The Eutrophication of the Baltic Sea has been Boosted and Perpetuated by a Major Internal Phosphorus Source

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The phosphorus (P) concentration \( c_1 \) in the surface layer of the Baltic proper in winter depends on the land-based P source \( LPS \), and the ocean P source \( OPS \), which are known. It also depends on the internal P source \( IPS \) from anoxic bottoms and the sum of internal and external P sinks \( TP_{sink} \), which are estimated in this paper. \( IPS \) is parameterized as \( fs \cdot A_{anox} \), where \( fs \) is the specific annual mass flux of P from anoxic sediments and \( A_{anox} \) is the area of anoxic bottoms, and \( TP_{sink} \) is parameterized as \( c_1 \cdot TRVF \), where \( TRVF \) is the total removal volume flux. We use a time-dependent P budget model, and 47 years of observational data, and the method of least squares to determine the best estimates of the unknown parameters \( fs \) and \( TRVF \). The result is \( TRVF = 3,000 \text{ km}^3 \text{ year}^{-1} \) and \( fs = 1.22 \text{ tons P km}^{-2} \text{ year}^{-1} \). With these parameter values, the model gives a quite good description of the observed evolution of \( c_1 \). The observed runaway evolution of \( c_1 \), with increasing \( c_1 \) since the 1980s although the land-based supply \( LPS \) has been halved, is well-described by the model. It is concluded that the internal P source \( IPS \) provides a positive feedback mechanism that has boosted and perpetuated the eutrophication of the Baltic proper and that \( IPS \) is the major driver of the Baltic Sea eutrophication since the late 1990s. It is suggested that measures to eliminate \( IPS \) should be included in the management strategy to reduce the eutrophication of the Baltic proper.

Keywords: tipping point, Baltic proper, oxygenation, restoration, environmental modeling, internal phosphorus source, anoxia

INTRODUCTION

The eutrophication of the Baltic proper, the salt-stratified part of the Baltic Sea, continues to worsen, despite large cuts in the land-based P (phosphorus) source \( LPS \) since the 1980s. The surface layer concentration \( c_1 \) of P (TP) in winter was about 0.27 mmol m\(^{-3} \) in 1958 (Stigebrandt, 2018) and it is now about four times higher although the land-based supply \( LPS \) has been halved, is well-described by the model. It is concluded that the internal P source \( IPS \) provides a positive feedback mechanism that has boosted and perpetuated the eutrophication of the Baltic proper and that \( IPS \) is the major driver of the Baltic Sea eutrophication since the late 1990s. It is suggested that measures to eliminate \( IPS \) should be included in the management strategy to reduce the eutrophication of the Baltic proper.

The eutrophication of the Baltic proper, the salt-stratified part of the Baltic Sea, continues to worsen, despite large cuts in the land-based P (phosphorus) source \( LPS \) since the 1980s. The surface layer concentration \( c_1 \) of P (TP) in winter was about 0.27 mmol m\(^{-3} \) in 1958 (Stigebrandt, 2018) and it is now about four times higher although the land-based P supply is about the same as then (Figure 1). Compared to the needs of algae, there is a large P surplus in the surface water that makes possible extensive blooming of nitrogen fixating cyanobacteria in summer, that in calm weather may form thick bad-smelling layers at the sea surface causing large nuisance to swimming and leisure boating (e.g., Stal et al., 2003). Anoxia started to occur in the bottom waters of the deep basins at the end of the 1950s (e.g., Fonselius and Valderrama, 2003; Savchuk et al., 2008) and the area \( A_{anox} \) of anoxic bottoms (Figure 1) has thereafter expanded (Hansson et al., 2019). It should be noted that both \( c_1 \)
Deepwater is transported to the surface (Holtermann et al., 2012; Viktorsson et al., 2013). Additional support and Leppäranta and Myrberg, 2009). The evolution since 1950 of the area suggested that (Stigebrandt et al., 2015b). Tides are practically absent in (Gustafsson and Andersson, 2001; Stigebrandt et al., 2015b). Only during seldom occurring so-called MBIs (Major Baltic Inflows), large amounts of high-saline water intrude through the shallow straits in the mouth (Matthäus and Frank, 1992; Gustafsson and Andersson, 2001; Stigebrandt et al., 2015b). The MBIs may exchange the deepest deepwater while smaller inflows are inserted (interleaved) higher up in the strongly stratified deepwater. The residence time of the deepest deepwater may be as large as 10 years, c.f. Supplementary Figure 1. The inflowing water from Kattegat plunges into the deepwater because the pycnocline in the Arkona Basin is below the shallow sills in Fehmarn Belt (15 m) and Öresund (8 m), c.f. Stigebrandt et al. (2015b). In the Baltic proper it proceeds as a dense bottom current toward the deep basins.

Due to extensive entrainment of overlying water into the dense bottom current, the highest salinity of the deepwater of the East Gotland Basin is only 12–13 despite the inflowing water from Kattegat may have salinities in the interval 20–30 (e.g., Stigebrandt et al., 2015b). Deepwater is transported to the surface layer by erosion during autumn and winter when the seasonal stratification in the surface layer has been eliminated and vertical convection reaches down to the halocline (e.g., Stigebrandt, 1985). Vertical convection and erosion of the upper part of the halocline thus reset the surface layer each winter. Vertical transport within the deepwater is due to breaking internal waves that by different mechanisms get much of their energy from the wind as inferred by Axell (1998). Tides are practically absent in the Baltic Sea. A large-scale tracer experiment shows that most of the diapycnal mixing in the deepwater takes place near the seabed (e.g., Holtermann et al., 2012).

The annual biological production of organic matter in the Baltic proper is determined by the P concentration \(c_1\) in the surface layer in winter, c.f. the seasonal cycles of \(\text{PO}_4\) and DIN at the sea surface in Figure 3. When the spring bloom has exhausted the nitrogen nutrients, most of the phosphorus is left in the surface layer which makes possible extensive blooms of cyanobacteria that fixate elemental nitrogen (e.g., Olofsson et al., 2016). The importance of N-fixing species in the phytoplankton community has varied much in time as can be understood from the evolution of the NP ratio in the surface layer in winter (Figure 4). Decomposition of organic matter sinking out of the surface layer leads to oxygen consumption in the deepwater. Because turbulent vertical diffusion is obstructed by the strong vertical salinity stratification, the deepwater receives oxygen primarily by plunging inflows from the Kattegat. During a long period, the Baltic proper virtually lacked anoxic sulfidic deepwater (Fonselius and Valderrama, 2003; Savchuk et al., 2008). This period terminated at the end of the 1950s when oxygen demand outpaced supply and the deep basins became anoxic (Fonselius, 1962). The evolution since 1950 of the area \(\text{Aanox}\) of anoxic bottoms in the Baltic proper is shown in Figure 1.

