HELCOM ACTION

# Analysis of total nitrogen in the Baltic Sea and implications for time lag in achieving good environmental status (GES)

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Eutrophication

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# Analysis of total nitrogen in the Baltic Sea and implications for time lag in achieving good environmental status (GES)

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### Abbreviations

| | |
|---|---|
| DIN | Dissolved inorganic nitrogen |
| DON | Dissolved organic nitrogen |
| GES | Good environmental status |
| MSFD | Marine Strategy Framework Directive |
| N | Nitrogen |
| PN | Particulate Nitrogen |
| TN- | Total nitrogen |

## 1. Aim

The overall aim of work package five in the HELCOM ACTION project is to gain a better understanding of the conditions in the Baltic Sea that influence the achievement of a good environmental status (GES), including natural conditions that cause a time-lag between implemented measures established and their effects in the marine system.

This report will analyze reasons for not achieving GES regarding eutrophication. The focus is on trends in total nitrogen (TN) loads to the Baltic Sea and TN concentrations in the water column. The analysis is based on data reported to the ICES database (> 300 000 data points) by the HELCOM member states. We present scenarios for the development of the TN pool and possible time lags between measures implemented and effects detected in the Baltic Sea.

## 2. Introduction

The Baltic Sea has received increased inputs of nutrients primarily from rivers and the atmosphere since the beginning of the 20´th century (Gustafsson et al. 2012). This increased nutrient flux has been largely linked with the intensification of agricultural activities including livestock production, discharge of urban sewage, industrial wastes, and fossil fuel burning (Galloway et al. 2004). Draining of wetlands, removal of lakes and channeling of rivers have removed some of the filtering and buffering capacity between fields and river, meaning that a larger proportion of the loss from agricultural activities reach the Baltic Sea These elevated inputs have induced a number of undesired changes in the ecosystem commonly termed eutrophication. In Fig. 1 we present a conceptual outline of these processes and their effect in the ecosystem. The processes and the effects on the ecosystem is described elsewhere (e.g.(Krause-Jensen et al. 2011; Lyngsgaard et al. 2014; Markager et al. 2011; Riemann et al. 2015). The aim in this report is to describe, and if possible quantify the time lag in the Baltic Sea from a possible reduction in nutrient inputs leading to a significant reduction in the negative ecosystem effects so the system can reach good environmental status (GES) according to the Marine Strategy Framework Directive (MSFD). It is clear that such a time lag is counted in decades. On such a time frame, many processes where nutrients are cycled through phytoplankton biomass and the organic matter pool (Fig. 1) will vary due to differences in the levels of nutrients, changes in species composition and other factors, e.g. climate change. However, the main factors which impacts eutrophication is the total pool of nutrients from which the bioavailable nutrients (as inorganic or bioavailable organic forms) are taken up by the biota. We have therefore chosen to focus on this pool and established a budget for this pool focusing on the inputs and outputs – outlined in red in Fig. 1.

