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

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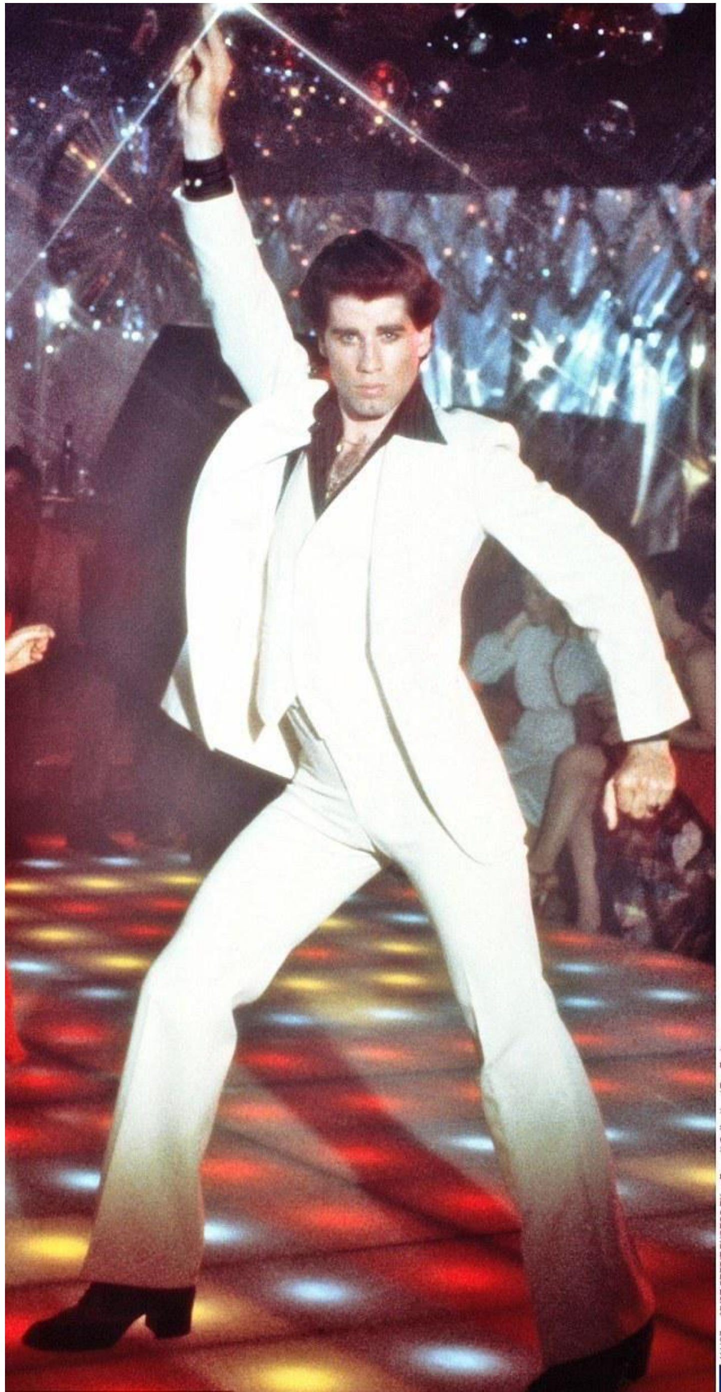


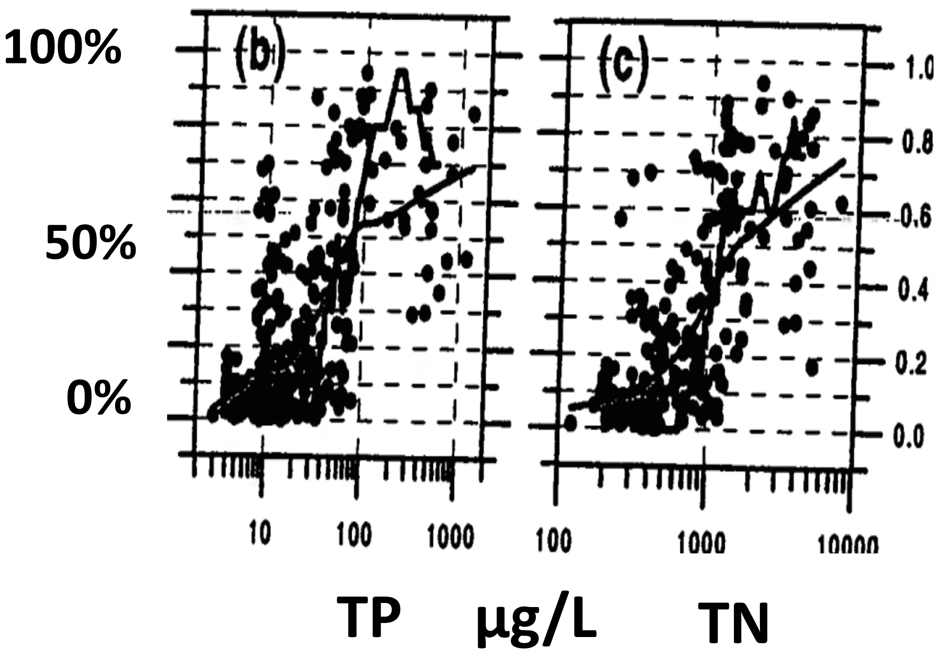
Four important scientific principles can guide cyanobacteria management

Principle #1 (old)   Low phosphorus (P) concentrations and inputs ensure low aquatic productivity and biomass.

