Guiding Principles for Preventing Cyanobacteria Blooms: Integrating Nutrient Limitation and Sediment Redox Science into Watershed Management

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Three important scientific principles can guide cyanobacteria management

Principle #1 (old)

Productivity and biomass can be lowered by lowering phosphorus inputs

- Well understood → Limiting nutrient principle
  - phyto biomass correlated with TP
  - whole-lake TP fertilization increases biomass (ELA)

- However, not understood until a few years ago why risk of cyanobacteria dominance over eukaryotic algae increases as P increases

Implications of Principle #1:

Lowering TP → lowers phytoplankton biomass and lowers *risk* of cyano dominance

- Blooms can occur at any TP and any TN concentration, but risk increases as nutrient concentrations increase. Some oligotrophic systems are dominated by cyanos (*Downing et al. 2001, Verschoor et al. 2017 CJFAS*).

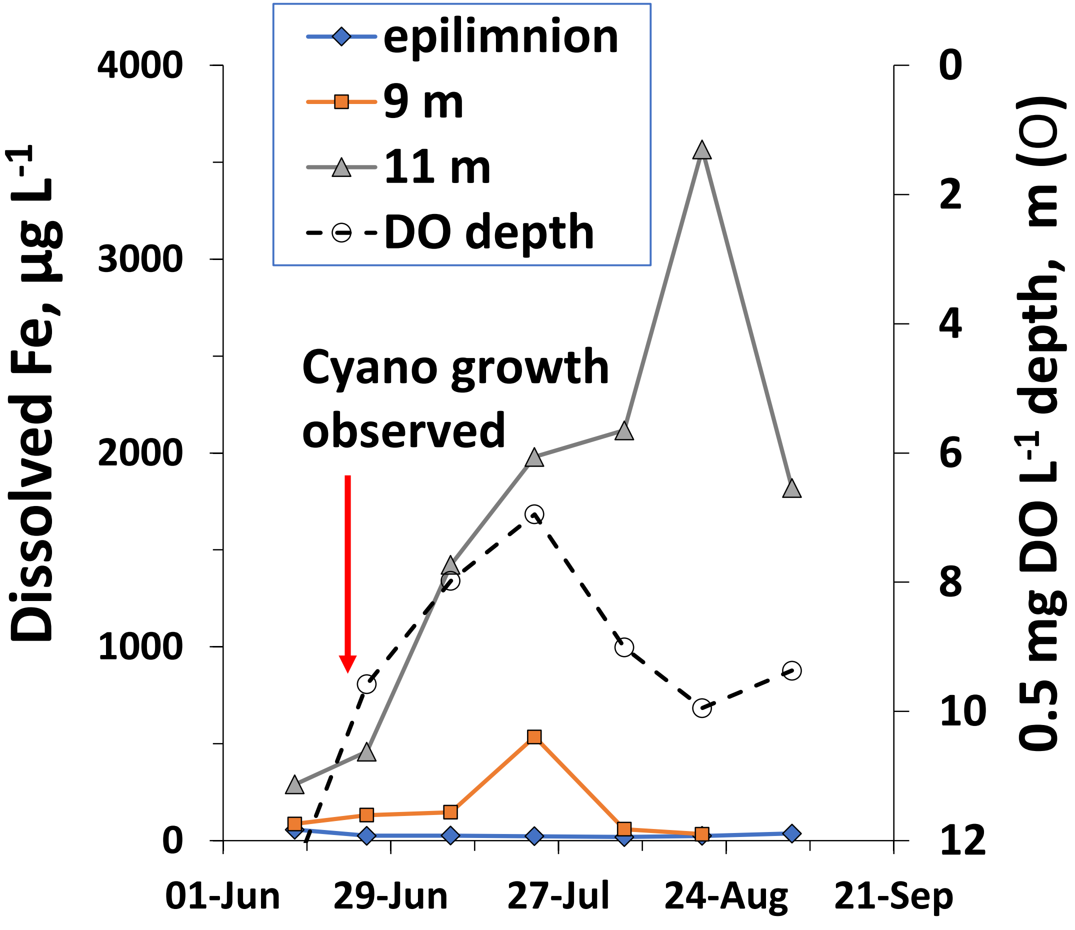
- What mechanism excludes cyanos from most oligotrophic systems <u>and</u> allows them to outcompete eukaryotic algae at higher TP?