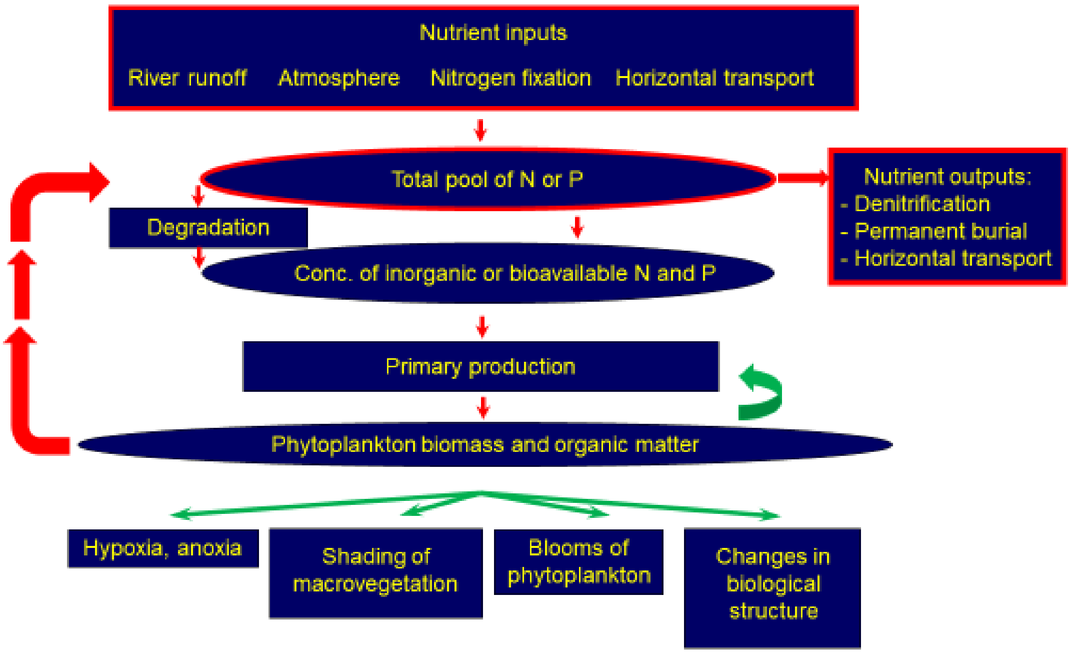

**Figure 1.** Conceptual model for eutrophication. The red arrow represent a flow of nutrients, the green arrow represent relationships which do not necessarily include nutrients, squares are processes and ellipses are pools. The focus of this analysis is highlighted with a red outline.

In the Baltic Sea, marine primary production is chiefly limited by the availability of nitrogen (N), but phosphorus can also be important in limiting production in certain geographical areas and during parts of the year (Tamminen and Andersen 2007). As a result, management actions, such as the HELCOM action plan, have aimed at improving ecosystem health in the Baltic Sea by reducing nutrient loads, with larger reduction targets for N compared with phosphorus (e.g.(Backer et al. 2010).

In marine environments, total N (TN) occurs in a variety of forms including dissolved inorganic nitrogen (DIN; Ammonium (NH4+), Nitrite (NO2-) and Nitrate (NO3-)) and both particulate (PN) and dissolved organic nitrogen (DON)[1]. The organic fractions of TN are present in both living marine organisms and non-living parts and exist across a wide continuum of sizes and structural complexities, ranging from simple amino acids through to detritus derived from e.g. plankton. All DIN forms can easily be assimilated by primary producers (e.g. phytoplankton, seagrasses), and can be assumed with confidence to be 100% available for growth ("bioavailable") over short timescales (min to days). On the other hand, not all organic compounds included in PN and DON are bioavailable for microbes over time scales (days) relevant for their growth, although a variable part can be consumed by microbes over short timescales (days) (Jørgensen et al. 2013; Knudsen-Leerbeck et al. 2017; Lønborg and Álvarez-Salgado 2012). Photodegradation of PN and DON is also an important process where

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[1] The distinction between dissolved and particulate forms of organic N is strictly operational. Particulate N is usually regarded as N, which can be collected mechanically; normally on a filter with a pore size between 0.2 and 0.7 µm. Dissolved N is what passes through the filter.

N is converted from organic to inorganic forms (Stedmon et al. 2007). In this report we used TN concentrations to account for all potential available N in the system. This includes all organic and inorganic forms of N, dissolved as well as suspended and particulate. We implicit assume that, over a time scale of decades to hundred year, will N circulate and be exchanged between sub-pools, so that all N can be regarded as belonging to one common pool. However, we do consider permanent burial of N as a sink.

In order to better understand the complex sources, delivery, transformation pathways, and fate of TN in the Baltic Sea we will: 1) determine the long-term changes in TN, 2) construct a simple TN budget, and 3) present possible scenarios for the time lag between implemented measures and their effects in the Baltic Sea. For simplicity we restrict our study to N, but this does not suggest that phosphorus is less important to the health of the Baltic Sea. The hope is that this information will improve our knowledge of the system and help make informed policy decisions that can support the recovery of the Baltic Sea.