- Well understood → P acts as a fertilizer in most oligotrophic freshwaters
- Not all eutrophic lakes are P-limited BUT P is only nutrient with natural, background levels low enough in most lakes to be focus of nutrient control program

❖ But increased productivity with P fertilization does <u>not</u> explain why risk of cyanobacteria dominance over eukaryotic algae increases as P increases

% of systems dominated by cyanobacteria, i.e., risk of cyano dominance



(Downing et al. 2001)

- Blooms can occur at any TP and any TN concentration, although risk increases as nutrient concentrations increase. Some oligotrophic systems are dominated by cyanos (e.g., several embayments along Georgian Bay; Verschoor et al. 2017 CJFAs) although most typically are not.

- Leaves us with question: What mechanism excludes cyanos from most oligotrophic systems <u>and</u> allows them to outcompete eukaryotic algae at higher TP *and* in some oligotrophic systems?

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 across trophic status range
(Molot et al. 2014; Verschoor et al. 2017)

Cyanos have higher Fe demand than eukaryotic algae.

Cyanobacteria cannot transport the oxidized form of Fe, ferric or Fe(III), which is virtually the only type found in oxygenated waters, across their cell membrane without first reducing it to Fe(II) but re-oxidation to Fe(III) before transport is rapid. Eukaryotes can transport ferric Fe(III).

- Results in Fe limitation of large cyano species in oligotrophic waters but not eukaryotes

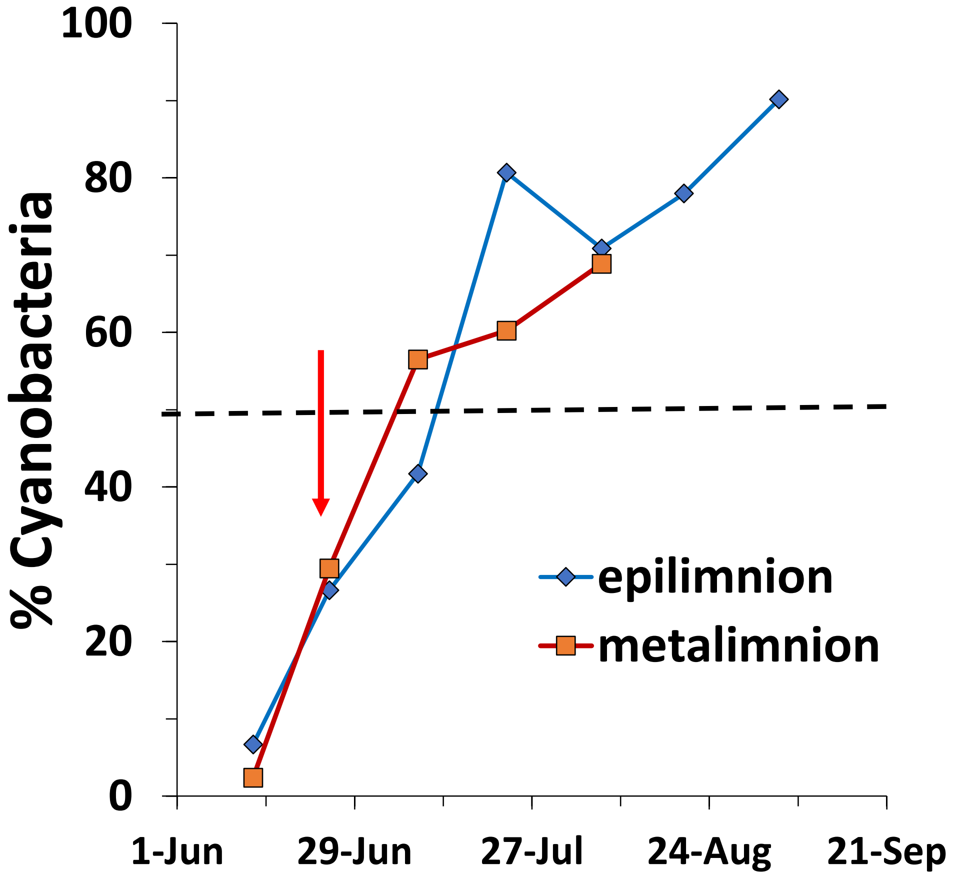
- Internal loading of Fe(II) from anoxic sediments provides large source of Fe(II) that does not need to be reduced first.