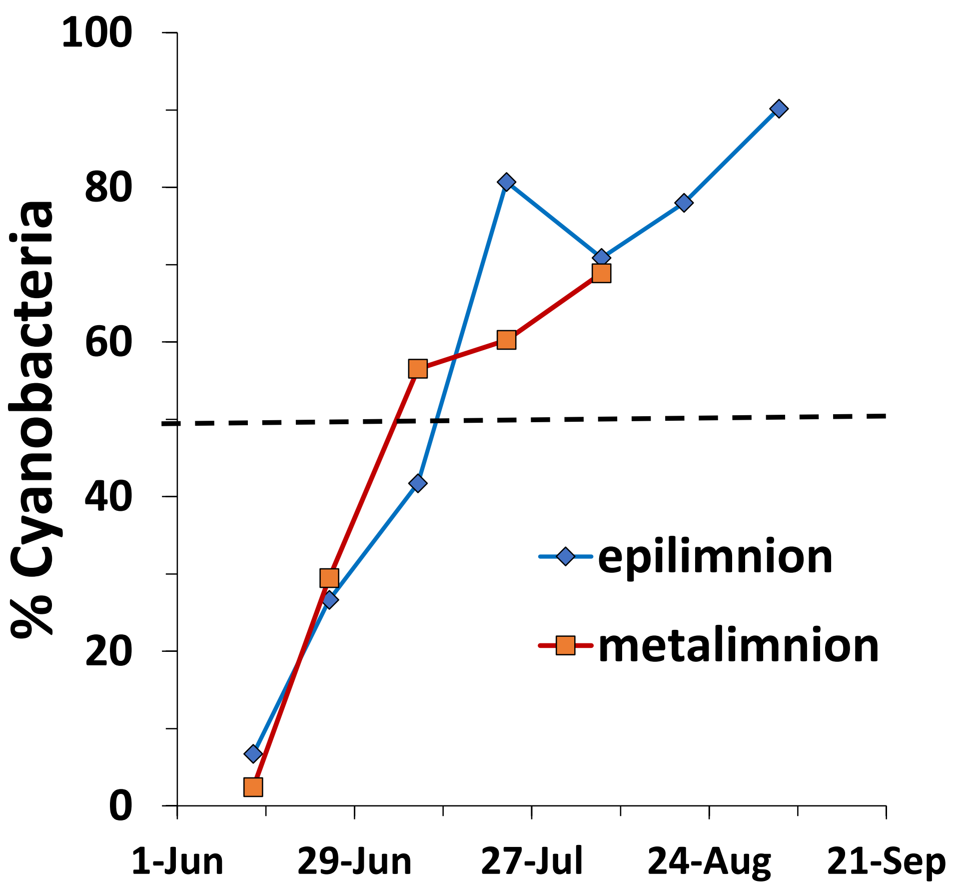
Principle #2 (new) **Release of ferrous iron, Fe(II), from anoxic sediments into overlying water triggers dominance of N_2-fixing and non-fixing cyanobacteria over eukaryotic competitors at any trophic status in warm waters** (Molot et al. 2014; Verschoor et al. 2017).

- Cyanos have higher Fe demand than eukaryotic algae but cannot transport only type of Fe found in oxidized waters, ferric iron (Fe(III)). Must reduce ferric Fe(III) to ferrous Fe(II) before transport across cell membrane. Eukaryotes can transport Fe(III).
- Biological reduction rate from Fe(III) to Fe(II) is slow so blooms require large source of accessible Fe(II) → supplied by diffusion of microbially reduced Fe into overlying waters from anoxic sediments (i.e., internal Fe loading).
- Internal Fe(II) loading into anoxic bottom waters only occurs when sediment redox falls below a level that permits microbial reduction of Fe(III) hydroxides.

Field evidence: Development of anoxia and release of Fe(II) from sediments ***always*** precedes cyano growth.

