The Baltic proper eutrophication - a runaway system that passed the tipping point at the end of the 1950s

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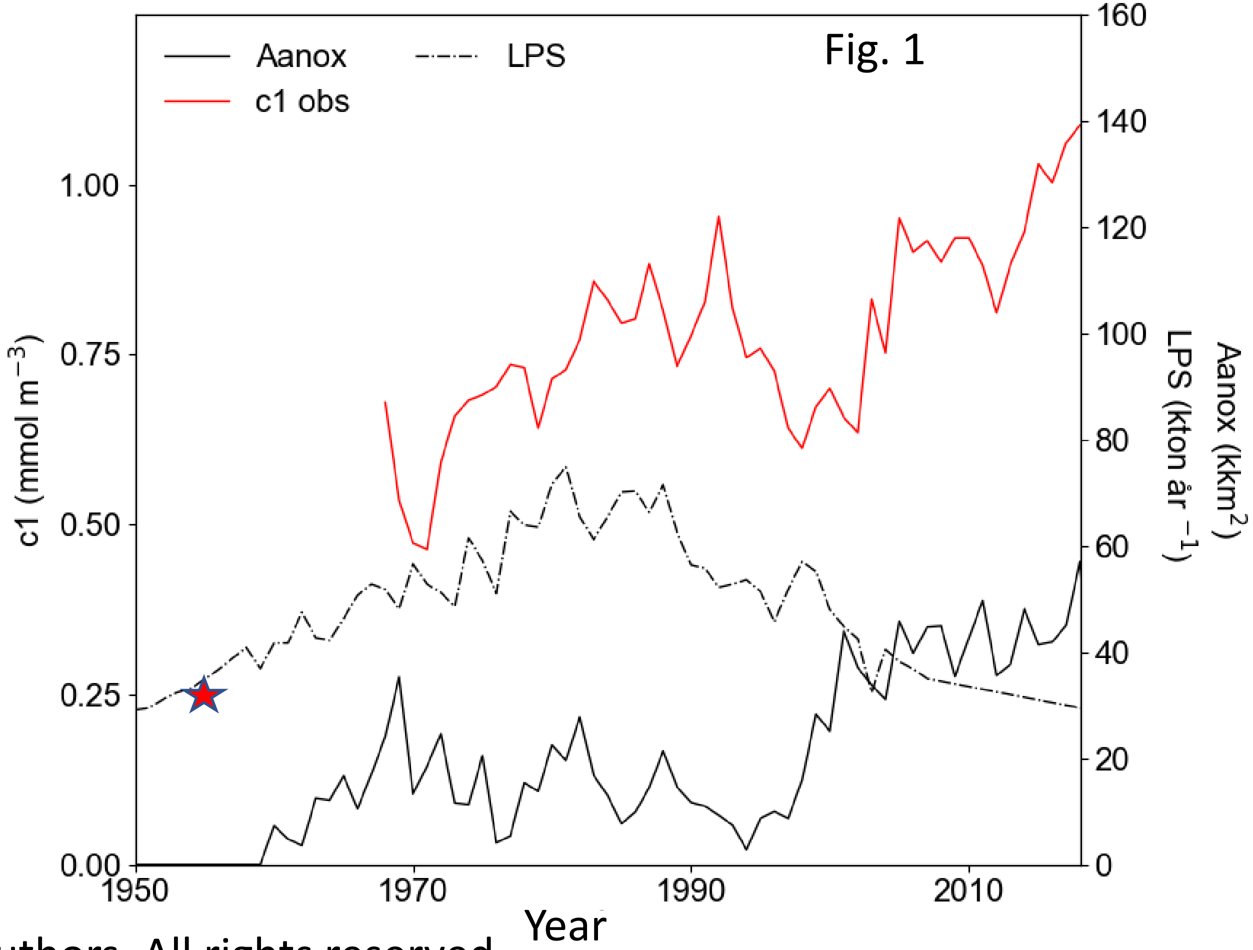
Observed states of the Baltic proper 1950 - 2018

The graph shows the volume mean concentration *c1 obs* of phosphorus (TP) in the surface layer (0-60m) in winter, and the area *Aanox* of anoxic bottoms, and the supply of P from land-based sources *LPS*. Observations show ★ that *c1obs* was about 0.25 (mmol m^{-3}) in 1958. P controls the annual biological production in the Baltic Sea.