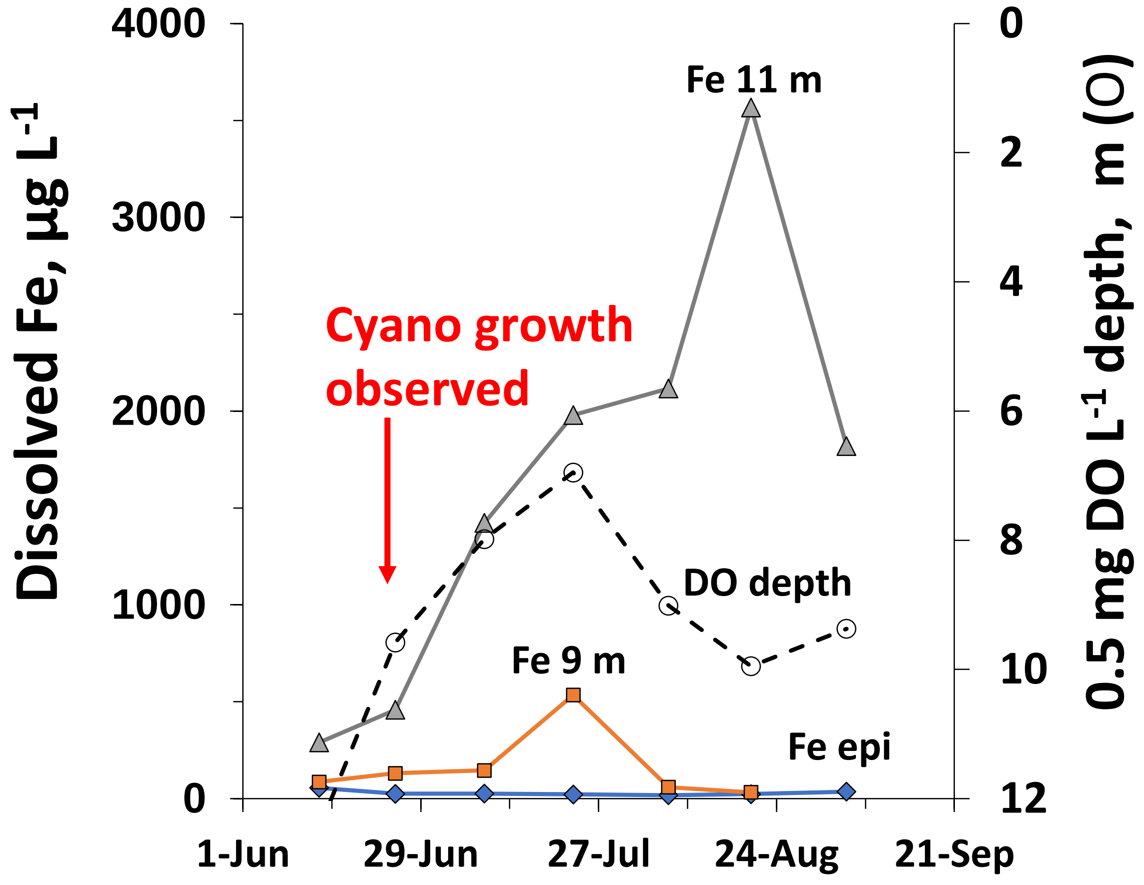
- Depletion of dissolved oxygen and nitrate at sediment/water boundary leads to
  → low surficial sediment redox
    → microbial reduction of solid Fe(III) hydroxides with Fe(II) release into overlying waters (internal Fe(II) loading)
      → bloom formation in warm waters

Important sequence: sediment anoxia → internal Fe(II) loading → bloom

Development of anoxia and release of Fe(II) from sediments *always* precedes cyano growth. Sequence: *anoxia → Fe(II) release → blooms* has been observed in 7 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 are maintained, say, > 2 mg/L in surficial sediments in waters shallower than approximately 12 m depth (or whatever is cyanobacteria maximum migration depth)

Principles #1 and #2 are inter-related

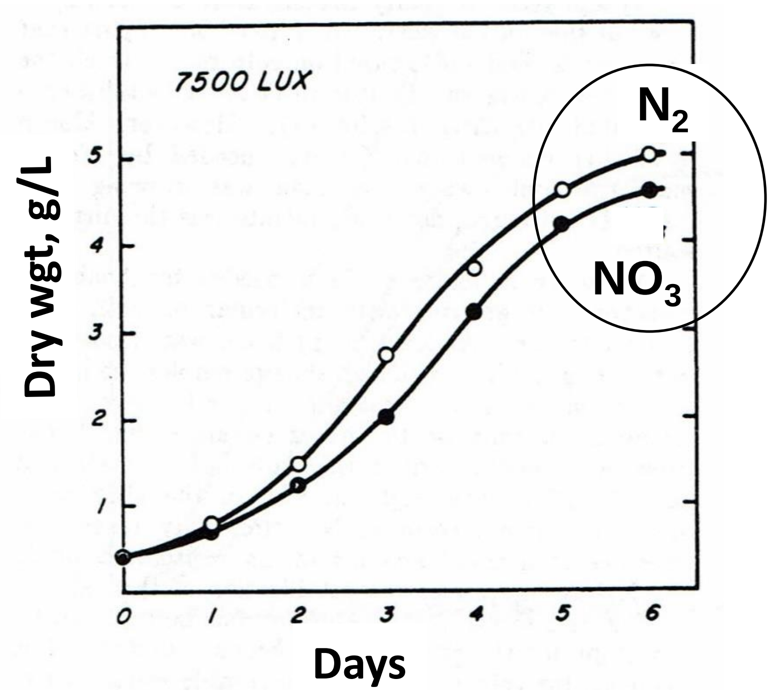
Primary management tool of lowering P loading works because…

- it lowers phytoplankton productivity which lowers risk of developing sediment anoxia → lower risk of cyanobacteria dominance.