Has been observed in 6 lakes so far, including 2 oligotrophic lakes.





eutrophic Sturgeon Bay 2012

Implication of Principle #2:

no sediment anoxia → no cyano dominance

This means that blooms can be prevented if oxygen concentrations in surficial sediments are maintained at, say, > 2 mg/L throughout a lake in waters shallower than their maximum ability to migrate → which might be about 14 m depth

Principles #1 and #2 are inter-related

Primary management tool of lowering P loading from point and non-point sources works because…

- it lowers phytoplankton productivity & population size
- lower productivity lessens risk of developing sediment anoxia which lessens risk of cyanobacteria dominance

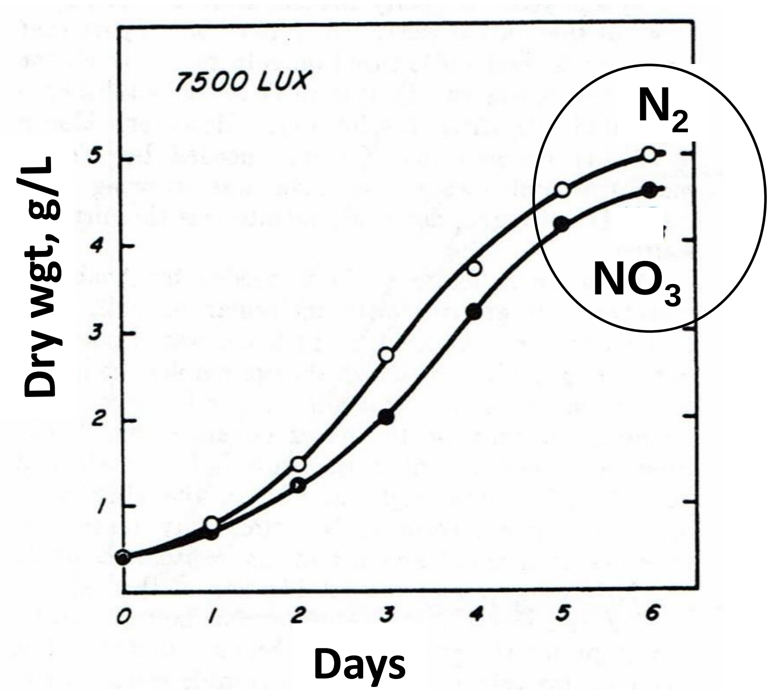
and…

Other methods that lower oxygen consumption and/or raise sediment redox might be effective *supplemental* management methods in specific cases…

- aeration of smaller systems with effective distribution of DO to sediments
- others…

<u>Principle #3</u> (newer) **Whole-lake (L227) and bench top N removal experiments show that N_2 fixation is efficient.** Therefore, blooms <u>cannot be starved of N</u> when trace metal cofactors for N_2 fixing enzyme (nitrogenase) are sufficient because N_2 pool is inexhaustible. Metal cofactors, Mo and Fe, are critical to nitrogenase activity. (*<u>Molot 2017, Environ Reviews</u>*).

Anabaena cylindrica



Ref: Allen and Arnon (1955)

NO_3 removal has negligible impact on growth rate and maximum yield in metal replete batch culture.

4 similar NH_3 and NO_3 removal experiments in batch culture have been published.

