Phosphorus Loading and Trophic State History of Waughop Lake: The Most Toxic Lake in Western Washington

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Abstract

Waughop Lake experiences toxic algal blooms that are believed to be largely the result of internal phosphorus (P) loading from sediment contaminated by a century of nearby agricultural operations. To better characterize this sediment and to reconstruct a trophic state history of the lake we collected and analyzed a 6.4 m core that represents ~12,000 years of accumulation. Chemical and stable isotope data indicate that P loading and sedimentation rates increased dramatically around 1900, coincident with the onset of farming. However these rates have continued to rise even after farming ended in the 1960's, and have doubled over the past 50 years. Annual internal P cycling alone cannot account for these trends; either Waughop Lake is continuing to receive P from external sources or upward migration of P from deeper in the sediment column is increasing the internal P loading rate.

Lake Characteristics & History

- Waughop Lake is a 13 ha kettle lake (z_{max} = 3m) located in Fort Steilacoom Park (Lakewood, WA) **(Fig. 1a, b)**.
- Sediment accumulated on the bottom is >6 meters thick and contains ash from the 7700 BP eruption of Mt. Mazama (**Fig. 2**). At the base of the sediment is a gray silt that probably dates to ~12,000 BP.
- Beginning around 1870 the land around the lake part of a hog and dairy farm operated by Western State Hospital. Agricultural wastes were dumped directly into the lake, a practice that continued until 1965.
- During the 1920's organic rich sediment was pumped from the lake and sprayed on the surrounding fields as a soil amendment.
- The first recorded algal bloom was in 1972; since 2007 the lake has exceeded the maximum allowable levels of microcystin on 80% of the test dates. As a result during the summer Waughop Lake is commonly closed to recreational use.

Fig. 1a

Fig. 1b

Fig. 2

Sediment Dating & Accumulation Rates

- Pb-210 dating indicates that roughly one meter of sediment has accumulated over the past 100 years **(Fig. 3)**. This estimate may be low as we know there was dredging of the lake in the 1920's.
- Between 7700 BP and 1900 AD the average sediment accumulation rate in Waughop Lake was 0.4 mm/yr. This rate increased >5-fold around 1900 AD and has risen steadily since then **(Fig. 4)**.
- The current accumulation rate of ~1 cm/yr **(Fig. 4)** or 850 g/m^2-yr **(Fig. 5)** is a factor of six higher than in nearby Lake Louise **(Fig. 1b)**, which experienced little or no impact from agricultural activity.
- If current rates of sediment accumulation continue Waughop Lake will likely become a wetland with the next 200-300 years.