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

Principle #3 (newer) **Bench top N removal experiments and Lake 227 experiment show that blooms cannot be starved of N when trace metal cofactors Fe and Mo for nitrogenase (N_2 fixing enzyme) are sufficient because N_2 pool is inexhaustible** (*Molot 2017, Environ Reviews*). **N_2 fixation is an efficient process.**



Ref: Allen and Arnon (1955)

NO_3 removal has negligible impact on growth rate and maximum yield in metal replete batch culture of N_2-fixing *Anabaena cylindrica*
(1 of 4 similar N removal studies in batch culture)

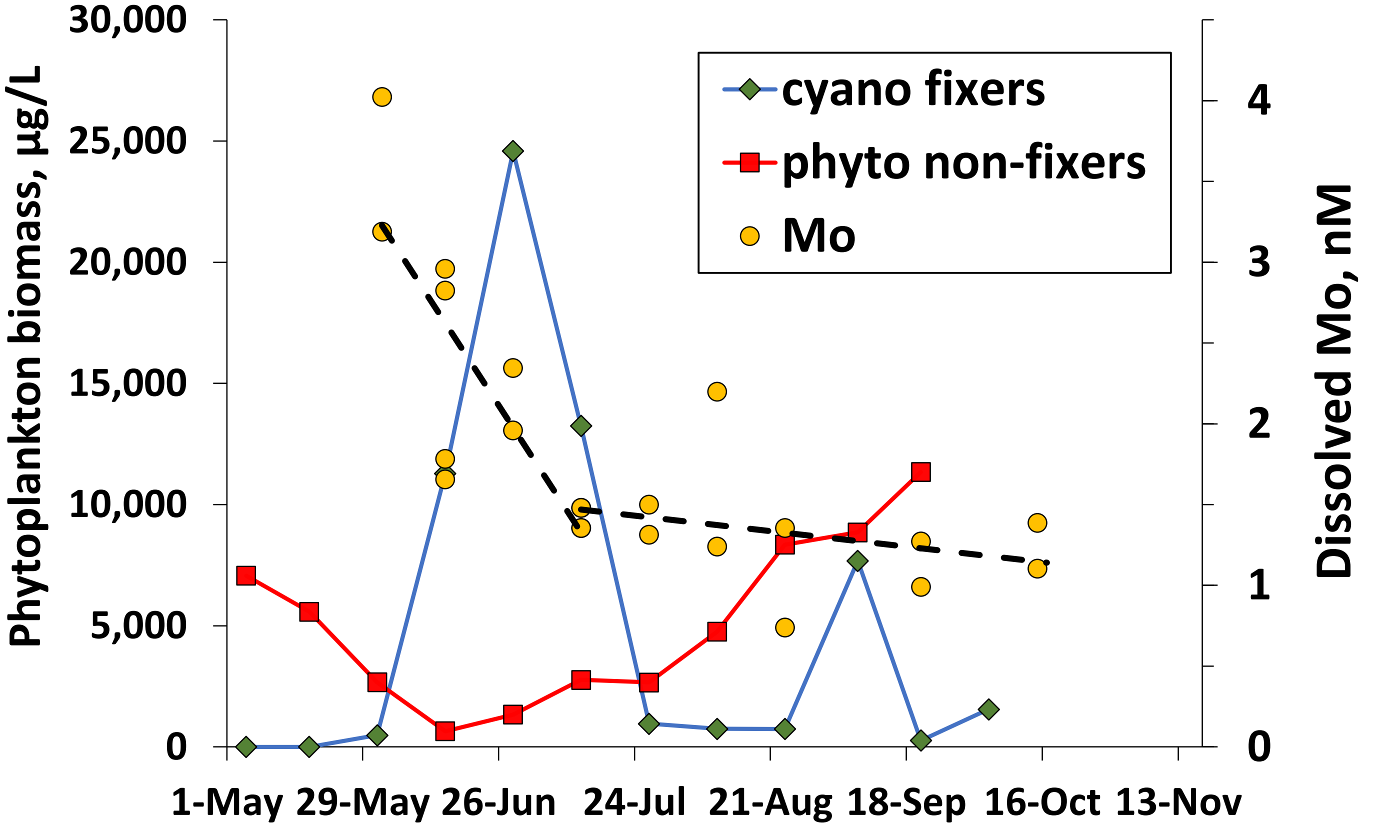
N_2 fixers alter their biochemical composition to 'conserve' N when N_2 is only source of N: less N-rich protein and more N-poor lipids and carbohydrates. May explain decline of nitrogenous cyanotoxins under N-limitation

In N-limited lakes, N_2 fixation is efficient but fixation can be resource limited, i.e., can run out of Mo, Fe or P

