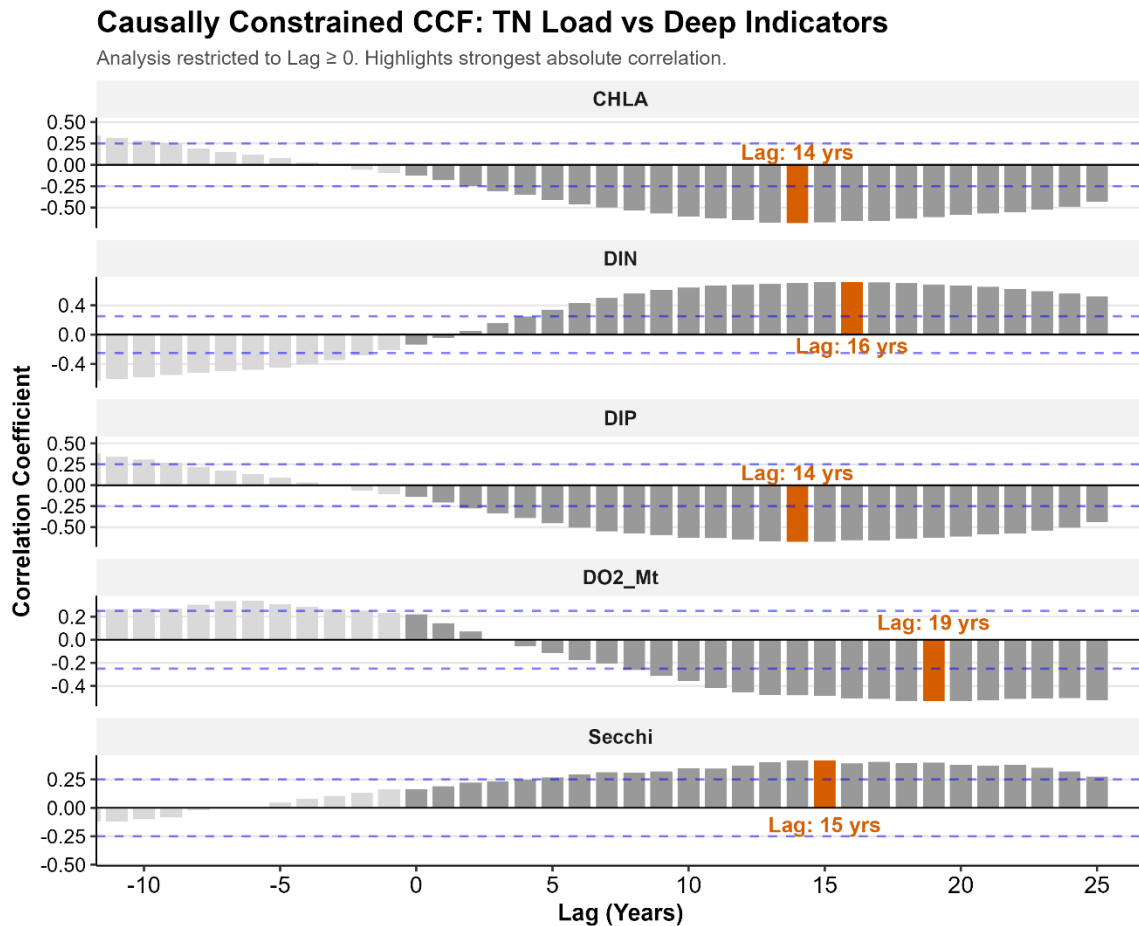