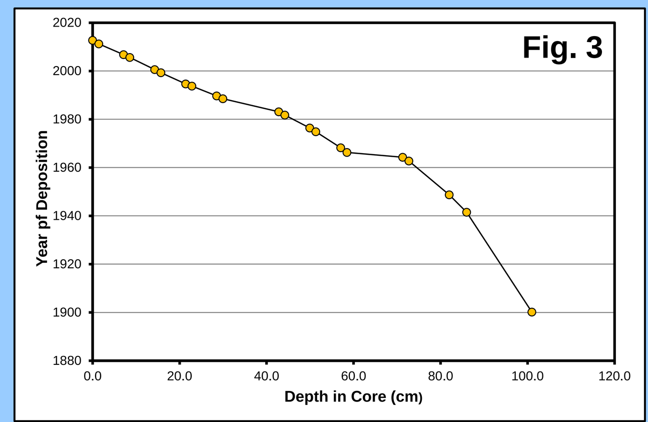

Fig. 3

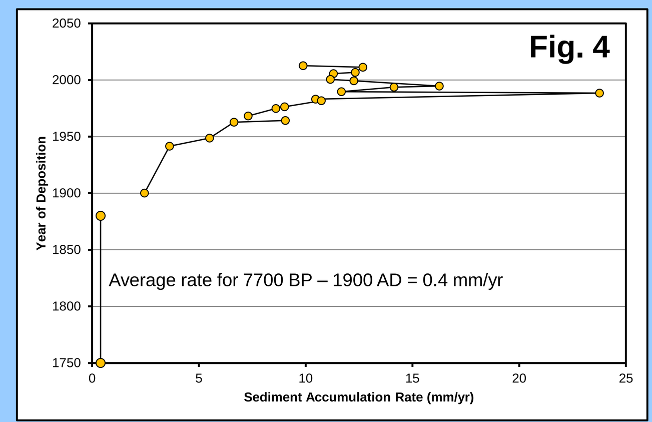

Fig. 4

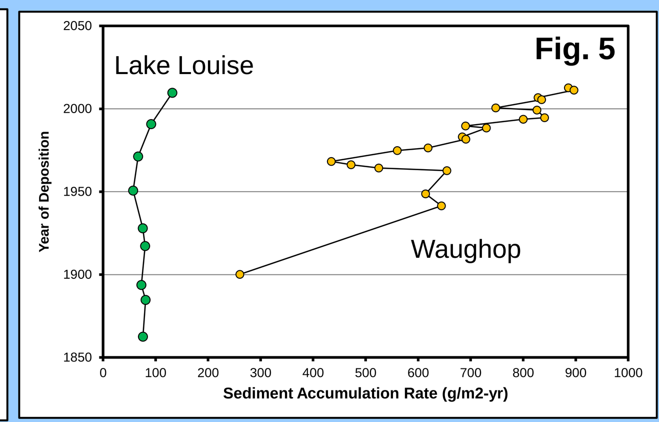

Fig. 5

Phosphorus and Metal Concentrations & Loading Rates

- Phosphorus concentrations (measured by ICP-OES after a 24-hour leach with 20% HNO_3) increase approximately 5-fold (<350 ppm to 1500-2200 ppm) between 1900 – 1940. The abruptness of the increase **(Fig. 6)** may in part reflect a gap in the core caused by dredging in the 1920's.
- Element profiles for Fe **(Fig. 7)** and Mn also increase abruptly between 1900 – 1940, with Fe concentrations jumping from <1000 ppm to 6200-9000 ppm.
- Fe/Mn ratios are higher in sediment deposited since 1940 (x = 30) than in older sediment (x = 16), which suggests more reducing sediment column conditions over the past 75 years than previously.
- Concentrations of Cu **(Fig. 8)**, Pb, Zn, and As also increase dramatically between 1900 – 1940 and are a legacy of ASARCO smelter operations from 1889 – 1986. Although 5 - 46 times above natural background levels, concentrations of these metals do not exceed sediment quality standards.
- The P loading rate has risen steadily since 1900 **(Fig. 9)** despite the fact that farming operations ended in the 1960's. Similarly, loading rates for Cu, Pb **(Fig. 11)**, and Zn increase upward and are now at their highest levels, although the smelter has been closed for 27 years.
- All of these elements show loading profiles that closely mimic the profile for Fe **(Fig. 10)**.