The total phosphorus supply \(\text{TPS}\) to the Baltic proper water column has three components; the land-based supply \(\text{LPS}\); the ocean supply \(\text{OPS}\); the internal supply \(\text{IPS}\) from anoxic bottoms. Over long timescales, \(\text{OPS}\) can be considered as approximately constant \(\approx 11\) kt tons year\(^{-1}\) (Stigebrandt, 2018). \(\text{LPS}\) culminated in the 1980s and in 2014 it had about the same value as in the middle of the 1950s (Figure 1). Despite this, the observed winter surface layer P concentration \(c_1\) still increases (Figure 1). This runway change of \(c_1\) cannot be explained as a simple response to the constant \(\text{OPS}\) and the declining \(\text{LPS}\).

It is well-known that anoxic conditions in the bottom water permit an internal P source, \(\text{IPS}\), from P storages in bottom sediments (Mortimer, 1941; Emeis et al., 2000; Gustafsson and Stigebrandt, 2007; Viktorsson et al., 2013; Stigebrandt et al., 2014; Hall et al., 2017; Sommer et al., 2017). The \(\text{IPS}\) in the Baltic proper has been described as a continuous reflux of P from the sediment during anoxic periods with hydrogen sulfide in the bottom waters (Emeis et al., 2000) although Gustafsson and Stigebrandt (2007) described the reflux as a single-dose release when the bottoms turned anoxic. Stigebrandt et al. (2014) suggested that \(\text{IPS}\) can be described as a continuous reflux proportional to the area \(\text{Aanox}\) of anoxic bottoms, thus \(\text{IPS} = \beta \cdot \text{Aanox}\) tons year\(^{-1}\). This formulation implies that \(\text{IPS}\) vanishes in the Baltic proper when \(\text{Aanox}\) vanishes which is supported by Stigebrandt and Kalén (2013) and Viktorsson et al. (2013). Additional support

![Figure 1](https://example.com/figure1.png)
is provided by Almroth-Rosell et al. (2015) who show that the P release rate from the sediment drastically decreased because of bottom water oxygenation by MBIs. Furthermore, sediment profile imagery showed that the deepwater sediment surface was oxygenated within a couple of months during natural oxygenation by a huge MBI (Rosenberg et al., 2016). This shows that the upward flux of hydrogen sulfide and ammonium, produced by anaerobic decomposition of organic matter in the deepwater sediments, is not large enough to hinder the formation of anoxic layer, containing P-adsorbing iron oxides, on top of the sediment when the bottom water is oxygenated. This contrasts with the situation in much more eutrophic lakes where the water/sediment interface remained anoxic during artificial oxygenation of the bottom water (Gächter and Wehli, 1998; Katsev and Dittrich, 2013). Much of the experience from highly eutrophicated lakes where restoration by oxygenation has failed is not applicable to the mildly eutrophicated salt-stratified Baltic proper (Stigebrandt, 2018).

Following Van Nes et al. (2016), the term tipping point may be used for any situation where accelerating change caused by a positive feedback drives the system to a new state. The tipping point is associated with the critical level at which a transition occurs. Once the threshold is passed, the dynamics of the system accelerate to cause a runaway change. The observed runaway change of $c_1$ in the Baltic proper (Figure 1) suggests that there is a positive feedback between the observed state $c_1$ and the total P supply $TPS$. The internal P supply $IPS$ may provide such a positive feedback via its dependence on $Anox$. In the beginning of the 1960s, when anoxia established in the deep basins of the Baltic proper, it was observed that large amounts of phosphorus accumulated in the anoxic deepwater (Fonselius, 1962). Apparently, the onset of anoxia turned on an $IPS$. The total P source $TPS = LPS + OPS + IPS$ thereby obtained a component, $IPS$, that gives a positive feedback to the area of anoxic bottoms which is dependent on the production of organic matter in the surface layer and thereby controlled by $c_1$.

Using the P budget model described in the section Model, we compute $c_1$ ($c_{1\text{mod}}$) for the period 1950–2014. The model is forced by known values of the external sources $LPS$ and $OPS$. It is also forced by an internal source $IPS$, computed from $IPS = f_s \cdot A_{Anox}$, where $A_{Anox}$ ($\text{km}^2$) is known from observations and the parameter $f_s$ ($\text{tons km}^{-2} \text{year}^{-1}$) is the specific P flux. The model is also forced by the internal and external sinks that are computed from $c_1 \cdot TRVF$, where the parameter $TRVF$ is the
annual volume flow (km$^3$ year$^{-1}$) carrying P to the sinks. Using the method of least squares, we determine the best estimate of the parameters TRVF and $f_s$, giving the best correspondence between the modeled $c_{1mod}$ and the observed $c_{lobs}$ concentration of P in the surface layer. This application of the model is diagnostic, allowing us to show that it is necessary to include $IPS$ in the P budget to explain the evolution of the observed state $c_{lobs}$. We also use the model to discuss effects of shutting off $IPS$ and reducing $LPS$ with the aim to force $TPS$ below its threshold value.

**MATERIALS AND METHODS**

**Data**

Nutrient load compilations are carried out by all HELCOM countries to evaluate and quantify the amount of nutrients annually discharged from land into the sea. The data are obtained from national monitoring programs and reporting from industries and municipal water works. Data for the annual land-based supply of phosphorus $LPS$ for the period 1970–2014 are obtained from Savchuk (2018) who use the best available estimates of external nutrient inputs from terrestrial sources (rivers, direct point, and diffusive sources) and the small atmospheric contribution. The supply for 1951–1969 is obtained by linear interpolation between the supply in 1950 from Savchuk et al. (2012) and the supply in 1970. For model purposes the water body is partitioned into two layers. The 60 m thick surface layer is thoroughly mixed down to the halocline each winter and below this is the lower layer. The observed P contents $V_1c_1$ and $V_2c_2$ in winter in the upper and lower layers of volumes $V_1$ and $V_2$, respectively, are volume weighted estimates obtained from vertical profiles of hydrographical data (of total phosphorus TP) from the main basins in the Baltic proper (Figure 2), obtained in the months December, January and February, from the hydrographical stations BY2, BY5, BY15, BY29, BY31 (ICES, 2020) and from station LL5 (SMHI, 2020) together with the hypsographic functions of the main basins, estimated from a hypsographic data base (Seifert et al., 2001). The observed time series of the P contents $V_1c_1$ and $V_2c_2$ describe the evolution of the system. The time series start 1968, before this year there are only sporadic P observations (see e.g., Stigebrandt, 2018). Examples of TP profiles from the East Gotland Basin are shown in Supplementary Figure 2.

