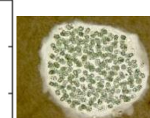


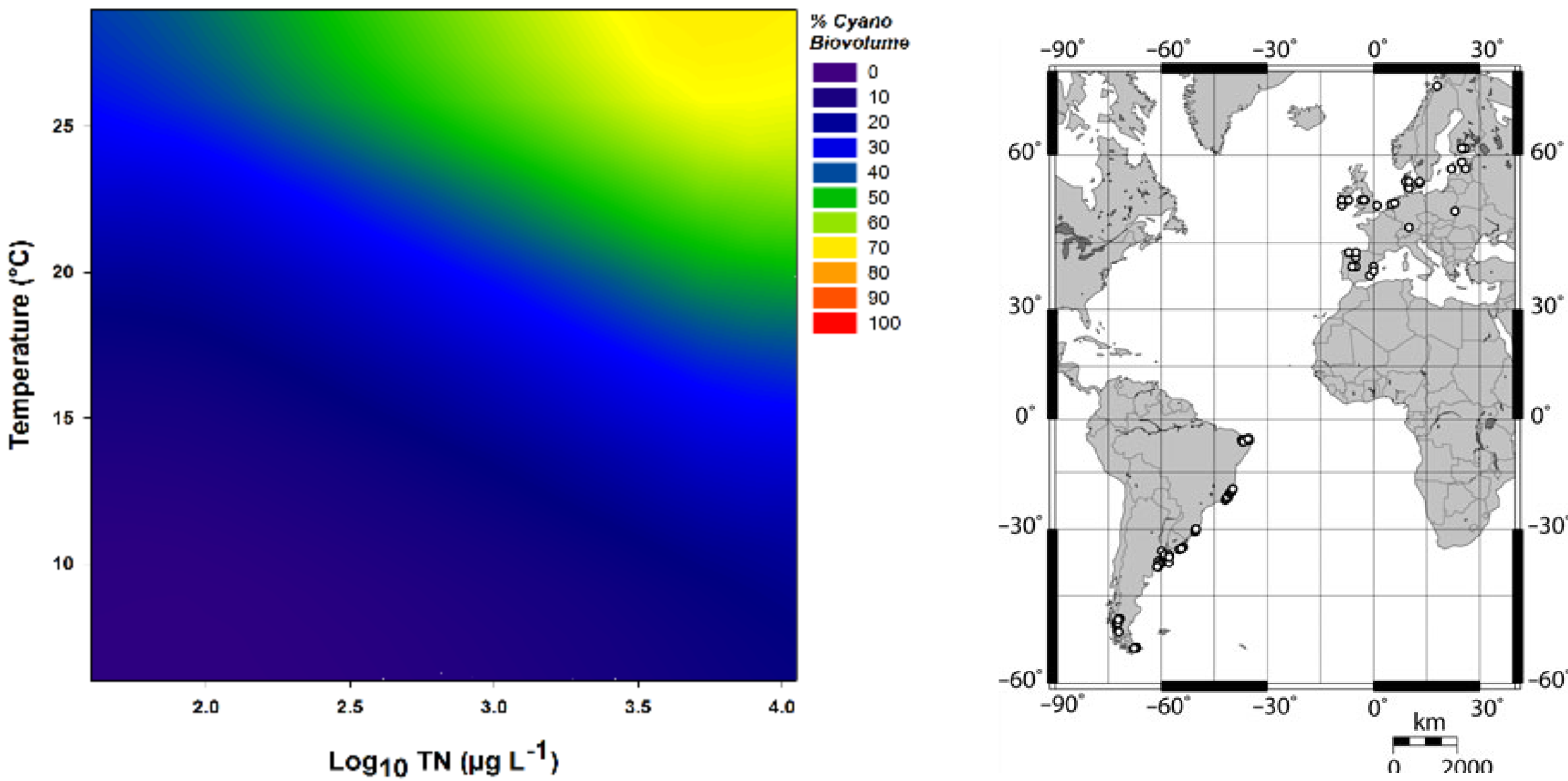
Fig. 8. Mean summer temperature in Lake Erie's western basin since 1983. Surface water temperatures for the western basin of Lake Erie have increased ~0.05 °C yr^{-1} (R^2 = 0.129, p = 0.066).

Lake Erie W. basin: Bullerjahn et al., 2016





Cyanobacterial dominance along temperature & nutrient (TN) 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.