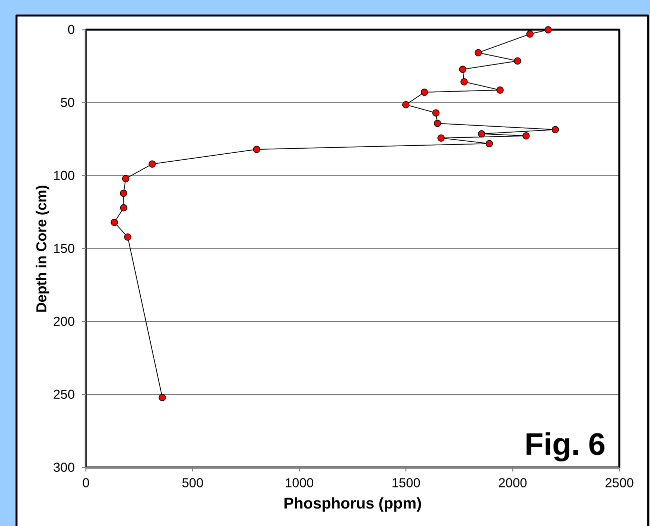

Fig. 6

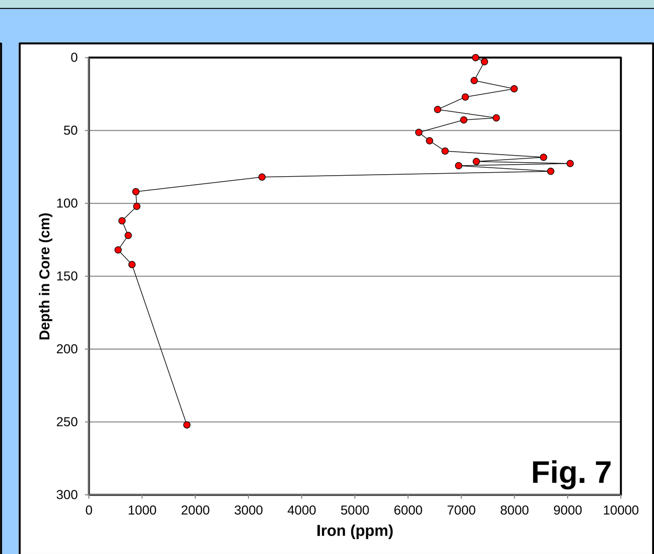

Fig. 7

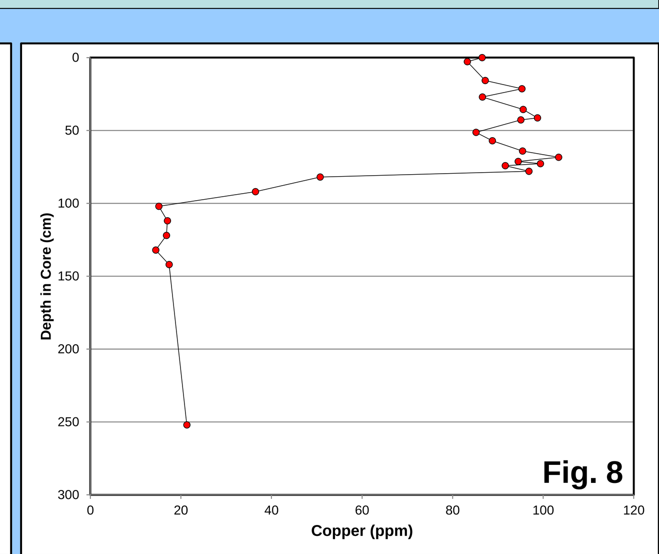

Fig. 8

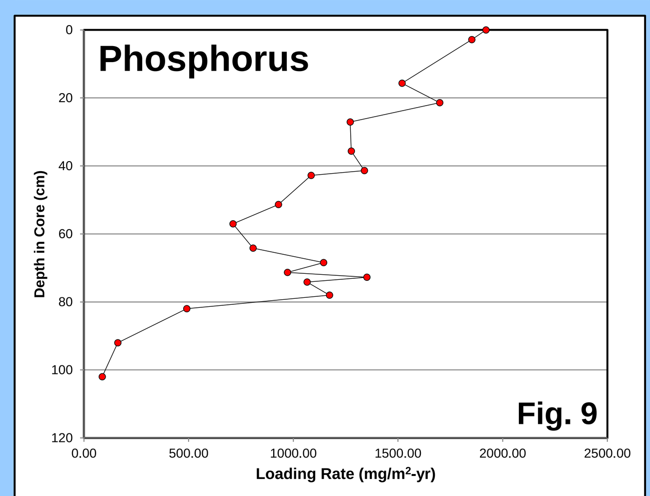

Fig. 9

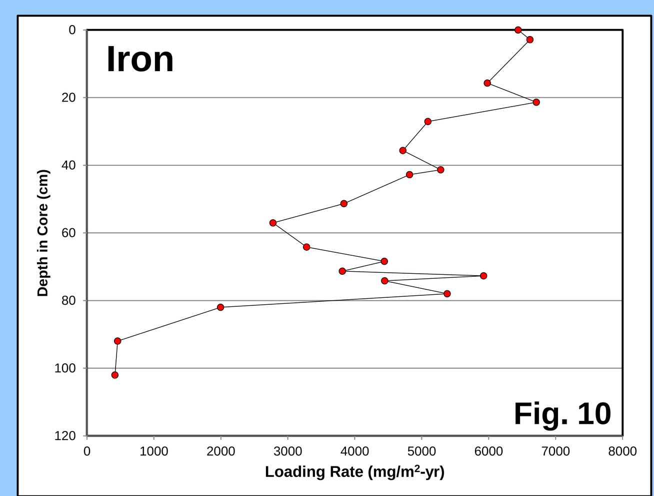

Fig. 10

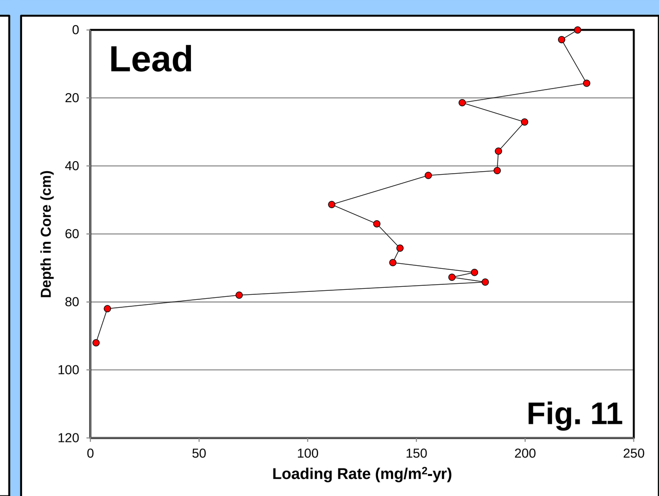

Fig. 11

Organic Matter Sources

- C/N ratios **(Fig. 12)** have remained very uniform (11-13) over the past 8,000+ years indicating that sedimented organic matter has been dominated by algal debris (C/N < 10) as opposed to vascular plant remains (C/N > 20). The algal component appears to have increased slightly over the past 50 years.
- Nitrogen isotope data are very uniform over most of the lake history, but shift to 4‰ heavier values after 1900 **(Fig. 13)**. This shift is consistent with input of manure and coincides with the establishment of farming at the lake.