Comments:

- *LPS* has decreased by 50% since the 1980s but *c1obs has* increased during the same time.
=>An internal P source *IPS* has more than well compensated for the decrease of *LPS*.

- *c1obs* has increased by a factor of 4 since the 1950s although *LPS* has about the same value as then.
=>This run away behaviour of *c1* can be explained if there is an internal source *IPS* that now should be about 4 times greater than *LPS*.

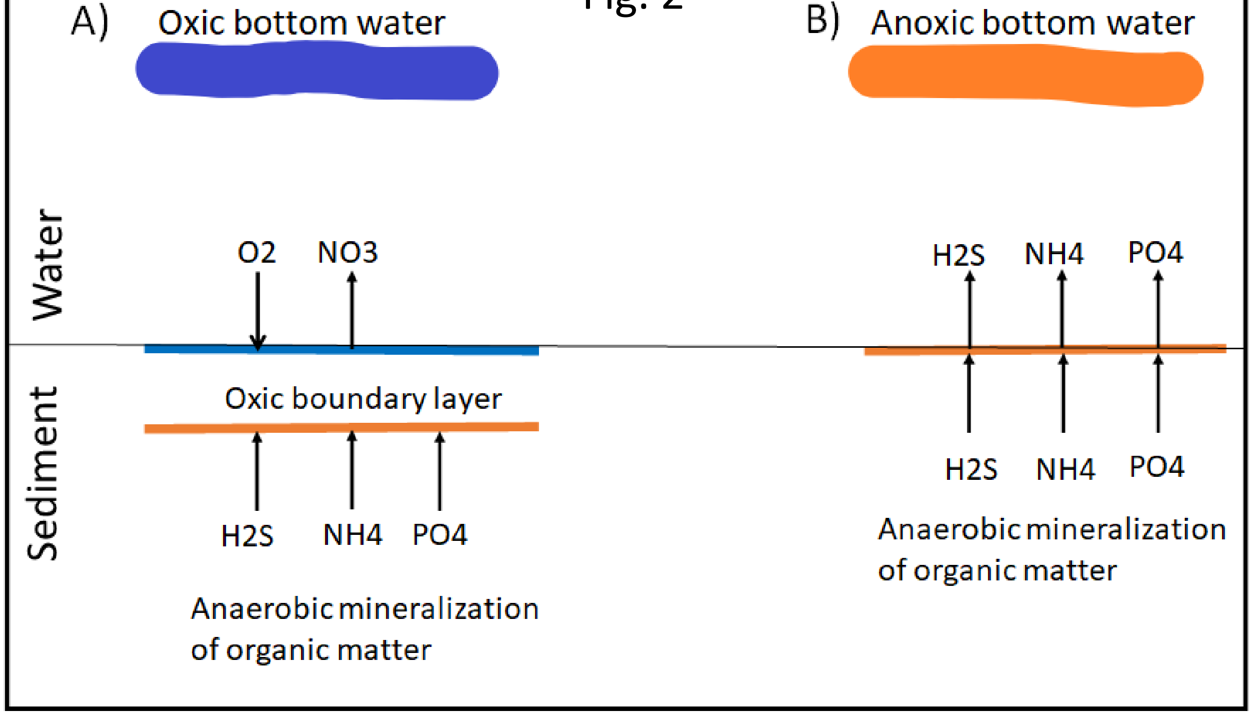
- *Aanox=0* until the beginning of the 1960s.

IPS - a feed-back mechanism leading to runaway behaviour of c1

Phosphate (PO4) produced by anaerobic mineralization of organic matter in the bottom sediment, is leaching into the water column if the bottom water is anoxic. This flux constitutes an internal P source *IPS* that is proportional to the area *Aanox* of anoxic bottoms. If the bottom water is oxic, there is an oxic boundary layer on top of the sediment containing iron oxides that adsorb PO4 (“filter effect”).

A) Iron oxides in the oxic boundary layer on top of the sediment adsorbs PO4. Ammonium is oxidized to nitrate and hydrogen sulphide is oxidized to sulphate in the oxic boundary layer.