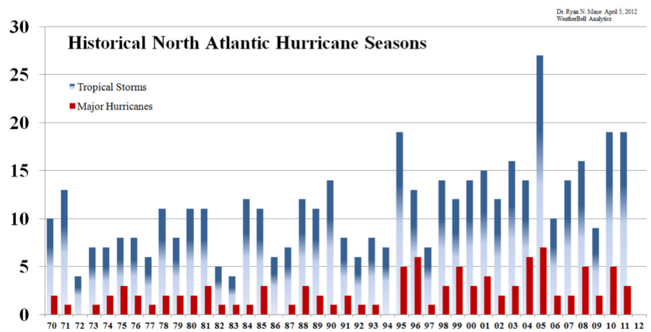
(a) Combined effects of temperature and nutrients as captured by a logistic regression model

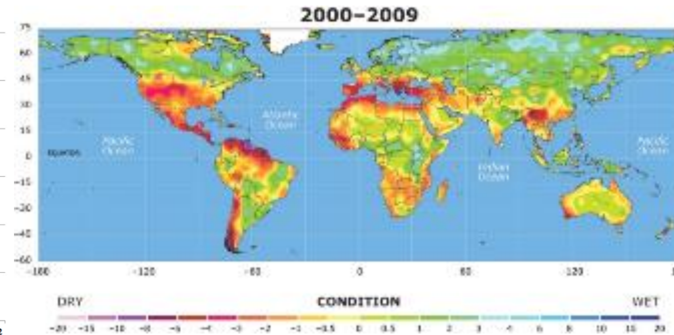
(b) Response surface obtained from interpolation of the raw data using inverse distance weighting.

Data replotted from Kosten et al. (2011). Global Change Biology DOI: 10.1111/j.1365-2486.2011.02488.x

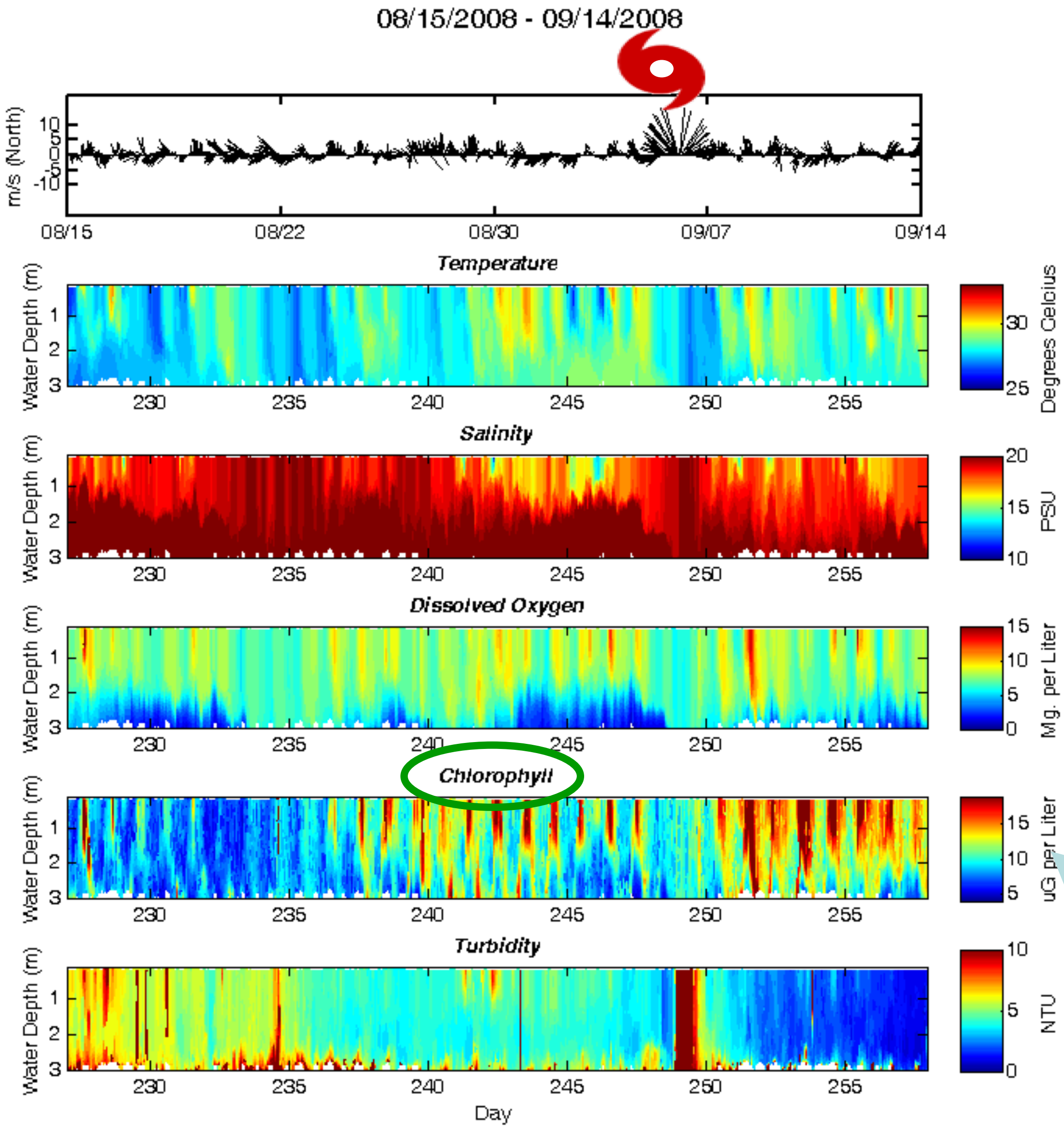
Hydrologically: Things are getting more extreme