## 3. Approaches and results

*Data compilation and long-term trends* – The river discharge into the Baltic Sea and TN loads for the period from 1995 to 2016 were obtained from the HELCOM data portal[2,3]. The water column TN concentrations were compiled from the ICES data base[4] and two criteria were applied for the inclusion of data. The criteria for the selection were that stations: 1) should have data after 2010 and a continuous time series of minimum 25 years or 2) should have data before 1975 and a continuous time series of minimum 10 years. Application of these two criteria resulted in the inclusion of 229 stations with a total of 330,000 observations spanning from 1923 to February 2019. These 229 stations are distributed widely in the Baltic Sea (Fig. 2). The data was grouped into the seven sub basins according to the Pollution Load Compilation areas and categorized as 'coastal' i.e. within 1 nautical mile from the coastline, 'intermediate' i.e. between 1 and 12 nm from the coastline, and 'offshore' i.e. further than 12 nm the coastline. In total, 62 stations were categorized as 'coastal', 98 stations as 'intermediate', and 69 stations as 'offshore'. Table 1 gives an overview of the distribution, average loads and concentrations in these sub basins.

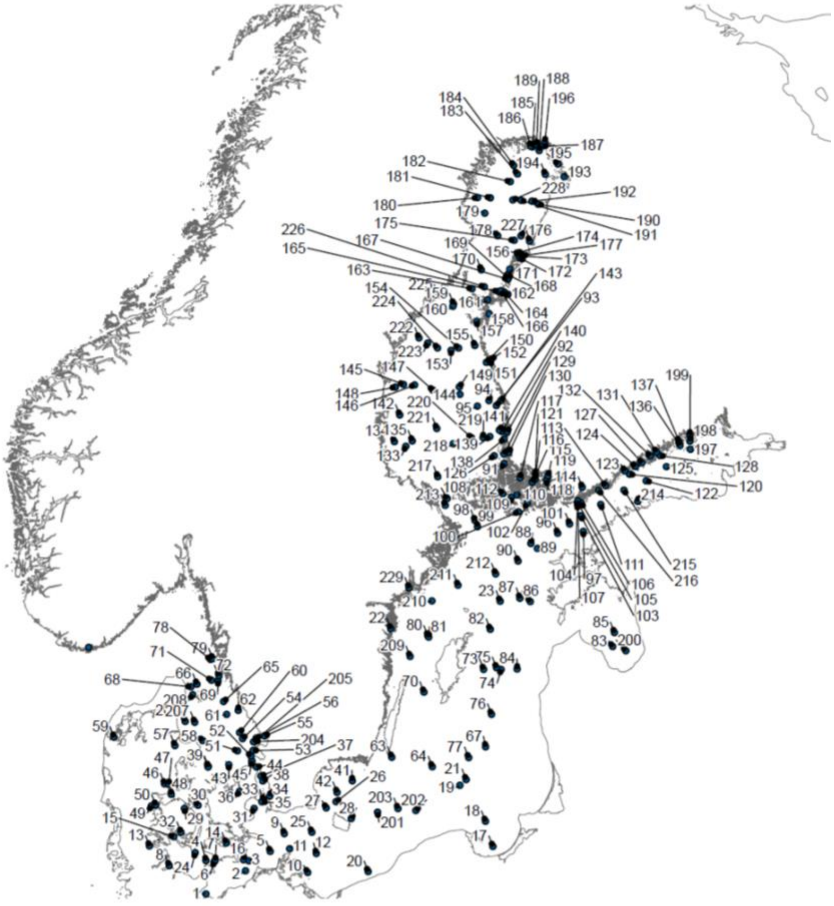

**Figure 2.** Map showing the location in the Baltic Sea of the stations included in the analysis.

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[2] http://maps.helcom.fi/website/mapservice/

[3] http://nest.su.se/helcom_plc/

[4] https://www.ices.dk/data/dataset-collections/Pages/HELCOM.aspx

In our Baltic Sea TN analyses we considered the major inputs (rivers, sediments, atmospheric deposition, nitrogen fixation and inflow from the North Sea) and sinks (outflow to the North Sea, sediment burial and denitrification) of N that have been identified in previous studies.

