TRACE METAL CO-LIMITATION CONTROLS ON NITROGEN FIXATION IN LAKES WITH VARYING TROPHIC STATUS

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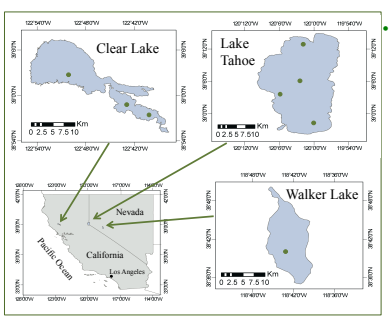
1. Introduction:

Biological nitrogen fixation drives the productivity of many aquatic ecosystems, but also can be limited by the availability of nutrients. Many of the key enzyme reactions in nitrogen fixation require metals (e.g. Molybdenum, iron) and other nutrients (e.g. phosphorus, sulfate) for its activity. In lakes, a major unknown is how nutrient trace metals that generally exist at very low concentrations control the cycling of nitrogen.

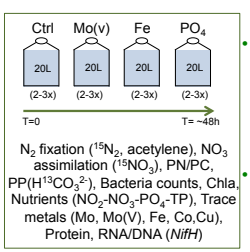
Specifically, we tested for:

A. Nutrient controls on nitrogen fixation in lakes with varying trophic status.
B. Co-limitation of Mo(V) with other nutrients in lakes as opposed to ocean open waters, to explain why N_2 fixation often does not occur in oligotrophic lakes, despite the presence of potential nitrogen fixers.

2. Study area and methods:



- Location of study stations at each lake.



N_2 fixation ($^{15}N_2$, acetylene), NO_3 assimilation ($^{15}NO_3$), PN/PC, PP($H^{13}CO_3^-$), Bacteria counts, Chl*a*, Nutrients (NO_2-NO_3-PO_4-TP), Trace metals (Mo, Mo(V), Fe, Co,Cu), Protein, RNA/DNA (*NifH*)

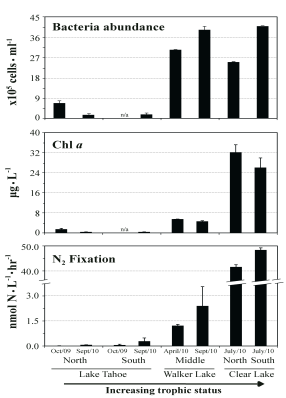
Incubation experiments:

- Water was collected from selected stations, enriched with nutrients and incubated for ~48h in lake water or in incubators with similar *in situ* conditions.
- Samples were collected for different measurements (see reference section for methods of data presented here).

3. Natural conditions:

Feature	Lakes: Lake Tahoe	Walker Lake	Clear Lake
Surface area (Km^2)	500	130	170
Mean depth (m)	313	22	10
Max. depth (m)	505	26	18
Elevation (m)	1898	1300	402
Trophic status	Oligotrophic	Mesotrophic	Eutrophic
Algae bloom	none	none	abundant
O_2 ($mg\ L^{-1}$)	9.3	7.6	8.8
Salinity (ppt)	0	17	0
TP (nM)	21.4 (10 - 40)	5030.0 (4729 - 5331)	274.8 (246 - 303)
Mo(VI) (nM)	33.7 (32 - 36)	3180.0 (3024 - 3335)	3.0 (2.8 - 3.1)
Mo(V) (pM)	0.0	205.1 (0 - 410)	333.9 (305 - 388)
Fe (nM)	34.1 (2 -121)	122.6 (92 - 153)	145.8 (110 - 182)
Co (nM)	0.1 (0 - 0.1)	1.9 (1.7 - 2.1)	0.6 (0.6 - 0.7)
Cu (nM)	6.9 (1 - 20)	5.0 (4 - 6)	12.4 (8 - 16)
Observed Cyanobacteria	none	Nodularia	Anabaena, Lyngbia, Aphanizomenon, Microcystis, Gloeotrichia

- Descriptive characteristics for each lake studied.

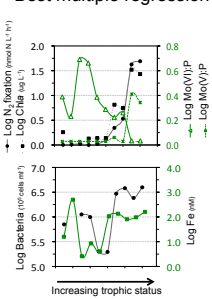


Contrasting lake systems with varying trophic status:

- On average, Walker and Clear lake have 6x more bacterial cells than Lake Tahoe.
- Walker and Clear lake have higher Chl*a* concentrations than Lake Tahoe (10x and 60x, respectively).
- Same trend for N_2 fixation but larger differences: Walker lake (20x) and Clear lake (600x) higher than Lake Tahoe.

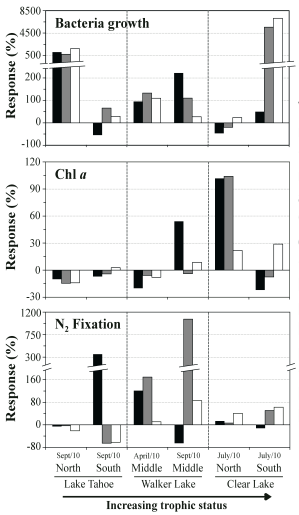
4. Linear response models:

Best multiple regression models with lowest AICc:



- N_2 fixation explained by the concentration of primarily Mo(V), and also Mo(VI) and P (Model: $R^2 = 0.95$; $P < 0.001$; AIC = 22.0)
- Chl*a* explained primarily by the concentration of Mo(V), Mo(VI) and P (Model: $R^2 = 0.99$; $P < 0.001$; AIC = 8.0)
- Bacteria explained primarily by the concentration of Fe (Model: $R^2 = 0.48$; $P < 0.05$ AIC = 29.4)

5. Responses to nutrient additions:



Variable co-limitation of nutrients among lakes:

- In most cases, a distinct response to nutrient additions among bacteria, Chl*a* and N_2 fixation in each lake was observed.
- Mo(V) plays a role in limiting N_2 fixation primarily in non-eutrophic lakes, contrary to the pattern observed for Chl*a*.
- No pattern among the lakes was observed for bacteria.

6. Summary:

- *In situ* and experimental responses indicate nutrients are used differently between groups (e.g. N_2 fixers vs phytoplankton).
- Co-limitation of nutrients (e.g. Mo:P) play a major role on N_2 fixation and Chl*a*.
- Our results support the hypothesis that co-limitation of Mo(V) with other nutrients explain why N_2 fixation often does not occur in oligotrophic lakes.

7. References:

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8. Acknowledgment

We would like to thank Anne Liston (Tahoe Environmental Research Center), Tom Smythe (Lake County Wayer Resources Department), Clear Lake Vector Control Center, Nevada Department of Wildlife, and Cecile Mioni for all their field support and assistance. Funding was provided by National Science Foundation.