- **Storms, droughts more intense, extensive & frequent**



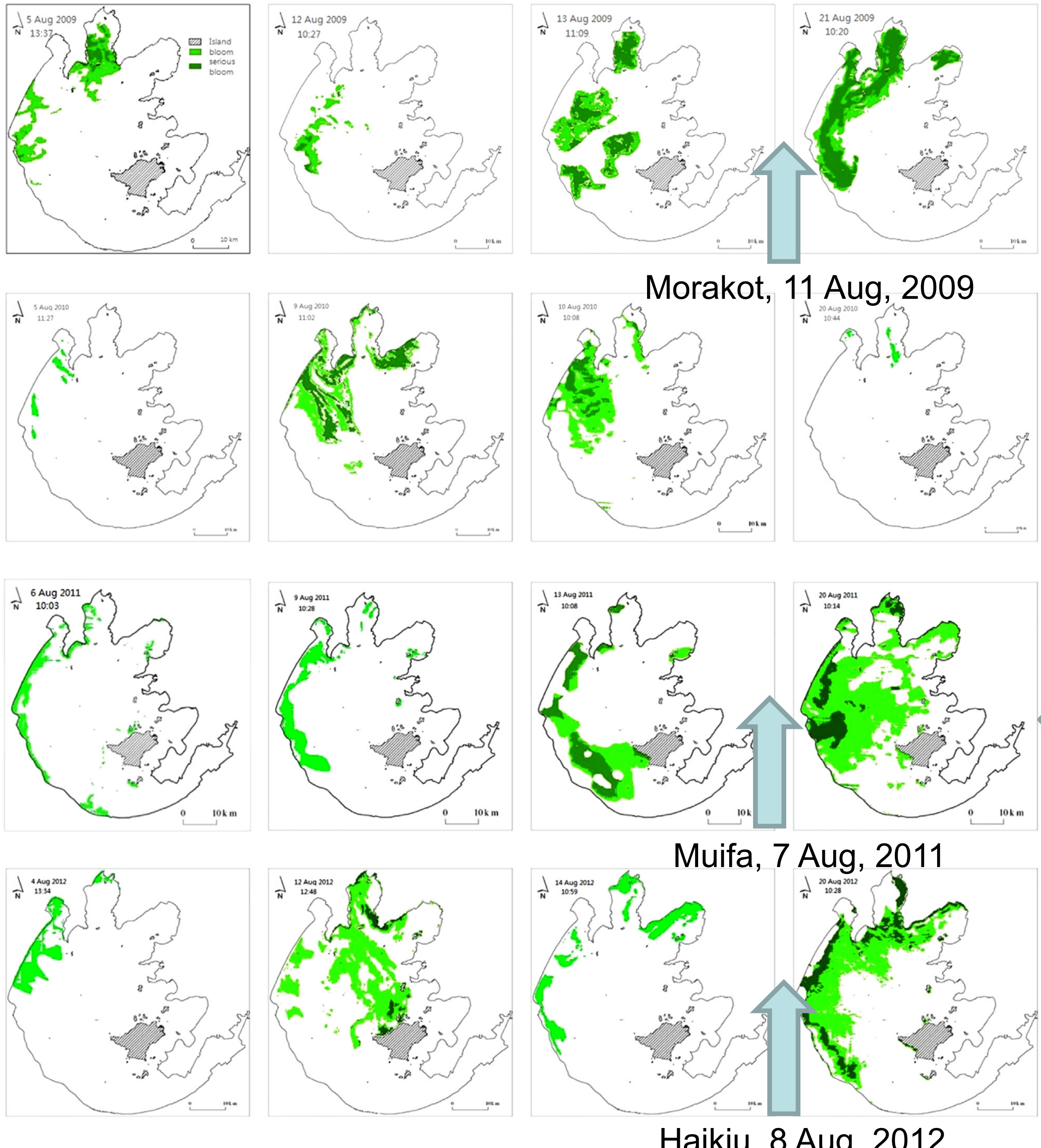


impacts of Tropical Storm Hanna (8/15/08 – 9/14/08) on The New River Estuary, North Carolina, USA