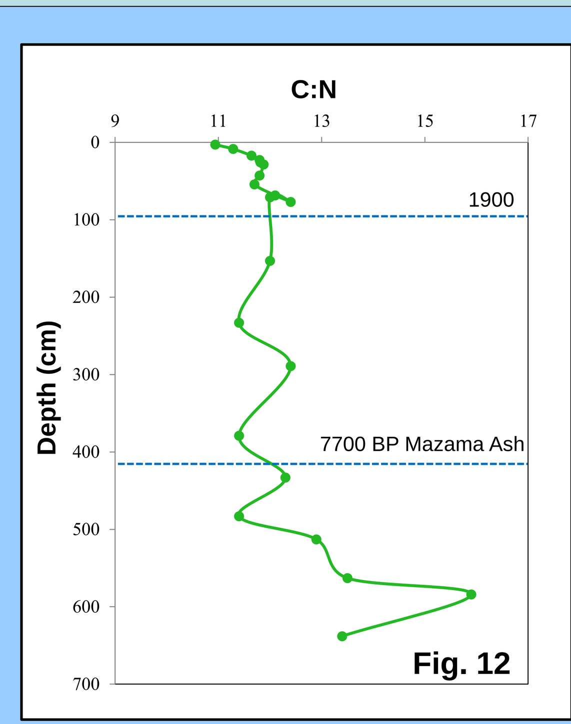

Fig. 12

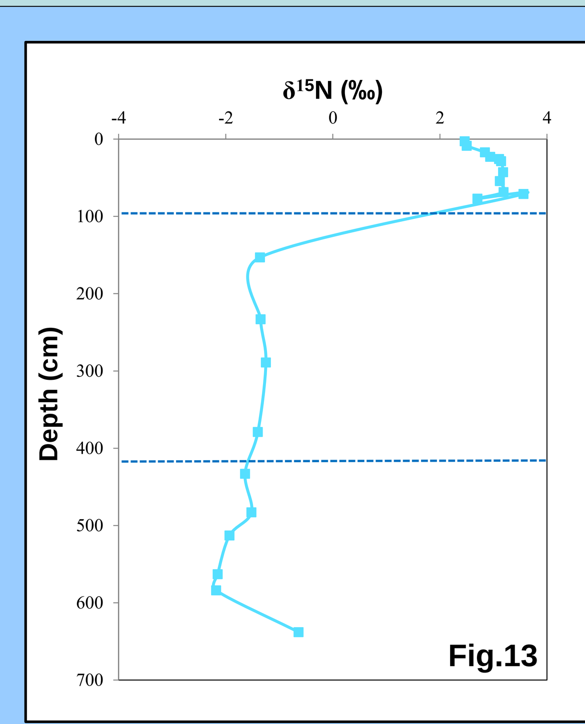

Fig.13

Migration of P in the Sediment Column

- P concentrations are highly correlated with Fe contents **(Fig. 14 and Figs. 9 & 10)**.
- The link between P and Fe is further corroborated by results of a sequential extraction study (adapted from Ruttenberg, 1992) that indicate 40-55% of the P is present in Fe-bound form. Another ~20% is loosely-sorbed **(Fig. 15)**.
- High concentrations of Fe in the upper 80 cm of the sediment column likely result from redox-driven dissolution at depth and subsequent reprecipitation near the sediment-water interface.
- Release and upward transport of P and Pb during this process would explain why concentrations of these elements are high in sediment deposited after the cessation of farming and smelting.
- Upward transport and release of P could also explain the steady increase in sediment accumulation rates **(Figs. 4 & 5)**. Liberation of Fe-bound P from deeper in the sediment column (perhaps due to a shift to more reducing conditions that enhances Fe solubility?) may be gradually increasing the mass of P that is available for internal cycling each year.

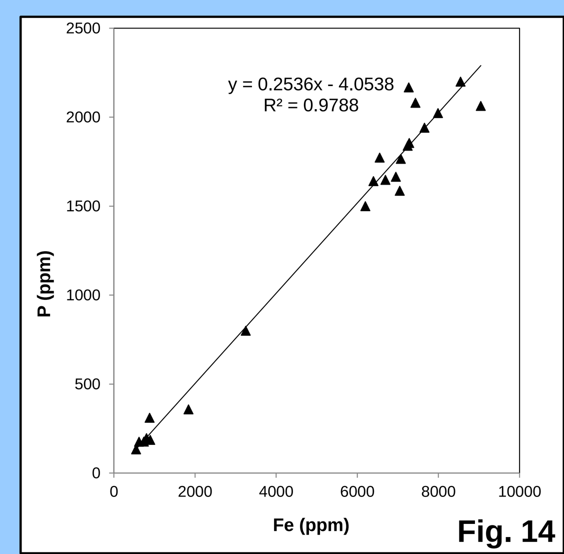

Fig. 14

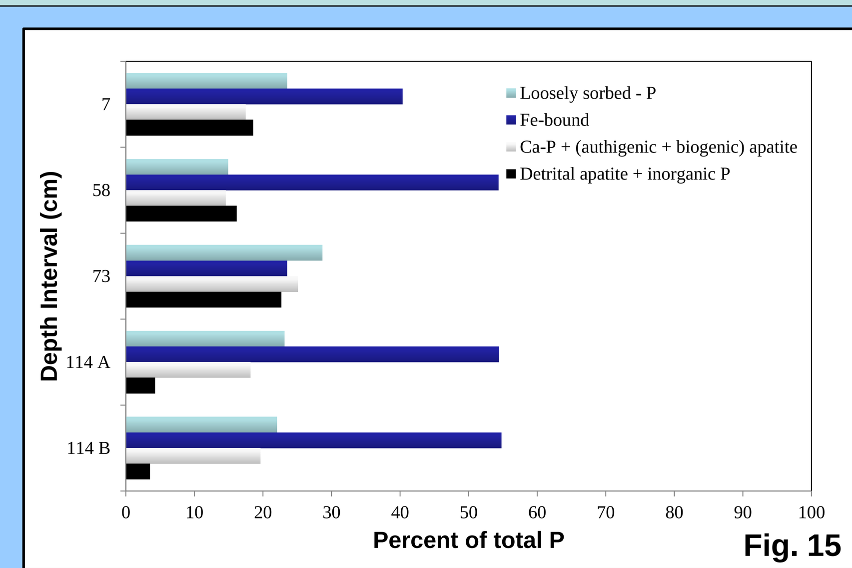

Fig. 15