**Table 1.** Summary of the water column total nitrogen (TN) concentrations in the Baltic Sea. The total number of stations, years included and observations are shown according to the seven sub basins and grouped into three groups (< 1 nautical mile from the coast (< 1nm), between 1 and 12 nm (1-12 nm), > 12 nm (> 12 nm)). The average (± standard deviation) water column TN concentrations (µmol $l^{-1}$) up to the year 2013 and the period between 2014 and 2019 are also shown. Data are from the available databases, primarily ICES. Some countries, e.g. Denmark, have experienced analytical problems for TN, where shifts in the oxidation procedure has resulted in variable detection of organic bound nitrogen (DON). Such problems are also likely for data back in time, but at present it is not possible to correct for such uncertainties.

| Basin | Groups | No. of stations | Years | No. of observations | Avg. [TN] up to end 2013 | Avg. [TN] 2014-19 |
|---|---|---|---|---|---|---|
| Baltic Proper | Total | 50 | 1969-2019 | 13,291 | 25 ± 18 | 29 ± 22 |
| | <1 nm | 2 | 1974-2018 | 778 | 21 ± 6 | 21 ± 2 |
| | 1-12nm | 15 | 1969-2019 | 5,093 | 32 ± 27 | 38 ± 32 |
| | >12nm | 33 | 1969-2019 | 7,420 | 20 ± 5 | 24 ± 7 |
| Bothnian Bay | Total | 40 | 1968-2018 | 5,197 | 25 ± 17 | 23 ± 12 |
| | <1 nm | 17 | 1968-2017 | 2,236 | 32 ± 23 | 26 ± 17 |
| | 1-12nm | 13 | 1968-2018 | 1,655 | 21 ± 6 | 20 ± 4 |
| | >12nm | 10 | 1968-2018 | 1,306 | 19 ± 3 | 18 ± 1 |
| Bothnian Sea | Total | 56 | 1955-2018 | 6,839 | 21 ± 11 | 22 ± 13 |
| | <1 nm | 20 | 1955-2018 | 3,459 | 25 ± 15 | 25 ± 15 |
| | 1-12nm | 20 | 1968-2018 | 1,788 | 19 ± 4 | 19 ± 3 |
| | >12nm | 16 | 1968-2018 | 1,592 | 17 ± 3 | 17 ± 2 |
| Danish Straits | Total | 26 | 1923-2018 | 18,288 | 37 ± 78 | 26 ± 36 |
| | <1 nm | 8 | 1970-2017 | 4,154 | 11 ± 16 | 7 ± 8 |
| | 1-12nm | 18 | 1923-2018 | 14,134 | 45 ± 86 | 32 ± 39 |
| | >12nm | - | - | - | - | - |
| Gulf of Finland | Total | 25 | 1968-2019 | 4,064 | 27 ± 8 | 25 ± 11 |
| | <1 nm | 13 | 1968-2018 | 1,715 | 29 ± 9 | 30 ± 17 |
| | 1-12nm | 9 | 1968-2019 | 1,951 | 25 ± 77 | 23 ± 5 |
| | >12nm | 3 | 1969-2018 | 398 | 24 ± 6 | 23 ± 3 |
| Gulf of Riga | Total | 3 | 1990-2019 | 528 | 36 ± 12 | 27 ± 6 |
| | <1 nm | - | - | - | - | - |
| | 1-12nm | 1 | 1990-2014 | 135 | 37 ± 12 | 33 ± 6 |
| | >12nm | 2 | 1990-2019 | 393 | 36 ± 11 | 27 ± 6 |
| Kattegat | Total | 29 | 1958-2019 | 7,656 | 27 ± 40 | 21 ± 25 |
| | <1 nm | 2 | 1972-2017 | 817 | 96 ± 91 | 36 ± 49 |
| | 1-12nm | 22 | 1958-2019 | 5,266 | 18 ± 7 | 16 ± 4 |
| | >12nm | 5 | 1973-2018 | 1,573 | 18 ± 4 | 17 ± 3 |
| **Baltic Sea** | | 229 | 1923-2019 | 55,863 | 29 ± 49 | 26 ± 25 |