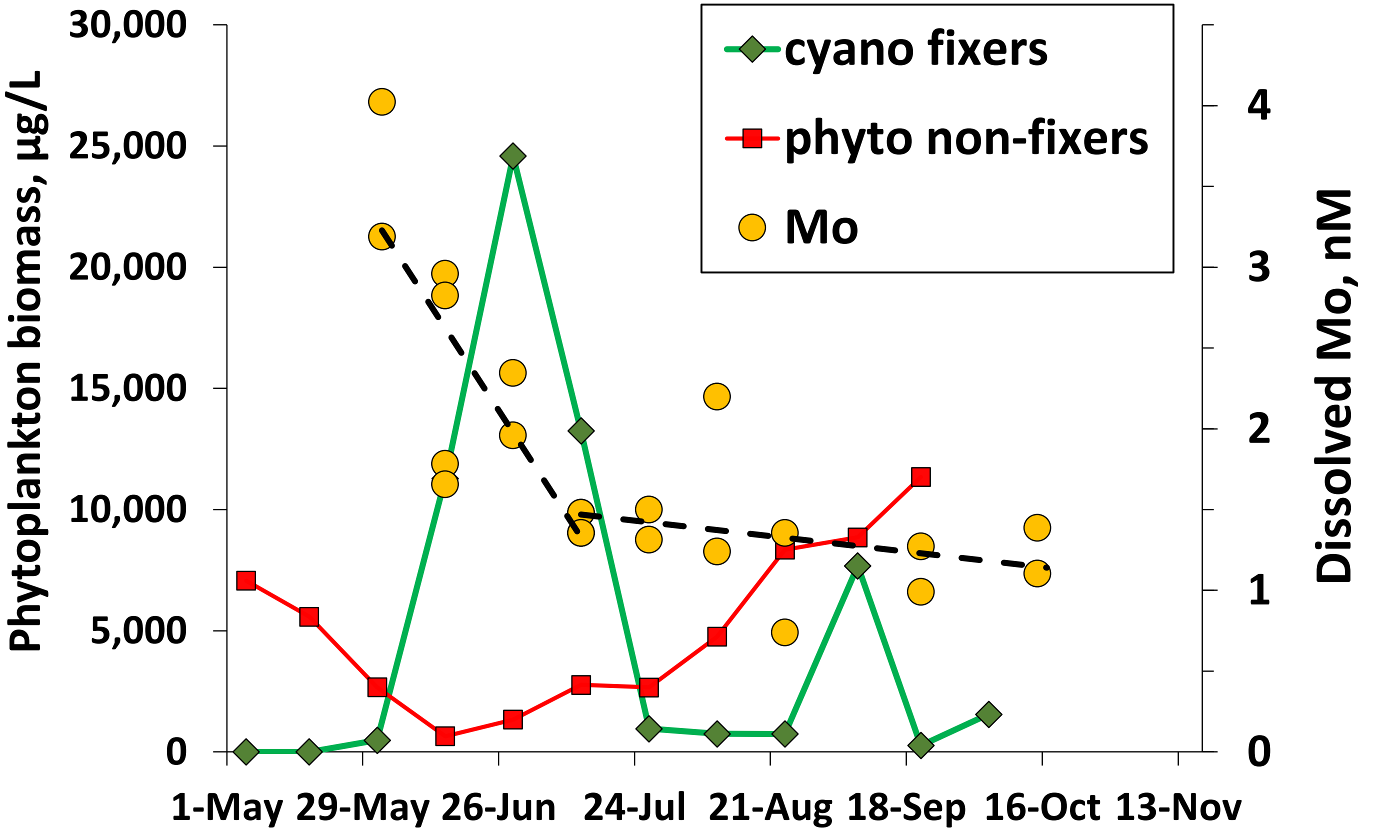
N_2 fixers compensate by altering biochemical composition when N_2 is only source of N: less N-rich protein and more N-poor lipids and carbohydrates. May explain decline of nitrogenous cyanotoxins under N-limitation.

