Nutrients from the deep: internal phosphorus loading in hyper-eutrophic Clear Lake

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Introduction

Eutrophication is a large problem globally that results from excess nutrients (i.e. nitrogen and phosphorus) entering aquatic systems. In the case of phosphorus, it enters lakes by external (runoff) or internal loading (from lake-bottom sediments). Efforts to restore Clear Lake, a hyper-eutrophic lake located in Lake County, CA, have largely focused on external loading as the cause of excessive phosphorus concentrations.

In this study, we sought to quantify the internal load of phosphorus for the first time in Clear Lake by measuring phosphorus flux rates from lake-bottom sediments.

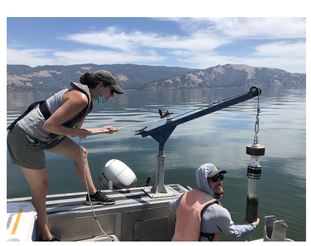
Results of this study will be incorporated into a whole-lake 3-D hydrodynamic model to aid in developing phosphorus management strategies for the lake.

Site Description

- Historically eutrophic lake due to high phosphorus content in local volcanic parent material
- Likely the oldest lake in North America with sediments dating back to 450,000 years ago and beyond
- Lake is now hypereutrophic and suffers harmful algal blooms (HABs) that cause fish kills from anoxia and produce toxins

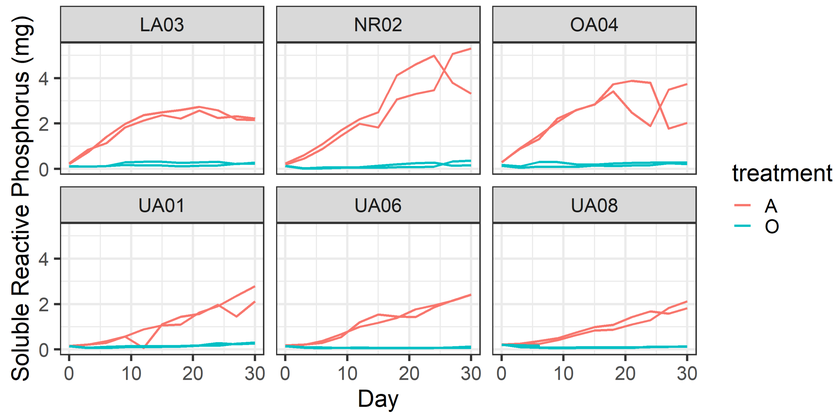
Materials & Methods

- Collected 4 cores from each of the 6 sites across the lake
- We oxygenated 2 of the cores from each site by bubbling with air, the remaining 2 cores kept anoxic by bubbling with N_2 gas
- Incubated cores at 15.2°C for 30 days, sampling every 3 days
- Analyzed water in cores for pH, redox (E_h), SRP, DP, NO_3, and NH_4
- Calculated maximum rate of flux of above analytes from linear portion of mass vs. time curves

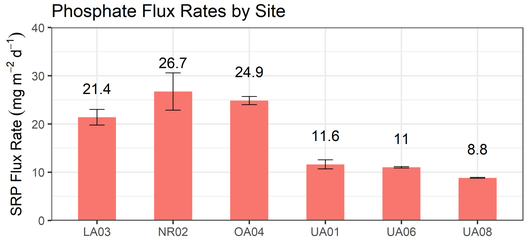


Results

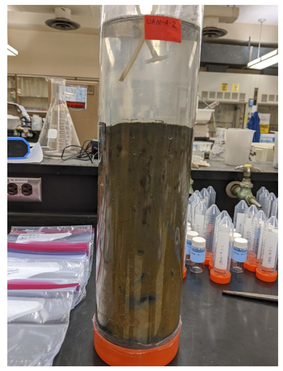
Phosphate Flux to Overlying Water of Cores