The total area $A_{anox}$ of anoxic bottoms in the Baltic proper for the period 1960–2018 are adopted from Hansson et al. (2019). In the period 1950–1959 there were apparently no anoxic bottoms, i.e., $A_{anox} = 0$ for these years. Hansson et al. (2019) use spatial interpolation of distributed oxygen profiles throughout the Baltic proper for the period August to October to determine $A_{anox}$ which should be a robust approach. To investigate how well these values of $A_{anox}$ may represent annual means, we computed both the annual oxygen mean and the oxygen mean for the period August to October in the deepwater of the Eastern, Northern and Western Gotland Basins. In the Eastern Basin there is practically no difference between the annual mean and the mean for the period August to October (Supplementary Table 2A), which means that there is almost no seasonal variation of the depth of the oxic-anoxic border. In the Northern and Western Basins (Supplementary Tables 2B,C, respectively), the oxic-anoxic border is about 7 m shallower in August to October than the annual mean. However, since the oxygen gradient at the oxic-anoxic border is quite weak, it is not

**FIGURE 3** | The mean seasonal cycles of PO$_4$ and DIN/16 at the sea surface (0 m) at BY 15 in the East Gotland Basin in the period 2004–2018. Data from SMHI (2020).

**FIGURE 4** | The long-term (1968–2018) evolution of the volume-weighted NP ratio, here (NO$_3$ + NH$_4$)/PO$_4$ in winter in the 60 m thick surface layer and in the deepwater of the Baltic proper. Data from SMHI (2020).
obvious that an oxidized layer, stopping the IPS, will develop on top of an anoxic sediment when exposed to water with very low oxygen concentration during a fraction of a year. We therefore assume that the values of Aanox estimated by Hansson et al. (2019) may rather well represent annual means in the Baltic proper. In the model, annual values of IPS are computed from the values of Aanox. A constant value of OPS is added to the model. The annual value of OPS was quite stable at about 10 ktons year\(^{-1}\) during the whole period. From their Figure 11 it seems that MBIs do not drive major inter-annual variability in OPS. The time series of c1, LPS, and Aanox are drawn in Figure 1. The observed values of LPS, Aanox, V1c1 and V2c2 are given in Supplementary Table 1.

In anoxic water in the Baltic proper, ammonia has been measured about 6 times more frequently than hydrogen sulfide as estimated from the hydrographical database Shark (SMHI, 2020). There is a quite good correlation between ammonium and hydrogen sulfide that we use to compute the concentration of hydrogen sulfide from the concentration of ammonium as follows; \(H_2S = 4.18 \cdot NH_4 - 5.89\) if \(NH_4 > 1.41\) and \(O_2 = 0\); otherwise \(H_2S = 0\). The oxygen debt is defined as the amount of oxygen needed to oxidize all hydrogen sulfide and ammonium present in the anoxic water column. The “concentration” of oxygen debt \(O_2d(t,z,i)\) at the time \(t\) and depth \(z\) in sub-basin \(i\), is computed as follows; \(O_2d(t,z,i) = 2 \cdot H_2S(t,z,i) + 2 \cdot NH_4(t,z,i)\) (mmol m\(^{-3}\)), e.g., Reed et al. (2011). The total mass of the oxygen debt \(O_2d(t,i)\) in the deepwater of sub-basin \(i\) at time \(t\) is obtained from the volume weighted vertical integral of \(O_2d(t,z,i)\).

**Model**

We apply a time-dependent model of the total amount of phosphorus P in the water column of the Baltic proper (Stigebrandt, 2018). The purpose of the model is to describe the long term evolution of the amount of P and this is best done by describing the state in winter when there is no primary production and the surface layer is reset by vertical mixing and entrainment of deepwater. In this type of model, the annual nutrient sink is related to the magnitude of the annual biological production which is assumed to be proportional to the surface layer winter concentration of the limiting nutrient (Vollenweider, 1969), which in the present case is P. Our model is a source-sink model of the type described by Vollenweider (1969) for lakes but compared to his model, our model is generalized in three ways namely; (i) introduction of time-dependence, (ii) introduction of an internal P source from anoxic bottoms, (iii) introduction of two layers to account for effects of long residence time of the deepwater due to permanent salinity stratification. Essential features of the model are shown in Figure 5. Our model deals only with annual fluxes from sources and sinks of P and this is not resolved in the present model. P will accumulate in the deepwater due to the several-years-long residence time of the deepwater in the Baltic proper, which is due to the salinity stratification. We account for this by the introduction of two layers in the model. In a two-layer context,
The total amount of P in winter in the water column $V_\Omega$ is composed of contributions from the upper and lower layers, thus

$$V_\Omega = V1 \cdot c1 + V2 \cdot c2 \quad (1)$$

Here $\Omega$ is the winter volume mean concentration of P in the water column and $V$ is the volume of the Baltic proper and $V1$ ($V2$) the volume of the upper (lower) layer and $c1$ ($c2$) is the winter volume mean concentration in the upper (lower) layer. The upper layer encompasses the depth interval 0–60 m and it has the volume $V1 = 10,790 \text{ km}^3$. The lower layer, beneath 60 m depth, has the volume $V2 = 3,990 \text{ km}^3$ (Stigebrandt, 2018).