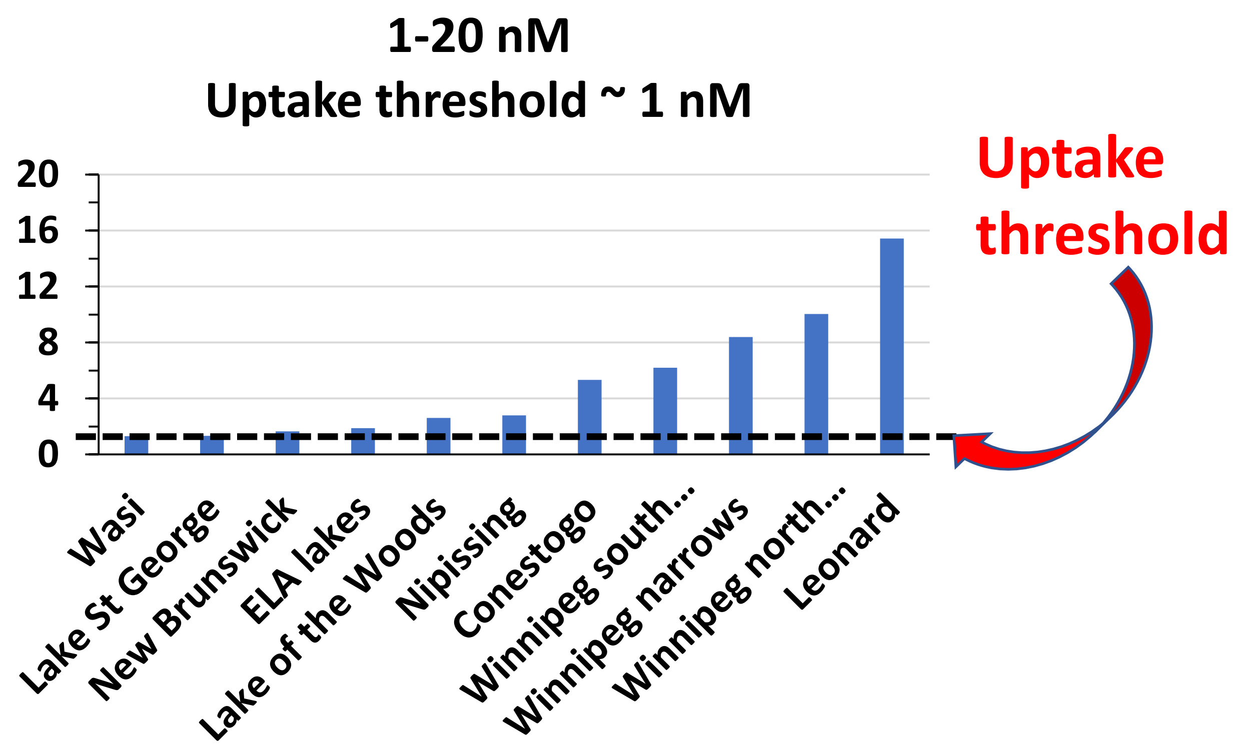
N_2 fixation is efficient but might be resource limited. Do some lakes have Mo and Fe levels low enough to limit amount of fixed N_2?

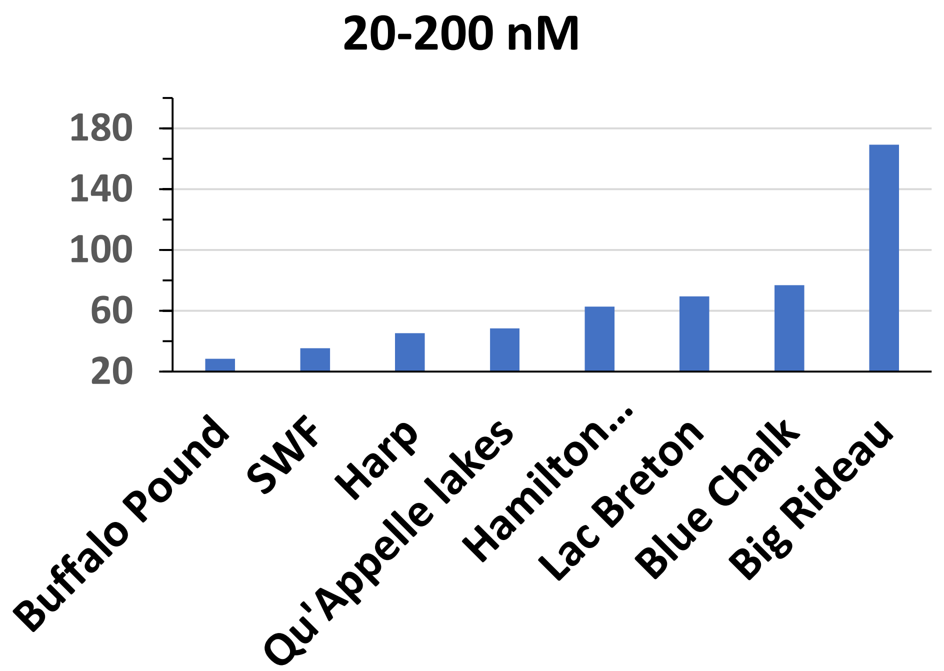
Mo might limit cyanos in N-limited, P-fertilized Lake 227 in Experimental Lakes Area (ELA):