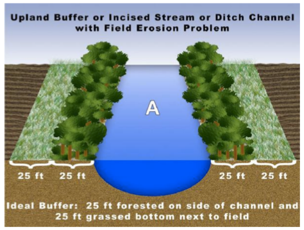
Impacts of Typhoon Passages on Cyano blooms in Lake Taihu, China, based on MODIS data

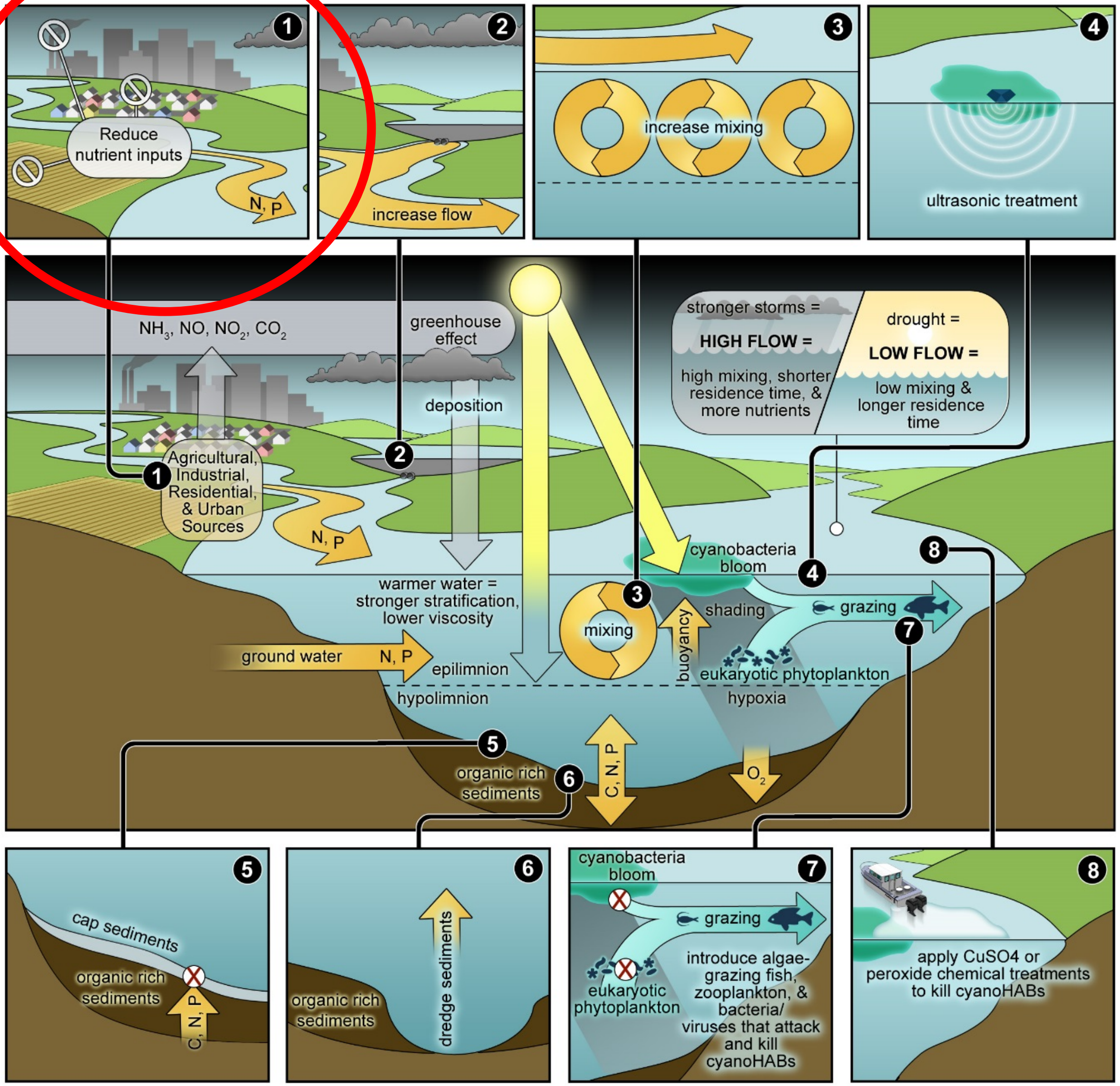
(Zhu et al., 2014)



So, in light of human and climatic drivers, what are the mitigation options?