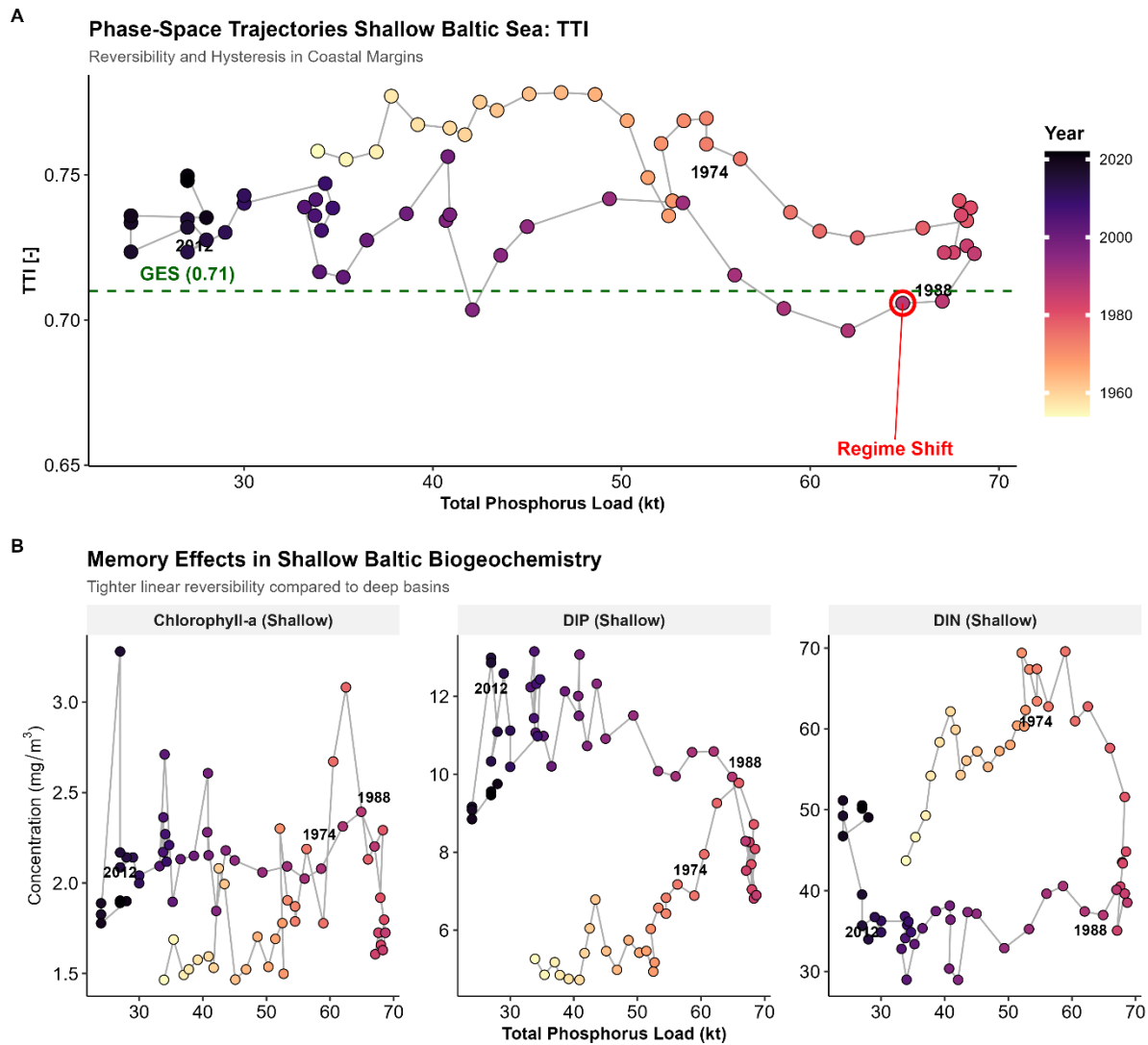