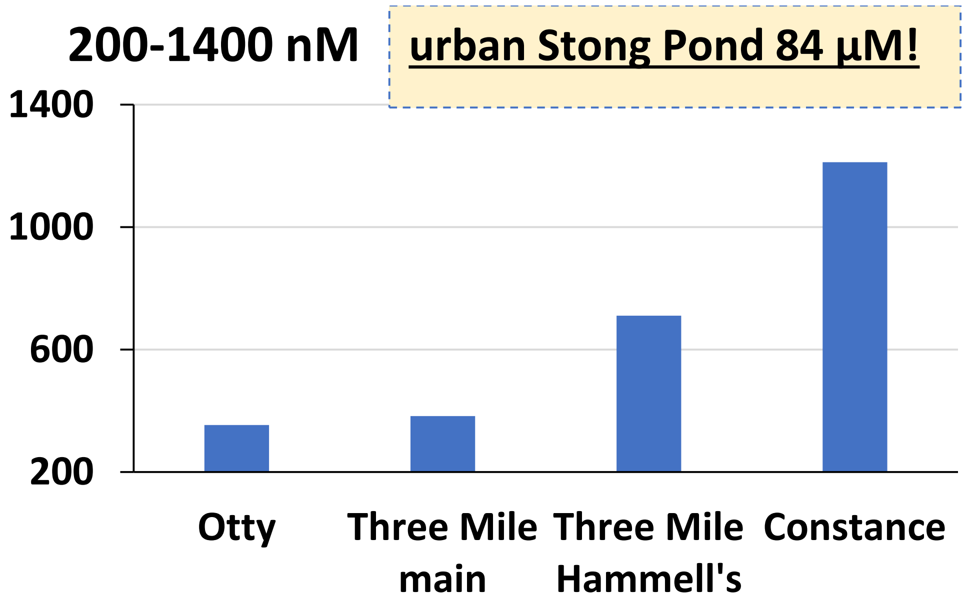
- N_2-fixing *Aphanizomenon* bloom occurs most years for about 4 weeks, from mid-June to mid-July.
- High growth rate for 2 weeks. Pop'n increased **51 fold** in 2 weeks in 2010 – doubled every 2.5 days.
- Bloom shuts down as total Mo approached 1.5 nM (approx. uptake threshold) ending before lake reaches warmest temp.

Rapid loss of total Mo in Lake 227 epilimnion from 3.5 to 1.5 nM during bloom in 2010