The Nutrient "knob" Is one we can "tweek" in any mitigation effort



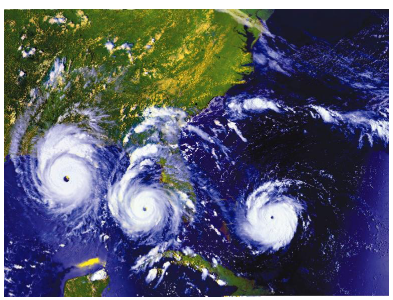


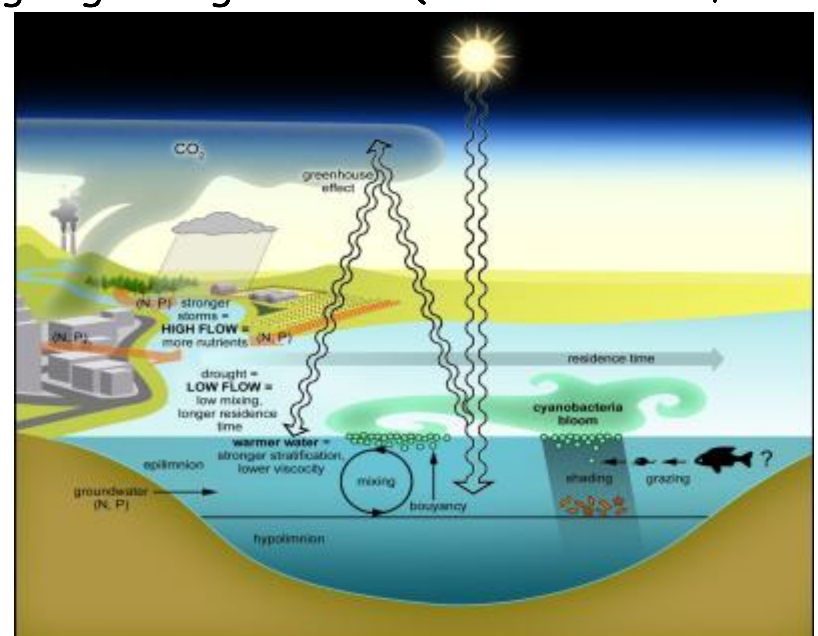
Conclusions/Recommendations for today and the future

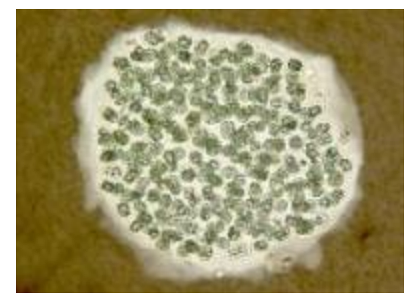
EPA United States Environmental Protection Agency | Office of Water | EPA - 820-S-15-001 | MC 4304T | February 2015

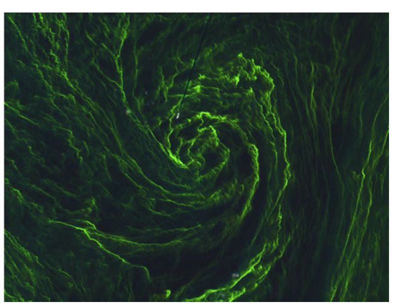
Preventing Eutrophication: Scientific Support for Dual Nutrient Criteria

- Reduce both N & P inputs in most cases
  - Nutrient-bloom threshold are system-specific
    - However, in many cases >30% reductions should be targeted
  - Salinity is not necessarily a barrier to CyanoHAB expansion
  - May need to reduce N and P inputs even more in a warmer, stormier world
    - Blooms "like it hot"
    - Episodic & extreme events favor CyanoHABs (typhoons, droughts)
- Impose nutrient input restrictions year-round
  - Residence time is long in many lakes,reservoirs and some estuaries (> 6 months)
  - Warmer, longer growing seasons (earlier ice off, later ice on)









Thanks to:

N. Hall
A. Joyner
Y. Li
T. Otten
B. Peierls
K Rossignol
S. Wilhelm
H. Xu
G Zhu
ModMon and
TLLER “crews”

THANKS

http://paerllab.web.unc.edu/research/cyanohabs

Special Thanks to:

* Lower Neuse Basin Assoc./Neuse River Compliance Assn.
* UNC Water Resources Research Institute
* NC Sea Grant

Additional support: Nanjing Instit. of Geography and Limnology, Chinese Academy of Sciences/NIGLAS, Ministry of Science & Technology