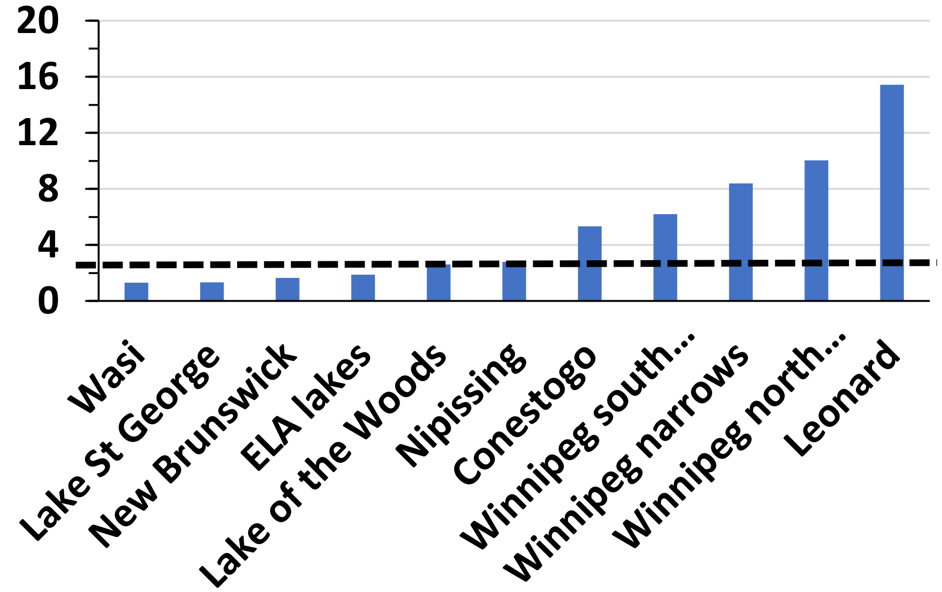
Mo might limit cyanos in N-limited, P-fertilized Lake 227 in Experimental Lakes Area (ELA):