The total amount of P in the water column of the Baltic proper changes with time $t$ as follows,

$$\frac{dV}{dt} = TPS + TP_{sink} \quad (2)$$

The term on the left side is the rate of change of P stored in the water column and the terms on the right side are the total P source $TPS$ and the total P sink $TP_{sink}$, acting on the water column of the Baltic proper. The time resolution $dt$ in Equation (2) equals one year. $TPS$ is the sum of the external sources $EPS$, i.e., the land-based source $LPS$ and the ocean source $OPS$, and the internal source, $IPS$, thus

$$TPS = EPS + IPS = LPS + OPS + IPS \quad (3)$$

The total sink $TP_{sink}$ has two components, the internal $IPS_{sink}$ and the external $EPS_{sink}$. The internal sink $IPS_{sink}$ is mainly located to the seabed and the external sink $EPS_{sink}$ is due to export of P with surface water to Kattegat (the ocean). The annual removal rate of P from the surface layer to $IPS_{sink}$ is related to the biological production and it is assumed to be proportional to $c1$ (Vollenweider, 1969). Since the photic zone in the Baltic proper is about 15 m, c.f. Kratzer et al. (2003), primary production should occur only in the surface layer. In the model also $EPS_{sink}$ is proportional to $c1$ and to the outflow of surface water which equals the sum of the freshwater supply $Qf$ and the inflow of ocean water (Wulff and Stigebrandt, 1989). $TP_{sink}$ can thus be written (Stigebrandt, 2018)

$$TP_{sink} = -c1 \cdot TRVF \quad (4)$$

Here the parameter $TRVF$ is the Total Removal Volume Flux ($\text{km}^3 \text{ year}^{-1}$), carrying P to the internal and external sinks. In the present application we can estimate the parameter $TRVF$ and thereby the total P sink $TP_{sink}$. To estimate the sink components $EPS_{sink}$ and $IPS_{sink}$, other methods must be used as briefly discussed later under section Results.

The nature of the internal P source $IPS$ was briefly discussed in the Introduction. $IPS$ is parameterized in the following way (Stigebrandt et al., 2014)

$$IPS = fs \cdot Aanox \quad (5)$$

Here $Aanox$ ($\text{km}^2$) is the area of anoxic bottoms in the Baltic proper and the parameter $fs$ (tons $\text{ km}^{-2} \text{ year}^{-1}$) the specific P flux from anoxic bottoms.

For simplicity, the following empirical relationship between $c1$ and $c2$ is introduced (Stigebrandt, 2018)

$$V2 \cdot c2 = \alpha \cdot V1 \cdot c1 \quad (6)$$

Here the empirical parameter $\alpha$ equals the average ratio between the amounts of P in winter in the lower and upper layers, respectively. The value of $\alpha$ is determined by the residence time of the lower layer and $\alpha$ should be stable in time if the long-term mean vertical circulation does not change. Using this relationship simplifies the model and implies that we replace two equations, one for each layer, by one equation for the upper layer.

Using observed annual values of the total P content in winter in the upper and lowers layers, $V1 \cdot c1$ and $V2 \cdot c2$, the mean value of $\alpha$ is computed as follows,

$$\alpha = \frac{\sum V2c2(i)}{\sum V1c1(i)} \quad (7)$$

Here the summation index $i$ runs from 1968 to 2018 for which period interval P has been observed regularly in the Baltic proper, see the section Data. It is found that $\alpha$ for that period equals 1.15. Using Equation (6), it follows that as an average there are 15% more P in the lower than in the upper layer and $c2 = 3.1 \cdot c1$.

In the model, the ratio $\alpha$ occurs only in the combination $K = (1 + \alpha)$. It is therefore reasonable to investigate how K varies in time. The mean value of $K = 2.15$. Values vary between 1.73 and 2.74 (Figure 6) and the standard deviation of $K = 0.20$. With these modest variations of K, we conclude that it is reasonable to use a constant value of $\alpha$ to simplify the model.
Using Equations (1), (4), and (6), we can rewrite Equation (2) as follows

$$ \frac{dc_1}{dt} = \frac{TPS - c_1 \cdot TRVF}{K \cdot V1} \quad (8) $$

From this follows that the lower layer, through the parameter $\alpha$, increases the inertia and thus the spin-up time of the system.

Equation (8) shows that $dc_1/dt > 0$ when the total source $TPS$ is greater than the total sink $c_1 \cdot TRVF$ and vice versa. In the present paper we integrate Equation (8) to compute the evolution of the concentration $c_1$ in the surface layer, starting from 1950.

The equilibrium concentration $c_{le}$ in the surface layer in winter occurs under steady-state (equilibrium) conditions when $dc_1/dt = 0$. For this case Equation (8) gives

$$ c_{le} = \frac{TPS}{TRVF} \quad (9) $$

The equilibrium concentration $c_{le}$ is thus proportional to the total P supply $TPS$ to the water column of the Baltic proper. Please note that the ratio $\alpha$ between the amounts of P in the lower and upper layers does not influence the equilibrium concentration $c_{le}$. This is easily realized because the sink is proportional to the surface concentration $c_1$, see Equation (4).

Analytical solutions of the time-dependent model for two cases, Case 1 and Case 2 were discussed by Stigebrandt (2018). Case 2 has the same vertical stratification as the model in the present paper. In Case 1, the salt stratification, and thereby the lower layer, is absent and is thus only one layer of volume $V = V1 + V2$. This situation has not been observed in the Baltic proper and should therefore be quite unusual. However, when it happens the deep bottoms are oxygenated by the surface layer, which is well-oxygenated through direct contact with the atmosphere at the sea surface, and this should be an efficient way for “self-restoration” of the Baltic proper (Stigebrandt, 2018). This is further discussed in the section Self-Restoration of Historic Episodes of Eutrophication in the Baltic Proper.

For Case 2, the two-layer case, Stigebrandt (2018) showed that the e-folding time $T$ equals

$$ T = \frac{V1}{TRVF} \quad (10) $$

The time-scale $T$ is inversely proportional to the total sink flux $TRVF$. The existence of a lower layer (i.e., $K > 1$) increases $T$, and thereby the time to reach equilibrium. Please note that $T$ is independent of the magnitude of the P source $TPS$.