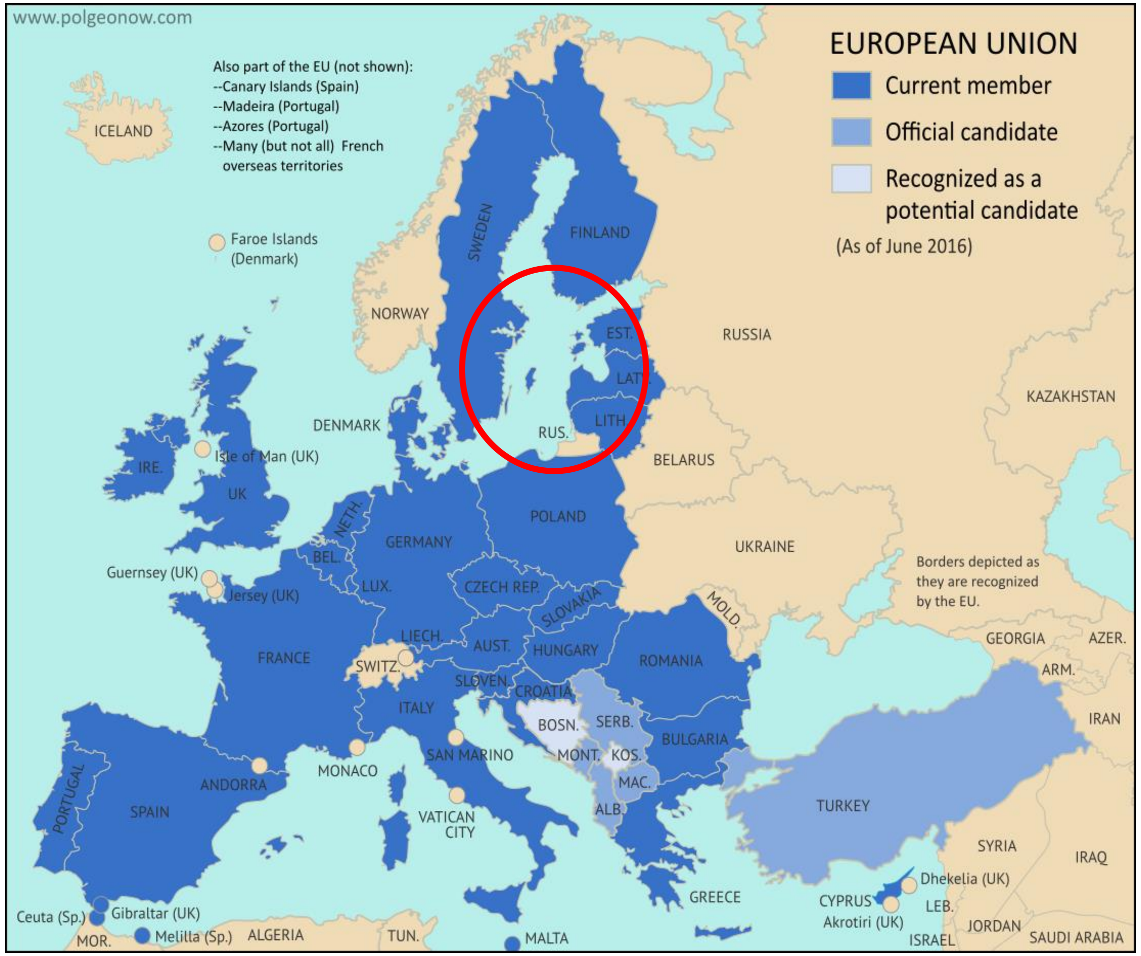


Dissolved Mo in Canadian surface waters ranged 1-1200 nM with 84 µM in an urban storm retention pond. Affected by…

- *Mo mineralogy*
- *urbanization and industrialization*, e.g., Mo levels in Erie sediments have doubled since 1850.

N_2 fixation limited by P in N-limited Baltic Sea despite EU N Removal Directive

- Baltic Sea is N limited with blooms dominated by N_2 fixers.
- N_2 fixation is mostly P-limited with occasional metal limitation (not Fe or Mo) in nutrient enrichment bottle assays (*Moisander et al. 2003 and 2007*).
- So… eukaryotic portion of Baltic is N limited but cyanos are not.
- Baltic cyano management programs might do better to focus on ways of maintaining DO > 2 mg/L at sediment/water boundary, especially in coastal areas.



<u>Implications of Principle #3</u>

Blooms of N_2 fixers cannot be prevented or mitigated by N starvation unless Mo or Fe levels are extremely low.

However, Mo levels in P-fertilized, N-limited Lake 227 are among the lowest in Canada, it has no anthropogenic N, yet bloom lasts <u>1 month</u>

If Lake 227 was a managed watershed in a highly populated, industrialized watershed instead of an experimental lake, with higher Mo and say, 75% of anthropogenic N removed rather than 100%: bloom would probably last <u>several months</u>

Managing N based only on its status as a macronutrient greatly increases risk of N removal policy <u>failure</u>

These three scientific principles allow us to apply two basic questions to any management program

1) How will a proposed management program affect phytoplankton productivity, *e.g., bloom size* (leaving aside species composition for the moment)?

2) How will a proposed management program affect DO consumption and sediment redox which will affect duration of cyano bloom?