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

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

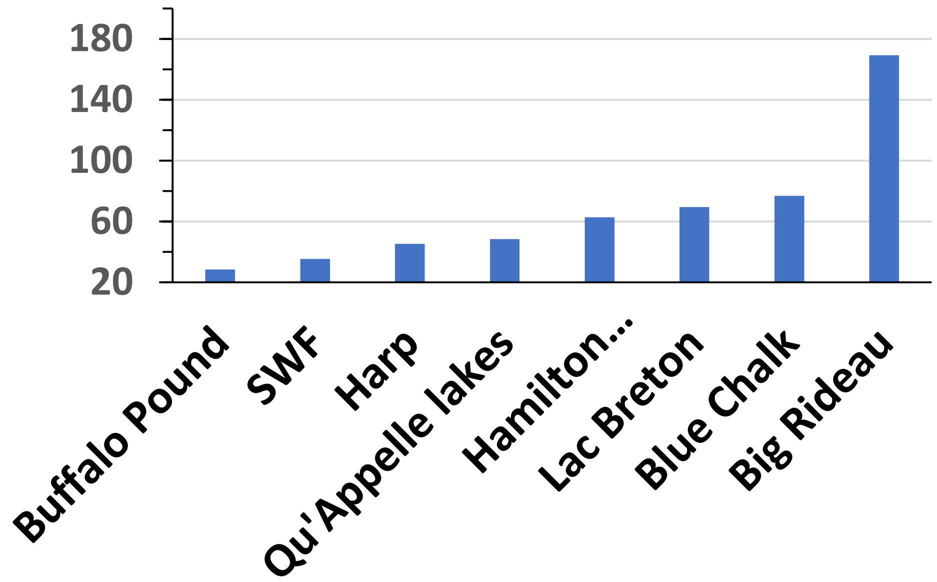


1-20 nM
Uptake threshold 1-5 nM

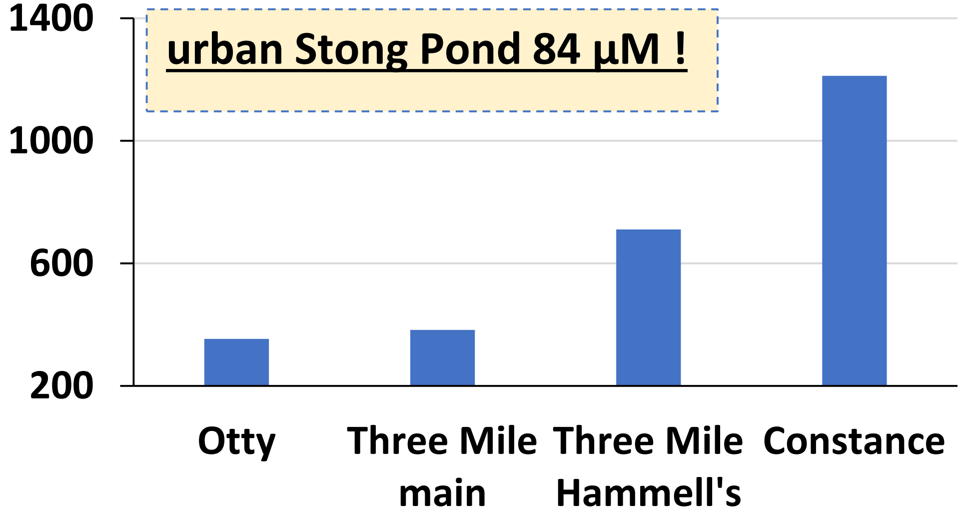


Uptake threshold

20-200 nM



200-1400 nM

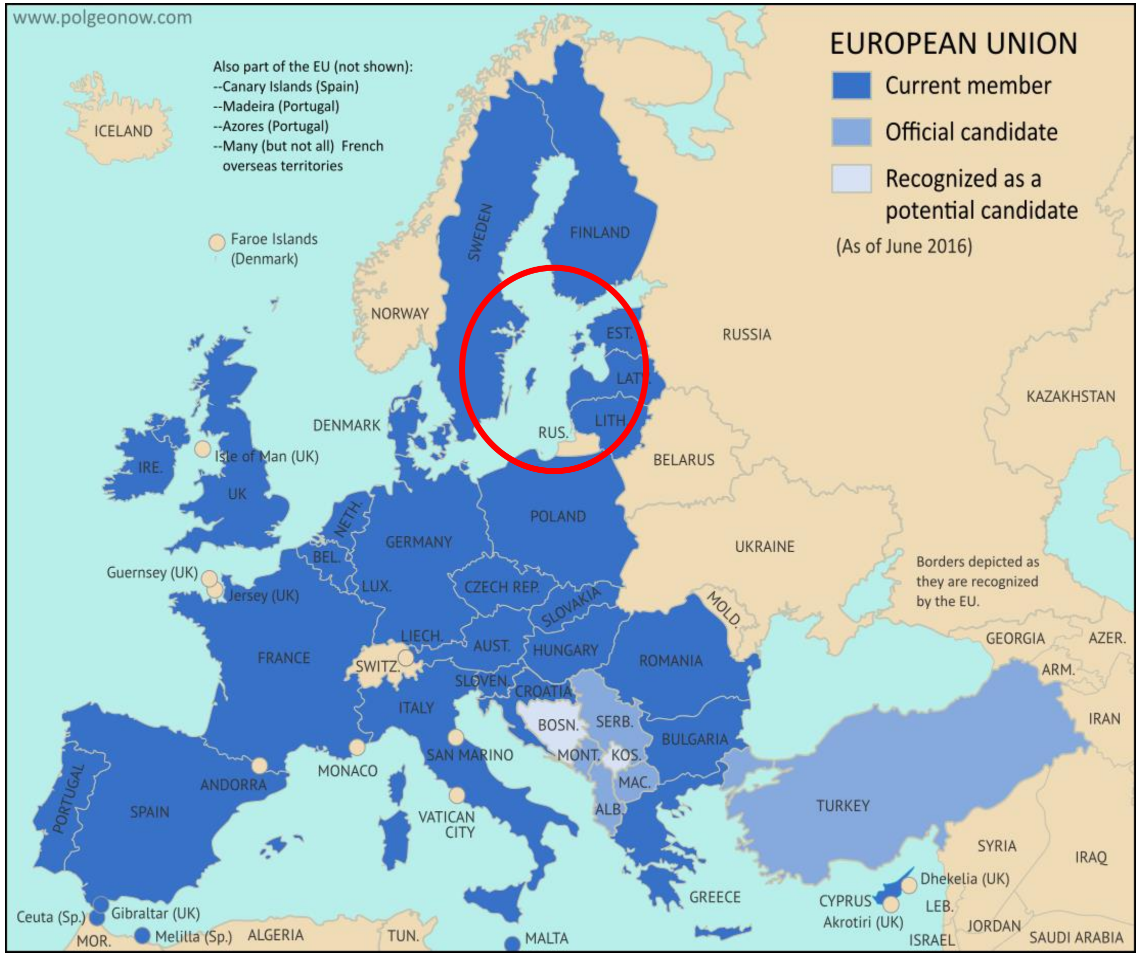


Dissolved Mo in Canadian surface waters ranged 1-1200 nM with 84 µM in an urban storm retention pond. Affected by…

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

Cautionary tale: N_2 fixation limited by P in N-limited Baltic Sea despite EU Directives to remove N

- Baltic is brackish (10% North Sea water which has high Mo) with blooms of cyano N_2 fixers – *Aphanizomenon, Nodularia* with less dominant *Anabaena* (aka *Dolichospermum*).
- N_2 fixation is mostly P-limited with occasional metal limitation (but not by Fe or Mo cofactors) in nutrient enrichment bottle assays (*Moisander et al. 2003 and 2007*).
- Baltic fixers are not Mo-limited → intruding Mo-rich ocean water (105 nM) and rivers provide adequate Mo
- Further N removal will not affect blooms unless metals are very close to limiting levels



Implications of Principle #3

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 annual bloom lasts 1 month and is still green 30 years after cessation of N fertilization.

Imagine if Lake 227 was not an experiment but a managed system in a highly populated, industrialized watershed like Erie or Taihu (China) with higher Mo and say, 75% of anthropogenic N removed rather than 100%: bloom would probably last several months

Managing/removing N to prevent blooms based only on its status as a macronutrient greatly increases risk of expensive policy failure

Principle #4 (new) Changing climate will promote cyanobacteria blooms, especially in temperate regions.

1. Optimal growth rates for many cyano species are between 25-30^{o}C but sediment anoxia still necessary pre-condition…
2. Higher temperatures promote higher microbial decomposition rate which increases risk of developing anoxia at the sediment/water boundary.
3. Longer ice-free seasons in thermally stratified temperate lakes result in longer O_2 depletion periods thereby increasing risk of late summer/fall hypolimnetic anoxia.
4. Anoxic episodes at sediment/water boundary may become more frequent and last longer in shallow, well mixed (polymictic) systems as air temperatures increase earlier, waters become warmer and lower wind speeds become more frequent (*untested hypothesis*).
5. Higher runoff volumes during spring melt in temperate latitudes and larger summer storms will export larger amounts of P, N and trace metals to lakes resulting in larger and longer lasting blooms once anoxia is re-established.