Stigebrandt (2018) introduced the restoration time $TR$, defined as the time it takes to achieve 95% of the expected concentration change due to an instantaneous change of $TPS$, which is approximately described by the following relationship

$$ TR = 3T \quad (11) $$

In the present application of the model, $TRVF$ in Equation (4) and $fs$ in Equation (5) are unknown parameters that govern the total sink and the internal source, respectively. We apply the least squares method to determine the best estimate of $TRVF$ and $fs$. The best fit in the least-squares sense minimizes the sum of squared residual $Ssr$. The residual is the difference between the observed value $c_{lobs}$ and the value $c_{mod}$ computed by the model. $Ssr(TRVF, fs)$ is defined as follows

$$ Ssr(TRVF, fs) = \sum_{i=1}^{N} (c_{lobs(i)} - c_{mod(i)})^2 \quad (12) $$

Here $N$ is the length (number of years) of the observational series $c_{lobs}$. In the present application $N$ equals 47 years (1968–2014). We compute $Ssr(TRVF, fs)$ for wide ranges in the parameter space $(TRVF, fs)$. The best estimate is given by the pair of values of $TRVF, fs$ that gives the least value of the sum of squared residual $Ssr(TRVF, fs)$.

**RESULTS**

**Estimation of the Parameters TRVF and fs**

We first apply the method of least squares to find the pair of values of the parameters $TRVF$ and $fs$, regulating the internal and external sinks and the internal source, respectively, that gives the best model description $c_{mod}$ of the observations $c_{lobs}$. Using the time series of $LPS$ and $Aanox$ and the constant value of $OPS$, see the section Data, and the initial value $c_1i = 0.20$ mmol m$^{-3}$ at the start of the computations in 1950, Equation (8) was integrated to compute the year to year evolution of the P concentration $c_{mod}$ in the surface layer in winter in the Baltic proper in the period 1950–2014. We repeated the computations for values of $TRVF$ from 1,800 to 5,000 km$^3$ year$^{-1}$ and values of $fs$ from 0 to 3 (tons km$^{-2}$ year$^{-1}$). We found that the least value of the sum of squared residual $Ssr(TRVF, fs)$, defined by Equation (12), equals 0.50 (mmol m$^{-3}$)$^2$. It occurs for the pair $TRVF = 3,000$ km$^3$ year$^{-1}$ and $fs = 1.22$ (tons km$^{-2}$ year$^{-1}$). Before plotting $Ssr(TRVF, fs)$ in Figure 7, we normalized by division with the least value, i.e., 0.50. It can be seen (Figure 7) that good solutions (i.e., small values of $Ssr$) are obtained for an elongated, trench-formed area of the parameter space, clearly showing that $TRVF$ and $fs$ are dependent, a greater source ($fs$) requires a greater sink ($TRVF$) and vice versa. However, as further discussed in the section The Baltic Proper Response to $IPS$, it is not possible to obtain the runaway behavior shown by $c_{lobs}$ from a model lacking an internal source $IPS$, i.e., with $fs = 0$.

The analysis gives the total sink flow $TRVF = 3,000$ km$^3$ year$^{-1}$. This solution does not depend upon the partition between different kinds of sinks. If needed, partition of the total sink into the two main sink components, $IPSink$ and $EPSink$, must be performed using other methods. The part of $TRVF$ belonging to the external sink $EPSink$ equals 720 km$^3$ year$^{-1}$ according to Wulff and Stigebrandt (1989). The part of $TRVF$ belonging to the internal sink, $IPSink$, should then be 2,280 km$^3$ year$^{-1}$ and the (fix) ratio between the external and internal sinks, $EPSink/IPSink$, equals 0.32. The external sink by export to the ocean (Kattegat) is responsible for 720/3,000 = 24% of the total sink.

**Initial Value and Spin-Up Time**

Due to lack of observational data, the initial value $c_1i$, in 1950, is not known. We run the model with $c_1i$ equal to 0.15, 0.20, and
95% of the change due to an instantaneous change of 0.25 mmol m$^{-2}$ to study the importance of the initial value for the result of the computations. From Equation (10) and using $K = 2.15$ and $TRVF = 3,000$ km$^2$ year$^{-1}$, one finds that the time constant $T$ of the system is about 7.7 years (e-folding time). 95% of the change due to an instantaneous change of $c_1$ should have occurred after the time $TR = 3T$, see Equation (11). The curves for the runs with different initial concentrations converge (Figure 8), showing that the memory of the chosen initial value is almost lost after about 23 years as predicted by Equation (11). We can also call this time the spin-up time. This spin-up time implies that our estimate of the best fit of $TRVF$ and $fs$ in the previous section, starting the computations in 1950 and using data on $c1mod$ beginning in 1968, should be very little influenced by the chosen initial value $c1i$.

**Model Performance**

The long-term evolution of $c1$ computed by the model for the best fit case, i.e., with $TRVF = 3,000$ km$^2$ year$^{-1}$ and $fs = 1.22$ tons km$^{-2}$ year$^{-1}$, mimics the observed concentration quite well and this comparison provides a successful test of the model (Figure 8). It should be noted that the large reduction of the land-based P source $LPS$ after the 1980s is not accompanied by a corresponding decrease of $c1obs$ (Figure 1). On the contrary, $c1obs$ shows an increasing runaway change after the 1990s, like the evolution of $Aanox$ and $IPS$. We conclude that the favorable comparison between $c1mod$ and $c1obs$ (Figure 8) shows that the internal P source $IPS$ as estimated in the present paper is of decisive importance for the successful model description of the evolution of $c1$ in the anoxic Baltic proper, see also the section The Baltic Proper Response to $IPS$.

**Evolution of Sinks and Sources**

The evolution of the total sink $TPsink$ and the total source $TPS$ and its components $LPS$, $OPS$ and $IPS$ are shown in Figure 9 for the best fit case displayed in Figure 8. As from about year 2000, the internal source $IPS$ is about 50 ktons year$^{-1}$ which is about two times larger than present time $LPS$ (Figure 9). The evolution of $IPS$ caused $TPS$ to increase from about 1997 which explains the obvious runaway change of $c1$ after the end of the 1990s. For comparison, we note that the internal sink $IPsink (\approx 2,280/3,000 TPsink)$ is about 50 ktons year$^{-1}$ after year 2000. The curve $IPsink + IPS$ (red) shows that there was a net growth (i.e., negative values) of the internal storage before year 2000, which thereafter has ceased (Figure 9).

We recall that $OPS$, the estimated oceanic import, equals 11 ktons year$^{-1}$. The export to the ocean $EPSink = 720/3,000 \cdot TPsink$, increases with $c1$ and before about 1965, $OPS$ was greater than $EPSink$ implying that the Baltic proper had a net import of $P$ from the ocean. Thereafter the Baltic proper has had a net export to the ocean and the present time net export ($EPSink – OPS$) is about 6 ktons year$^{-1}$.