Phosphate Flux Rates by Site

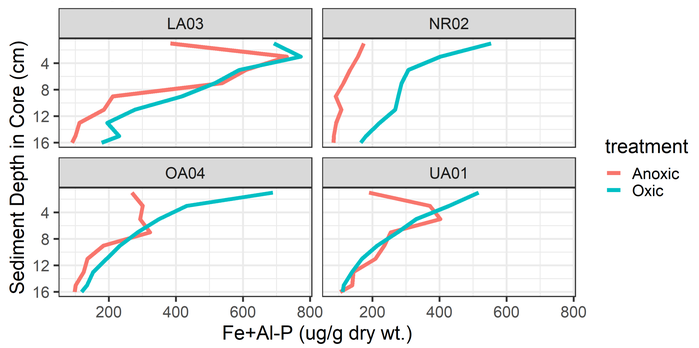


How fast does phosphorus enter the lake and where? *P flux rates in Clear Lake are significantly larger than other eutrophic lakes[2]. Sites showed high spatial variability in SRP flux rates. Site NR02 had the highest rate (26.74 mg m^{-2} d^{-1}) and the Oaks and Lower Arms had over double the P-flux rates and thus are nutrient hotspots in the lake.*



Sediment-Associated Fe and Al-bound Phosphorus from Anoxic and Oxic Cores

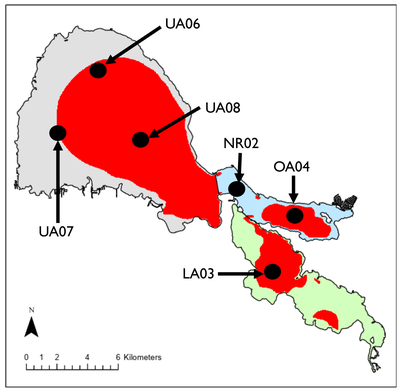
How much phosphorus is at the bottom of the lake? *Phosphorus flux is mainly driven by iron and aluminum-bound phosphorus in Clear Lake, and results indicate that the top 5cm of sediment fuels most internal loading.*



Annual Internal Load

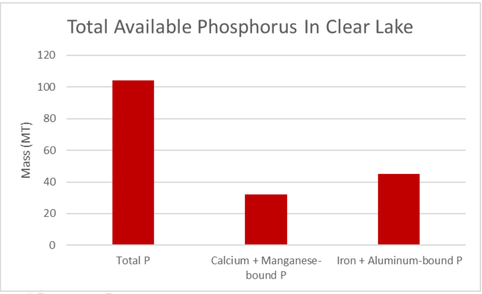
P-Loading Source	P-Species	Annual Load (MT yr^{-1})	% Annual SRP load
External	SRP	37.1 - 51.4[1]	59-67%
Internal	SRP	25.6	33-41%
External	Total-P	89.9 - 125[1]	NA

Annual inputs from either external or internal sources shown in metric tons (MT). Internal loads of SRP contribute to 33-41% of the total SRP load to the lake each year.



Widespread anoxia in Clear Lake. *The red portion of the lake-bottom represents the anoxic zone during the period of stratification in March-October 2019 that could allow sediments to actively exchange phosphorus to the water column. Sediment sampling sites are shown as black dots.*

How long will internal P-loading persist? *Internal loading cycles around 25.6 MT of phosphorus a year, yet the pool of available phosphorus is larger than 41 MT. It will likely take a long time to expel this legacy of phosphorus to the lake and reduce the amount of phosphorus cycling in the lake.*



Implications

- High rates of SRP flux lead to annual internal loads nearly equal to external loads of SRP, thus contributing a significant source of phosphorus to the lake.
- Large spatial variability in anoxic phosphorus flux rates as sites NR02 and UA08 showed 3-fold differences.
- Managers pursuing restoration efforts should consider internal loading when examining current total maximum daily loads (TMDLs) of phosphorus.

Acknowledgments

I would like to thank the California Department of Fish and Wildlife, the TERC biogeochemistry lab, as well as members of the Sadro, Forrest, and Schladow labs for their support in this research. Specifically, I would like to thank Lindsay Vaughan and Steven Sadro for their dedicated and patient help with running these experiments.

References:
[1]Lundquist, E., and Smythe, T. 2010. Clear Lake Integrated Watershed Management Plan. County of Lake Department of Public Works Water Resources Division. West Lake and East Lake Resource Conservation Districts, Lakeport, CA, USA.
[2]Orihel, D. M., Baulch, H. M., Casson, N. J., North, R. L., Parsons, C. T., Seckar, D. C., & Venkiteswaran, J. J. (2017). Internal phosphorus loading in Canadian fresh waters: a critical review and data analysis. *Canadian Journal of Fisheries and Aquatic Sciences*, 74(12), 2005-2029.