Implications of Principle #4

If climate change increases spatial and temporal extent of sediment anoxia, TP loading targets will have to be adjusted downward to reduce risk of developing anoxia

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

1) **Will a proposed management program lower phytoplankton <u>productivity</u>, *e.g., cell density* (leaving aside species composition for the moment)?**

2) **Will a proposed management program lower DO consumption and raise <u>sediment redox</u>?**

    ***Will redox be high enough to prevent internal Fe(II) loading*?**

    How long will anoxia/low redox period 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 lowering P, BOD & COD with loads designed to maintain DO at, say, > 2 mg/L at sediment/water boundary (will protect fish habitat).
2. If loads remain too high to suppress cyano blooms using WWTP current technology, additional funds could be allocated for other approaches *but cost/benefit studies are needed.*

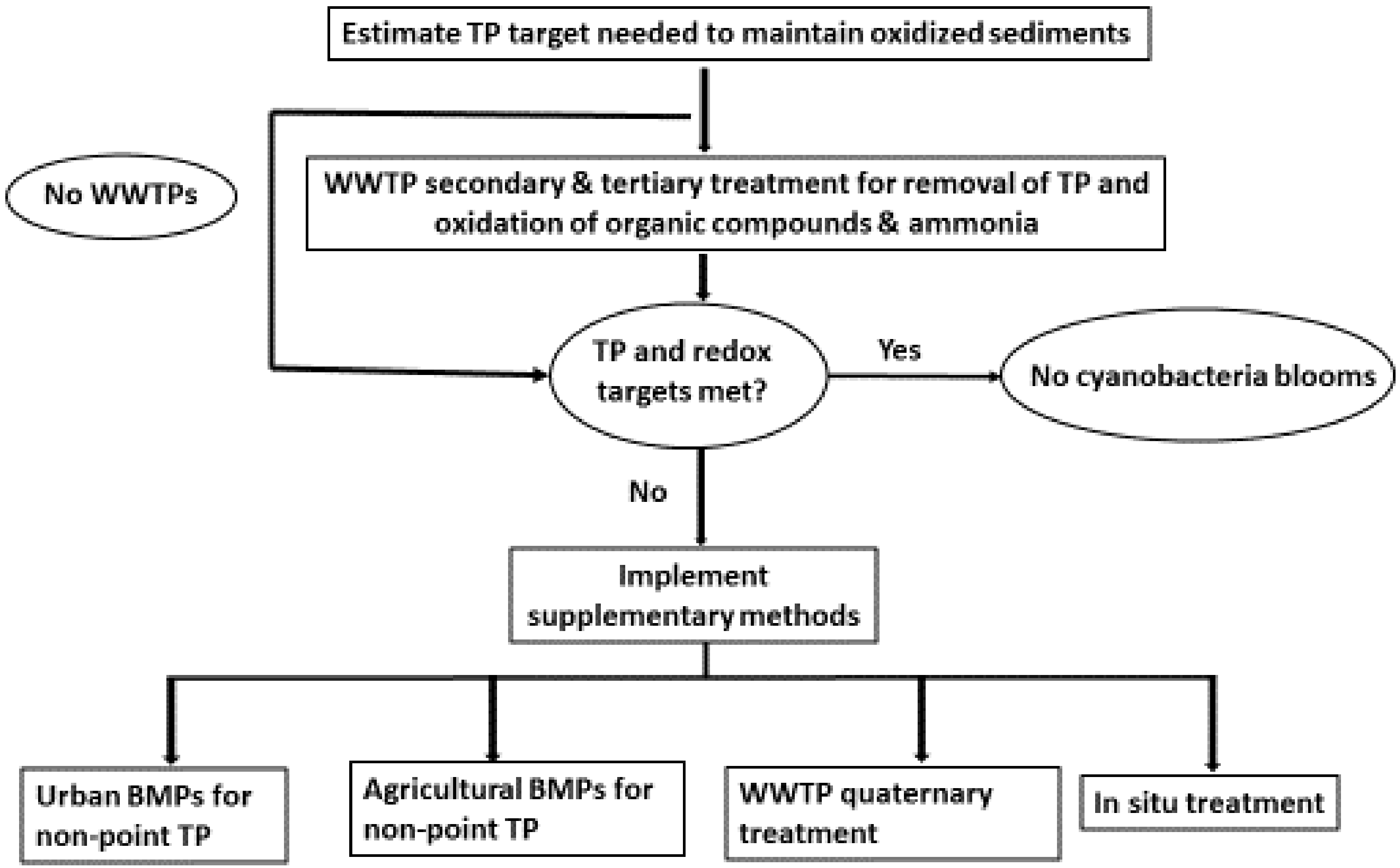
WWTP’s:

(i) Installation of next generation (but expensive) P treatment technologies in WWTP’s, but perhaps not good investment in watersheds dominated by non-point sources, e.g., western Erie.