**The Baltic Proper Response to $IPS$**

To further elucidate the effect of $IPS$, we compare the best fit curve $c1mod$ (with $TRVF = 3,000; fs = 1.22$), which rather well describes the evolution of $c1obs$, and the curve $c1hyp$ ($TRVF = 3,100; fs = 0$) which is the hypothetical evolution of $c1$ if $Aanox = 0$ and $IPS = 0$ for the period 1950–2014 (Figure 10). The curve $c1hyp$ thus shows the hypothetical response of the Baltic proper in the absence of $IPS$ so that the total P supply equals $LPS$. 

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**Figure captions**

- **Figure 7**: Model results showing the normalized sum of the squared residual $Ssr(\text{TRVF}, fs)$, see Equation (12), in the parameter space $1.800 \leq \text{TRVF} \leq 5.000$, $0 \leq fs \leq 3$. The least value of $Ssr(\text{TRVF}, fs)$ occurs for $\text{TRVF} = 3,000$ km$^2$ year$^{-1}$ and $fs = 1.22$ tons km$^{-2}$ year$^{-1}$.

- **Figure 8**: Computational results $c1mod$ from the best fit model with $fs = 1.22$ tons km$^{-2}$ year$^{-1}$ and $\text{TRVF} = 3,000$ km$^2$ year$^{-1}$. Three different initial concentrations $c1i$ were applied. The graphs show the computed concentration $c1mod$ 1950–2014 (black lines) and the observed concentration $c1obs$ 1968–2014 (red line) of phosphorus in the surface layer in winter.
concluded from the results of their Baltic Sea P-budget during the second half of the 1950s. According to c1 and c2 feedback. Due to the typically decadal-long residence time of the accompanying curves they took different routes. The existence of anoxic bottoms and about 0.27 mmol m$^{-2}$-year$^{-1}$ estimate that TPS$\leq$LPS, c1 turned on the IPS when anoxic bottoms established and during several years in the period 1963–1988 (Figure 9). The computed curves c1mod and c1hyp shows the contribution by the internal supply IPS (Figure 10). The role of IPS increased rapidly at the end of the 1990s and at the present, IPS is evidently a major driver of the eutrophication of the Baltic proper. This is also evident from the evolution of LPS, OPS, and IPS (Figure 9) as discussed above. Apparently, the IPS has severely boosted and perpetuated the eutrophication of the Baltic proper. Interestingly, IPS was relatively large already during several years in the period 1963–1988 (Figure 9) but to the best of the authors’ knowledge, the effect of IPS in that period has not earlier been quantified. However, Wulf and Stigebrandt (1989) concluded from the results of their Baltic Sea P-budget modeling, using data from the 1970s, that there seemed to be a contribution from an internal P source, but they did not estimate its magnitude.

The computed curves c1mod and c1hyp (Figure 10) are identical from the start in 1950 to the onset of deepwater anoxia in 1960. Anoxia occurred because c1 increased, due to increasing LPS, and passed the threshold value c1m making the deepwater oxygen consumption larger than the oxygen supply. The system passed a tipping point when anoxic bottoms established and turned on the IPS which affects c1mod, but not c1hyp, and the curves took different routes. The existence of anoxic bottoms and the accompanying IPS means that the system obtains a positive P feedback. Due to the typically decadal-long residence time of the deepwater, the threshold value c1 was likely passed in the second half of the 1950s. According to Stigebrandt (2018), c1 was about 0.27 mmol m$^{-3}$ in 1958 and we adopt this value for c1. We estimate that TPS was about 36 ktons year$^{-1}$ when the threshold value c1 was passed (Figure 9). This value of TPS should thus be the threshold value TPS$\leq$ for the total P supply. Since IPS was zero before the tipping point was crossed, the threshold value of the land-based supply LPS$\leq$(=TPS$\leq$−OPS) should be about 25 ktons year$^{-1}$. For larger supplies we expect that c1$>c1t$ and deepwater anoxia may develop and thereby turn on an IPS in the Baltic proper.

**Reversing Eutrophication and Crossing the Tipping Point by Shutting Off IPS**

To predict the future evolution of c1, the unknown area of anoxic bottoms Aanox must be predicted. Normally, this would require the coupling of an oxygen model to our P model. However, for the special case Aanox = 0 due to oxygenation of the bottom water there is no need to predict Aanox and we may use the present model without a coupled oxygen model. We thus use our model to predict the response of c1 to shutting off IPS by keeping all bottoms oxygenated. For these computations, the oxygenation starts in 2015 and we set Aanox(2015) = Aanox(2014)/2. For 2016 and the subsequent years we set Aanox = 0. The IPS time series is extrapolated to 2050 by assuming an annual reduction of LPS by 0.5 ktons year$^{-1}$ for the subsequent years from the value in 2014 which is consistent with the Baltic Sea Action Plan (HELCOM, 2007).

The result of the computations for the period 2014–2050 is shown on the right-hand-side of Figure 10. The computed concentration c1mod decreases drastically in an exponential way when IPS is shut off and approaches asymptotically the curve c1hyp. The timescale of this adjustment process is given by the restoration time RT, see Equation (11), which we above estimated to about 23 years. At about 2044, c1mod is predicted to have declined below the threshold concentration c1 implying that the Baltic proper has been restored to a state below the tipping point like that in the early 1950s.

During the oxygenation process, most of the P that is removed from the water column (about 500 ktons) will end up in the internal sink IPsink. The export EPsink of P to the Kattegat (ocean) by the export of surface water will decrease rapidly since the export is proportional to c1. In the restored state, there will be a net import of P (OPS + EPsink $>0$) from Kattegat, like before about 1965 as discussed above. In the simulation, LPS is reduced by 0.5 ktons year$^{-1}$ for the whole period after 2014, see the section Data, and therefore c1hyp is slowly decreasing until the end of the simulation in 2050 (Figure 10).