Supplementary Material: “The multidecadal delay of the Baltic Sea ecosystem recovery”

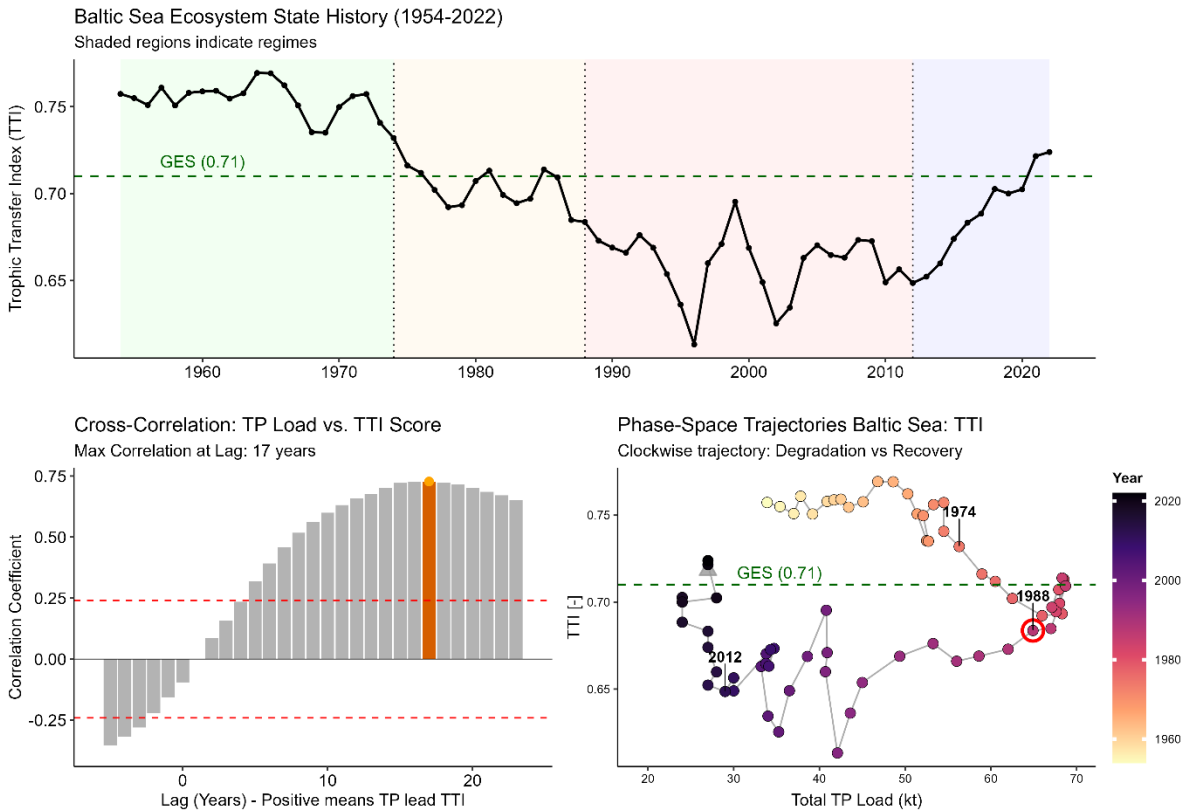


Supplementary Figure SI 1. Causally constrained Cross-Correlation Function (CCF) profiles evaluating the temporal delay between external Total Nitrogen (TN) loads and internal deep-basin MSFD related ecosystem indicators (1954–2022). Analysis is restricted to causal lags (> 0), with the orange bars highlighting the maximum absolute correlation. The results demonstrate a multi-decadal decoupling, where the main biogeochemical variables (DO_2 , CHLA, DIN, DIP, Secchi) lag external load reductions by 14 to 19 years.



Supplementary Figure SI 2. Chronological phase-space portraits mapping shallow coastal ecosystem variables (< 50m depth) against external Total Phosphorus load (1954–2022). Panel A (Shallow TTI) illustrates a tighter, more reversible trajectory compared to the deep basins, remaining proximate to the GES threshold (0.71 dashed line) and demonstrating higher ecological resilience without a catastrophic collapse. Panel B (Shallow CHLA, DIP, DIN) reveals unexpected diverging memory effects within the coastal margins. While primary production (CHLA) exhibits tighter linear reversibility, the main nutrient pools (anti-clockwise DIP and clockwise DIN) retain pronounced hysteresis loops comparable to those in the deep basins. This indicates that while the integrated biological and trophic response in shallow waters recovers symmetrically, localized benthic nutrient reservoirs still exert substantial legacy memory effects.