Fig. 2



B) Substances produced by anaerobic mineralization in the sediment are diffusing into the water. The flux of PO4 constitute an internal P source *IPS*.

Anoxic bottoms supply both a P source *IPS* and an oxygen debt O2debt to anoxic deepwater.

The internal phosphorus source *IPS* from anoxic bottoms increases the concentration *c1* of P in the surface layer => the production of organic matter increases => the amount of organic matter sinking into the deepwater increases => the oxygen consumption in the deepwater increases => the area of anoxic bottoms increases => *IPS* increases (i.e. positive feedback).

Entrainment and mixing of old anoxic deepwater containing hydrogen sulphide and ammonia into new deepwater decreases the oxygen content of new deepwater because some of the oxygen in the new deepwater is used to oxygenate the entrained hydrogen sulphide and ammonium => expansion of *Aanox* => *IPS* increases (i.e. positive feedback)

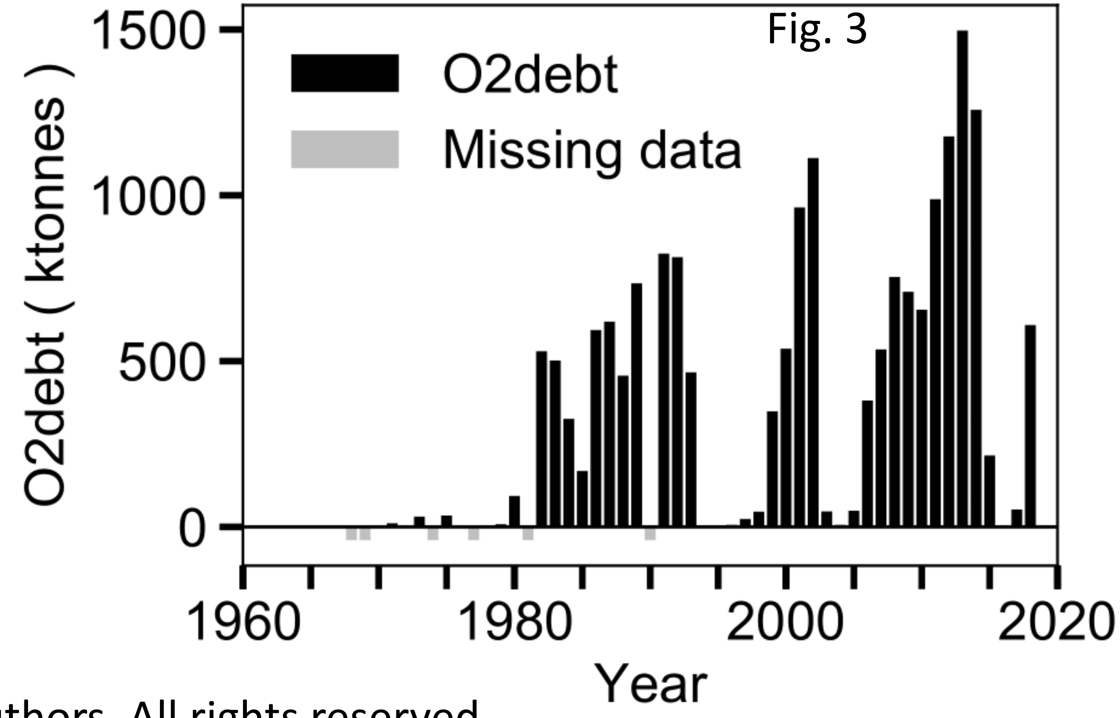


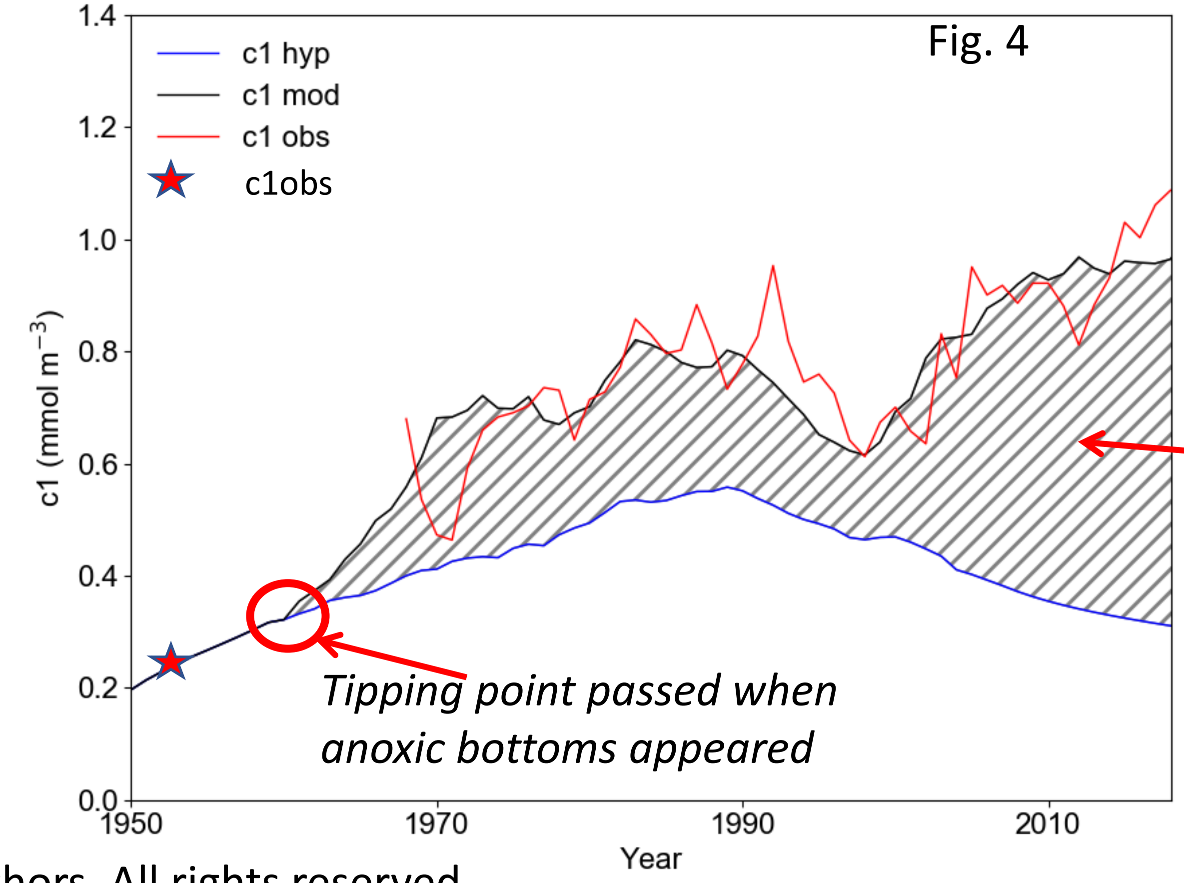
Fig. 3 The oxygen debt in the East Gotland Basin.

The oxygen debt *O2debt* equals the amount of oxygen needed to oxygenate all hydrogen sulphide and ammonia in the deepwater.

The oxygen debt is increasing => the natural oxygenation of the deepwater through inflows decreases.

Model simulations of the concentration *c1* of P in the surface layer of the Baltic proper in winter.

The total P supply *TPS* = *LPS* (land-based supply)+ *OPS* (ocean-based supply) + *IPS* (internal supply from anoxic bottoms). A model (Stigebrandt & Andersson, 2020, work in progress) was run to compute *c1.* In the first run *IPS*=0 and the result is *c1hyp* which has a maximum about 1990 and then decreases to about the same level as in the 1950s. *c1hyp can*not describe the observations *c1obs* - the curves diverge strongly from about 2000. In the second run *IPS*=2.19·*Aanox (tonnes year*$^{-1}$*)* where *Aanox* is expressed in km^2*.* The result *c1mod* describes quite well the observations *c1obs* (R=0.80) showing that including *IPS* is crucial for a decent description of the evolution of *c1*.



Conclusions

- A tipping-point was crossed at the end of the 1950s when anoxic bottoms first appeared and *IPS* started to develop.
- *IPS* is proportional to *Aanox* which leads to positive feedback and a runaway behaviour.
- The hatched area shows the importance of *IPS*
- *IPS* is now about four times larger than *LPS*
- The system can be reset by sustained oxygenation of deep bottoms so that *Aanox*=0 and *IPS*=0 for at least 10 years.

The End