**DISCUSSION AND CONCLUDING REMARKS**

The specific flux $f_s$ of P from anoxic bottoms estimated in the present paper, 1.22 tons km$^{-2}$ year$^{-1}$, is only about 53% of the flux estimated by Stigebrandt et al. (2014) from a P budget using observational data from only 2 years (1980 and 2005). The $f_s$-value computed in the present paper should be the correct value to use because (i) it is derived using a budget model and the least squares method and 47 years of observational data describing the state c1obs of the Baltic proper, (ii) the model describes quite well...
the runaway evolution of $c_{1obs}$ during the last decades despite a simultaneously halved $LPS$. The value of $fs$ estimated in this way represents the temporal average over many (47) years and the spatial average across the model area.

The results from our model may be compared to results obtained from more complex biogeochemical models. Almroth-Rosell et al. (2015) use a detailed biogeochemical model coupled to a high resolution hydrodynamical model. The oxygen penetration in the sediment is computed using 7 empirical constants and the detailed P model contains 14 empirical constants. Simulation of the Baltic proper in the period 1980–2008 shows that compared to observations the modeled oxygen and phosphate concentrations below the halocline are too high and too low, respectively, with largest differences closest to the bottom. They estimated the mean transport of P from anoxic bottoms (i.e., the $IPS$) for the period 1980–2008 to a about 77 ktons year$^{-1}$. For the same period the present model computes a mean $IPS$ of only about 25 ktons year$^{-1}$.

In the section Results, it was shown that the internal P supply $IPS$ from anoxic bottoms gives a positive feedback that boosts and perpetuates eutrophication in the Baltic proper. This self-amplifying process of eutrophication starts when the total P supply $TPS$ exceeds the threshold value $TPSt$ so that anoxic bottoms are created, which obviously is the tipping point of the system, c.f. Van Nes et al. (2016). The discovery that the Baltic proper eutrophication system has passed a tipping point and that $IPS$ is a decisive component that now is the major driver of eutrophication (Figure 9) calls for a paradigm shift for the management strategy for the Baltic Sea that should include sea-based measures to reduce eutrophication.

Self-amplifying eutrophication due to $IPS$ should occur also in other permanently stratified basins with anoxic deepwater. Provided there are long time series of the P content in the water body, and of the external P sources, and of the area $Aanox$ of anoxic bottoms, the magnitude of $IPS$ might be estimated using the same kind of regression analysis as used in the present paper.

**Anoxia Boosts Eutrophication in Two Ways**

Hydrogen sulfide and ammonium from anaerobic decomposition of organic matter in the sediment may
accumulate in anoxic bottom water and thereby contribute to an oxygen debt $O_{2\text{debt}}$ as defined in the section Data. The debt may cause oxygen loss (two moles of oxygen for each mole of hydrogen sulfide and ammonium, respectively) in inflowing new deepwater when this entrains old deepwater with oxygen debt. This should occur geographically in the Bornholm Basin and in the adjacent part of the southern East Gotland Basin (EGB) (e.g., Stigebrandt et al., 2015b). This phenomenon was discussed by Fonselius (1970) who concluded that the Baltic proper no longer in a natural way can recover from what he called “the hydrogen sulfide shocks.” It should be noted that $O_{2\text{debt}}$ in EGB shows a strong increasing trend, starting from small values in the 1970s (Figure 11), which should imply co-occurring decreasing trends in both the oxygen supply and the oxygen content of the deepwater in the EGB. The deepwater oxygen debt should be a more important factor for the observed decrease of the oxygen content in the deepwater of the Baltic proper than the reduction of oxygen saturation due to a higher temperature, which only may explain about 3% reduction of oxygen content per degree Celsius temperature increase, c.f. Carstensen et al. (2014).

As shown by the model in the present paper, anoxia and the accompanying IPS leads to increased $c_1$ and biological production, which increases the oxygen demand in the deepwater. As discussed above, an oxygen debt $O_{2\text{debt}}$ in anoxic deepwater leads to reduced oxygen supply to the deepwater. Thus, anoxia both increases the demand and reduces the supply of oxygen to the deepwater, which tends to increase the oxygen debt in the deepwater and the area of anoxic bottoms and thereby boost IPS and eutrophication.

**Self-Restoration of Historic Episodes of Eutrophication in the Baltic Proper**

The threshold value $TP_{St}$ of the total P supply depends on the rate of oxygen supply to the deepwater. Since the rate of oxygen supply to the deepwater of the Baltic proper varies in time, $TP_{St}$ should be defined for a period of minimum supply of oxygen like that in the 1950s caused by the unrivaled salty inflow in 1951 (Fonselius and Valderrama, 2003). The establishment of extremely strong vertical stratification, like in 1951, will likely prevent oxygen supply to the deep parts of the basins for many consecutive years, which may cause anoxia and thereby IPS and a runaway change of $c_1$ that can explain the emergency of historic periods of eutrophication in the Baltic proper (c.f. Bianchi et al., 2000). The ending of historic periods of eutrophication by episodes of self-restoration was discussed by Stigebrandt (2018). He suggested that the deep bottoms may be oxygenated by contact with the well-oxygenated surface water during sufficiently long episodes of large-amplitude halocline deepening that eliminate the vertical stratification and Aanox and IPS. When this occurs, $c_1$ should decrease as predicted during oxygenation of deepwater bottoms (Figure 10). This scenario is supported by sediment observations of rapid termination of historic anoxic periods (Jilbert and Slomp, 2013). The statistical recurrence time of decadal-long episodes of large-amplitude halocline deepening may be many hundred years (work in progress).

**Business-as-Usual**

The present management strategy to reduce the eutrophication of the Baltic Sea, here called the “business-as-usual” scenario, is to reduce $LPS$ according to the Baltic Sea Action Plan (HELCOM,
2007). The LPS has been successfully reduced since the 1980s (Figure 1; HELCOM, 2017) but this has neither led to reduced cl nor to reduced area Aanox of anoxic bottoms (Figure 1). The reason for this is the positive feedback provided by the IPS as shown in the present paper. Since both the area Aanox of anoxic bottoms (Figure 1) and the oxygen debt O2 debt in EGB (Figure 11) show increasing trends, it is consistent to assume that the self-amplifying eutrophication process driven by IPS from anoxic bottoms will continue with an expected modest rate of increase of cl, as also suggested by the extrapolated linear trend cl obstrend of the observations cl obs (Figure 10).