Dynamics of Baltic Sea Ecosystem Degradation

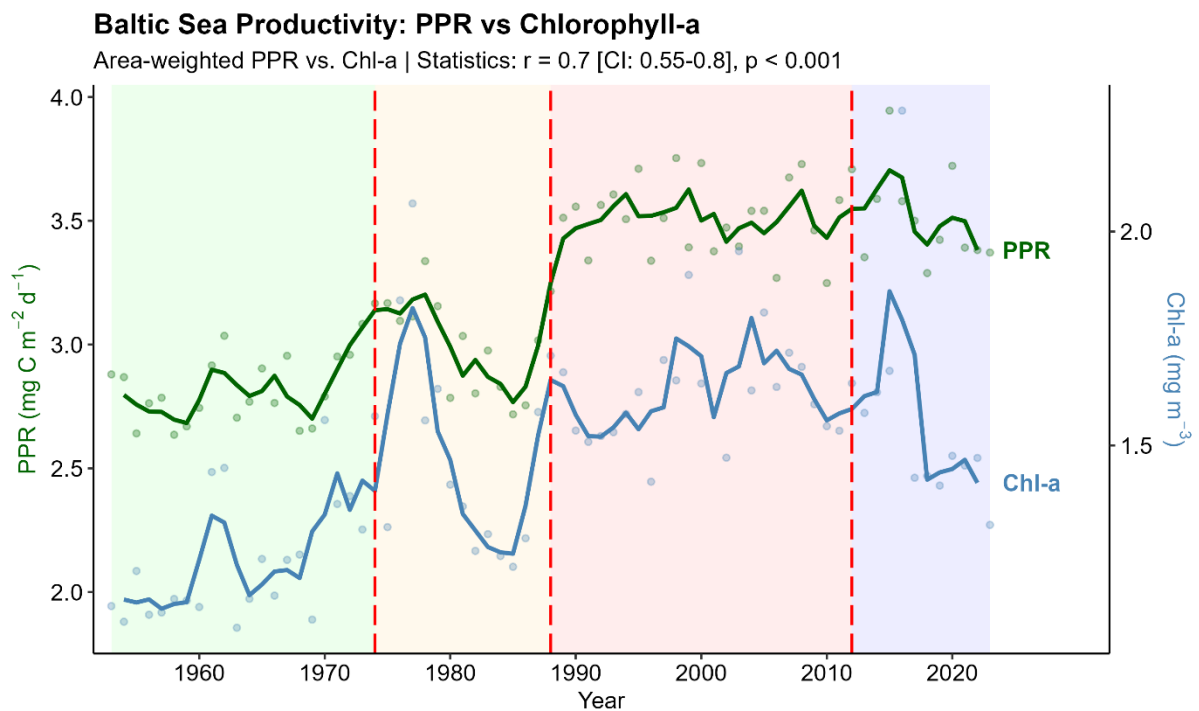


Supplementary Figure SI 3. Dynamics of Baltic Sea Ecosystem Degradation.

Overview figure illustrating the integrated time series, temporal lags, and state-space trajectories of the whole-basin Baltic Sea ecosystem based on the Trophic Transfer Index (TTI) from 1954 to 2022.

- Top panel: Baltic Sea Ecosystem State History (1954–2022).** A time series showing the Trophic Transfer Index (TTI) score (basin-wide average) over seven decades. The horizontal green dashed line marks the Good Environmental Status (GES) threshold of 0.71. Degradation is evident as scores drop markedly below GES starting in the mid-1970s. Vertical dotted lines and differentiated shaded backgrounds delineate four specific ecosystem regimes identified by regime-shift analysis.
- Bottom-left panel: Cross-Correlation: TP Load vs. TTI Score.** Statistical analysis determining the temporal lag between changes in drivers and whole-system response. The bar chart shows the correlation coefficient between Total Phosphorus (TP) load and TTI score at various lags (years). Horizontal red dashed lines represent the significance threshold. The analysis identifies that changes in TP load precede responses in TTI, with the maximum positive correlation occurring at a lag of 17 years (highlighted bar in orange).

- Bottom-right panel: Phase-Space Trajectories Baltic Sea: TTI.** A phase-space portrait plotting Trophic Transfer Index (TTI) against Total TP Load chronologically, color-coded by year (see gradient legend). This panel visualizes ecosystem hysteresis, tracing a distinct clockwise trajectory indicating a decoupled degradation vs. recovery path. Movement goes from top-left (high TTI, low TP, high status) to bottom-right (low TTI, high TP, degraded status) during the degradation phase. Key year's corresponding to regime shifts are labelled along the path (1974, 1988, 2012), with specific states indicated by ending icons and highlighted points. The green dashed line marks the GES threshold (TTI=0.71).



Supplementary Figure SI 4. This figure displays the temporal evolution of area-weighted Primary Production Rate (PPR, green) and Chlorophyll-a concentration (Chl-a, blue) in the Baltic Sea from 1954 to 2022. The two different productivity metrics exhibit remarkably similar curve forms, closely tracking each other through major trend shifts and synchronous structural breakpoints indicated by the vertical red dashed lines. This strong visual coherence is confirmed by a statistically significant Pearson correlation coefficient of $r = 0.7$ ($p < 0.001$), justifying their comparison and collective utility as indicators of ecosystem productivity state.