Non-point sources:

(iii) Investments in urban and agricultural BMP programs to lower export of P may be good investment in watersheds dominated by non-point sources.

Decision tree for cyanobacteria management based on the four scientific principles beginning with the current practice of regulating WWTPs. Watersheds lacking point sources would skip second step

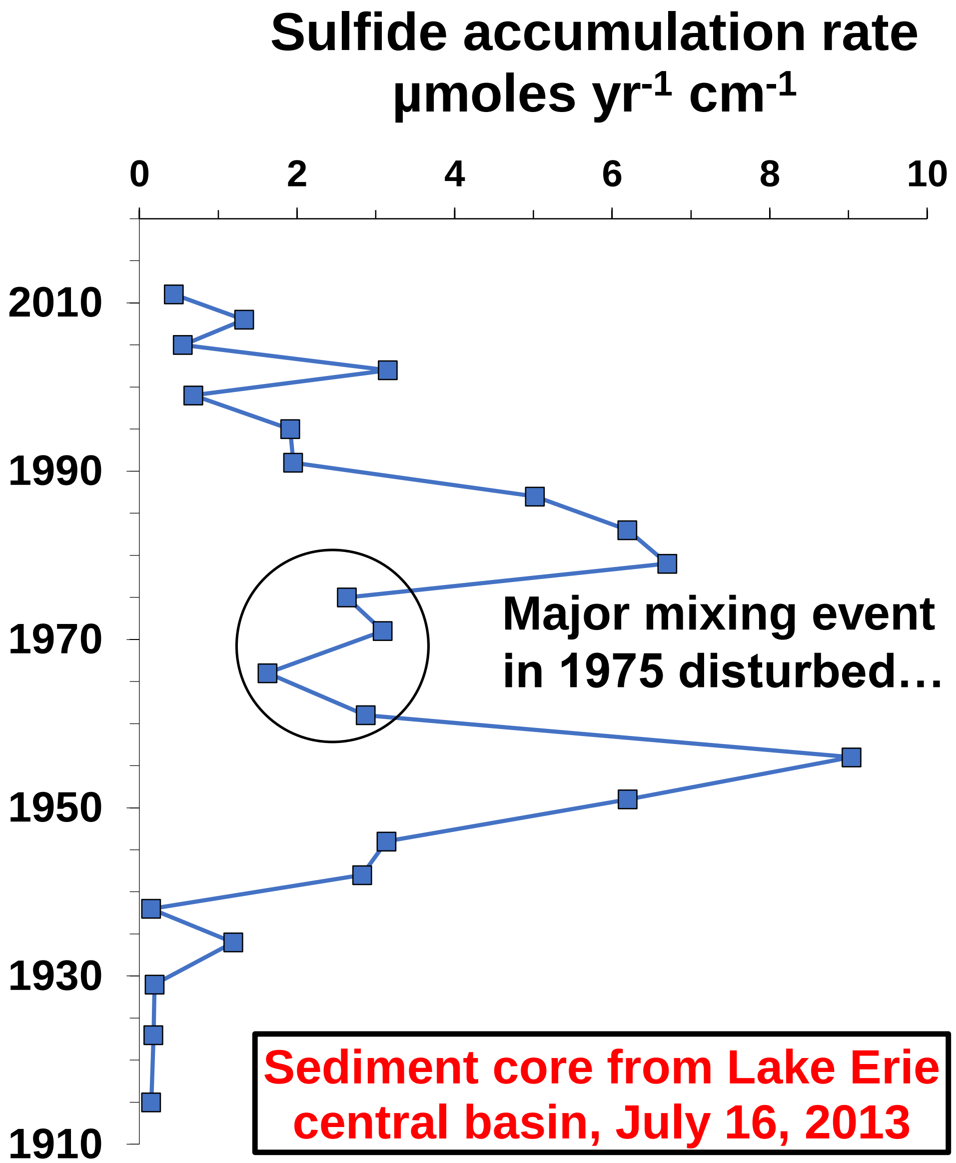


Multiple drivers may be responsible for cyanobacteria resurgence in Lake Erie beginning mid-1990s

- Climate change (warmer spring temps, more anoxia?)
- P inputs (still high enough to cause blooms despite point source reductions)
- Acid gas controls: less sulfate → less sulfide under anoxia → higher internal Fe(II) loading

- Spring TP conc'n declined after 1975 due to point source controls and has been 'stable' since 1995. Resurgence not due to increase in TP.
- N export to lake, and TKN and nitrate conc'ns in lake have also declined. Most N is nitrified before it reaches the lake. Resurgence not due to change in N inputs.
- Still anoxic - no decline in anoxia in central basin in ~ 30 years (climate signal?)

…only lowering non-point P inputs will mitigate bloom severity.



- 75% decline in Acid Volatile Sulfides in Lake Erie central basin sediments since 1980. Sulfide formation driven by sulfate and organic matter under anoxic conditions.
- 25% decline in sulfate conc’n; remainder (50%) due to less organic fuel?
- Large decline in point source TP and the dreissenid mussel invasion → lowered delivery of organic C to hypo → less sulfide formation (S^-)
- **Anoxia still occurs**
- **lower S^- formation could lead to higher internal Fe(II) loading as long as sediment anoxia still occurs**