In the “business-as-usual” scenario one may expect increased annual production of cyanobacteria (Vahtera et al., 2007) and the neurotoxin BMAA (Jonasson et al., 2010). One may also expect still worsened conditions for the Baltic cod which has experienced a strong decline in mean body conditions linked to hypoxia exposure (Limburg and Casini, 2019). An increased cl would also lead to ecological changes at shallower water depths including all coastal and most inshore areas, c.f. Elmgren (1989).

**Sea-Based Measures Stopping the IPS Might Restore the Baltic Sea**

Since IPS from anoxic bottoms is the present time major driver of the eutrophication, as shown in the present paper, it follows that measures to eliminate IPS should be included in the management strategy to reduce the eutrophication of the Baltic proper. In the model simulation for the period 2015–2050 (Figure 10), IPS is shut off by natural or engineered sea-based deepwater oxygenation removing bottom anoxia. The Baltic proper might be restored to a state similar to that prevailing before the crossing of the tipping point in the end of the 1950s. The engineered oxygenation can be turned off when cl < cl t and TPS has been pushed below the threshold value TPS t which means that LPS should be less than LPSt, estimated to about 25 ktons year⁻¹ in the section The Baltic Proper Response to IPS. The measures undertaken on land until now to reduce LPS have been successful (Figure 1) and LPS should be far below LPSt when cl falls below cl t. It should be stressed that all bottoms must be kept oxic during the whole restoration process so that IPS vanishes. If some bottoms remain anoxic, the IPS from these may make TPS greater than TPS t so that restoration would fail. When the deep bottoms have been oxidized and colonized by animals, there might possibly be an IPS of a different kind caused by animal decomposition of organic matter stored in the bottom sediment as discussed in Stigebrandt (2018). However, this should not jeopardize the restoration if TPS < TPS t.

Only systems fulfilling the following requirements can be restored by sustained oxygenation of the bottoms: (i) the IPS from anoxic bottoms provides a major P loading component and (ii) LPS can be reduced to less than LPSt. The anoxic By Fjord, for instance, that was oxygenated during a pilot experiment (Stigebrandt et al., 2015a), does not belong to this category and, as expected, a few years after the end of the experiment the fjord had returned to a state similar to that before the experiment.

The first proposal to oxygenate the deepwater of the Baltic proper to reduce cl was presented by Stigebrandt and Gustafsson (2007) who suggested that the cool and almost oxygen saturated so-called winter water, located above the halocline, should be mixed into the deepwater by pumping. This method was applied in a theoretical experiment of oxygenation of the Bornholm Basin (Figure 2), which shows that the deepwater may be kept well-oxygenated, of great benefit for e.g., the Baltic Sea cod, by mixing about 1,000 m³ s⁻¹ of winter water into the deepwater (Stigebrandt et al., 2015b). Several environmental effects of pumping and mixing 2 m³ s⁻¹ of well-oxygenated surface water of often low salinity into the deepwater were investigated in a pilot experiment in the small anoxic By Fjord (Stigebrandt et al., 2015a). Among others, it was found that the top of the anoxic sediment was oxygenated and colonized within about 1 year. A rapid decrease of sediment phosphate fluxes when anoxic bottoms in eutrophic estuaries were oxygenated by engineered destratification and reaeration was reported by Harris et al. (2015). Different methods to alleviate bottom layer hypoxia through induced downwelling on shallow stratified shelves have recently been described by Koweek et al. (2020) and Xiao et al. (2018).

A recent publication investigating the legal aspects of sea-based engineering measures to combat the eutrophication of the Baltic Sea concludes that the legality of any sea-based measure depends on the risks they present balanced against their benefits (Ringbom et al., 2019). The benefit of a restored Baltic Sea is huge; estimates suggest that the present deteriorated state of the Baltic proper reduces the annual value of Baltic Sea services to mankind by about 32 milliards EUR (Boston Consulting Group, 2013). The annual cost to oxygenate the deep basins by mixing well-oxygenated winter water into the denser deepwater as described in Stigebrandt and Kalén (2013) and Stigebrandt et al. (2015b) should be of the order of 1% of the estimated benefit. The ecological response in the whole water mass to the reduced P concentration c l in the surface layer, and risks, benefits, and costs should be thoroughly described in an Environmental Impact Assessment.

**Important Research Questions**

The specific internal P source f s = 1.22 tons km⁻² year⁻¹ from anoxic bottoms and the total sink flow TRVF=3,000 km² year⁻¹, estimated in the present paper are temporal system averages, determined using 47 years of data on input and response of the Baltic proper to the P loading. There are numerous in situ observations of the flux of P between the seabed and the bottom water (e.g., Viktorsson et al., 2013; Hall et al., 2017; Sommer et al., 2017). These fluxes may obtain contributions from both internal storages (the internal source) and decomposition of fresh organic matter, the latter is not included in our sink-source P-budget model. So far, there are no published estimates of temporal and spatial Baltic proper averages of the reflux from internal storages, based on in situ observations, that may be compared to our value f s = 1.22 tons km⁻² year⁻¹.

The values of f s and TRVF estimated in the present paper can be used to constrain P budgets in more complex models. The total sink flow TRVF is composed of sink flows to internal sinks IP sink and to external sinks EP sink by export to external areas. According to the present model, the total P sink after year 2000, for instance, equals about 65 ktons year⁻¹ (Figure 9). With this constrictions on the total sink, it would be very interesting to set up a table of the magnitude of the partial P sinks,
including sinks in oxic and anoxic bottoms, sinks due to changing masses of living biota, sinks due to fish brought on land and stranded algae, and sinks due to export to Kattegat and the Bothnian Sea.

Finally, more research is needed to describe the nature of the internal P source IPS from anoxic bottoms that still is only vaguely known, e.g., Emeis et al. (2003), Gustafsson and Stigebrandt (2007), Viktorsson et al. (2013), Stigebrandt et al. (2014), Hall et al. (2017), Sommer et al. (2017). The $f_s$-value estimated in the present paper includes all internal sources and cannot differentiate between continuous and short-term single-dose releases from oxic bottoms that turn anoxic. As a first step toward learning more about IPS it would be important if the relative magnitudes of these two types of contributions to IPS could be estimated.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Materials, further inquiries can be directed to the corresponding author.

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AUTHOR CONTRIBUTIONS

AS designed the study and wrote the manuscript. AA prepared data, made the calculations, prepared the figures. AS and AA discussed the results. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTAL MATERIAL

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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