   Will redox be high enough to prevent cyano dominance?

   How long will anoxia/low redox episode last?

With these principles, we can develop a hierarchy of watershed management approaches that optimize cyano bloom mitigation and allocation of resources

1. WWTP's must continue to focus on P removal with loads designed to maintain DO at, say, > 2 mg/L **at sediment/water boundary**, not just protect fish habitat.
2. If point source P loading remains too high to suppress cyano blooms using current technology, additional funds could be allocated to suppress blooms with other approaches *but cost/benefit studies are needed.*

WWTP's:

(i) Installation of next generation (but expensive) P treatment technologies in WWTP's is an option, e.g., membrane technology.

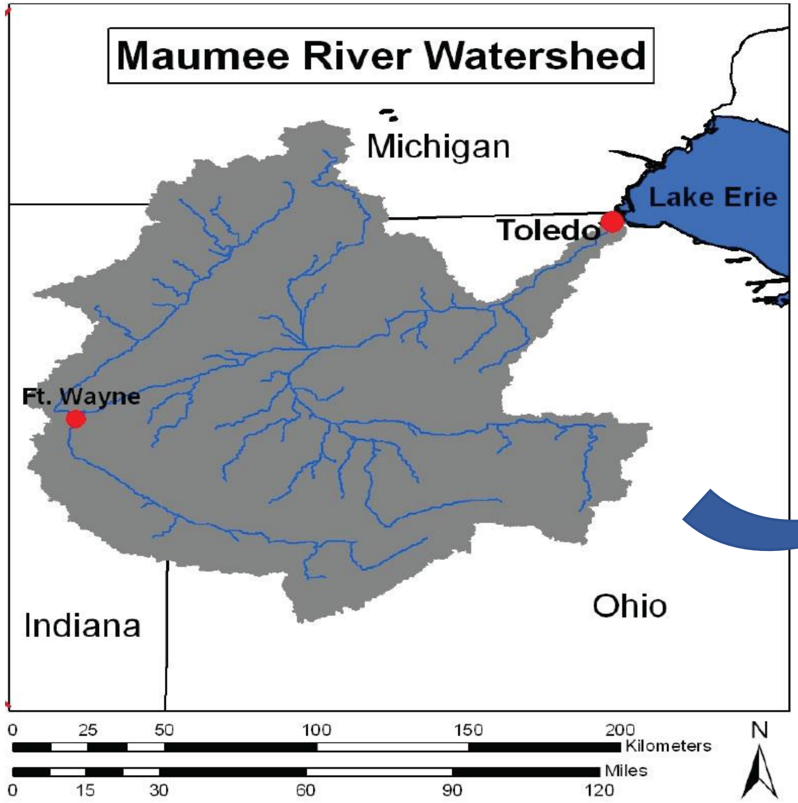
(ii) If WWTP discharges of BOD and ammonia are relatively large, investments in treatment may be warranted.

Non-point sources:

(iii) Investments in urban and agricultural BMP programs to lower export of P

Managing Lake Erie

Incidence of *Microcystis* blooms has increased in Lake Erie since mid 1990s although TN has declined and TP stabilized. Why?



Majority of P loading is from diffuse sources, not WWTP’s. Management attention shifting to BMPs.

What drivers are responsible for the increased incidence of blooms in Erie since the mid 1990s?

- **Total P** concentration declined after 1975 but has been ‘stable’ since 1995, fluctuating around 9 to 19 µg/L.
- **N** export to lake, and lake **TKN** and **nitrate** conc’ns have declined. Most N is nitrified before it reaches the lake.
- Metal levels in sediments have increased since settlement → Mo and Fe have doubled.

Changes in N and P probably not responsible for resurgence…so, what is?

Climate change?

- warm waters are optimal for growth but nutrients are needed. Are surface waters **warmer**, especially inshore areas which appear to be nurseries?
- has longer ice-free season increased spatial and temporal extent of episodic **anoxia** inshore?

SO_2 emission controls?

- Has the 75% decline in sulfide accumulation rate in sediments (as AVS) since 1980 allowed higher internal Fe(II) loading?

Thank you