Generally the highest average water column TN concentrations were measured in Kattegat (36 µmol $L^{-1}$) and lowest in the Bothnian Sea (22 µmol $L^{-1}$; Table 1). In the same period the grouping of data according to distance from the coastline, showed that generally TN concentrations declined from inshore to offshore (coastal: 24 ± 10 µmol $L^{-1}$; intermediate: 26 ± 8 µmol $L^{-1}$; offshore: 12 ± 4 µmol $L^{-1}$). In table 2 the catchment and sea surface area as well as the average water depth and volume of the seven basins are presented. Due to the variability in the area and volume of each basin, the impact of changes in one basin will have different overall influence on our Baltic Sea TN analysis and budget (Table 2). In our calculations we assume that the Baltic Sea occupies a total area of 417 288 $km^2$ and has an overall average water column depth of 37 m.

The TN pool size in the water column of the whole Baltic Sea could, due to limited data prior to 1990, only be calculated for the period 1990 to 2018, showing for this period an average of 7480 ± 672 kt N, which is similar to previously reported values (Gustafsson et al. 2017; Wulff et al. 1990). In the period 1990 to 2004 the TN pool varied between 5852 to 8377 kt N, with an increasing trend of 91 kt N $year^{-1}$. Contrary to this in the period from 2005 until 2018 the TN pool varied from year to year but remained at an overall stable level (Average: 7864 kt N). This suggest that in the period from 2005 to 2018 there has been no accumulation of new N in the system (input ≈ output). While the Baltic Wide TN pool remained more or less stable in the period 2005 to 2018, there were regionally differences, with decreases in the two most northern basins and no overall change in the other areas of the Baltic Sea (Fig. 3).

**Table 2.** Summary of the catchment and sea surface area, average water depth and volume of the seven basins in the Baltic Sea. The average river and atmospheric nitrogen (N) loads are shown for the period up to 2004 and the period 2005 to 2016, as well as those loads standardized to the size of the catchment (Rivers only) and sea surface area.

| Variable | Period | Baltic Proper | Bothnian Bay | Bothnian Sea | Danish Straits | Gulf of Finland | Gulf of Riga | Kattegat | Baltic Sea |
|---|---|---|---|---|---|---|---|---|---|
| Catchment area (km$^2$) | | 493690 | 259000 | 224860 | 27370 | 422580 | 96480 | 79530 | 1603510 |
| Seasurface area (km$^2$) | | 209258 | 36249 | 78802 | 20974 | 29998 | 18646 | 23360 | 417288 |
| Avg. Water depth (m) | | 60 | 43 | 53 | 16 | 41 | 24 | 22 | 37 |
| Volume (km$^3$) | | 12555 | 1559 | 4137 | 344 | 1233 | 438 | 514 | 20780 |
| River load (kt N y$^{-1}$) | up to 2005 | 321 ± 64 | 49 ± 11 | 56 ± 13 | 44 ± 16 | 110 ± 15 | 79 ± 16 | 59 ± 14 | 718 ± 103 |
| | 2005-2016 | 262 ± 61 | 54 ± 10 | 52 ± 9 | 37 ± 7 | 108 ± 14 | 77 ± 18 | 51 ± 9 | 640 ± 84 |
| River load (t N km$^{-2}$) per catchement area | up to 2005 | 0.7 | 0.2 | 0.2 | 1.6 | 0.3 | 0.8 | 0.7 | 0.4 |
| | 2005-2016 | 0.5 | 0.2 | 0.2 | 1.3 | 0.3 | 0.8 | 0.6 | 0.4 |
| River load (t N km$^{-2}$) per sea surface area | up to 2005 | 1.5 | 1.4 | 0.7 | 2.1 | 3.7 | 4.3 | 2.5 | 1.7 |
| | 2005-2016 | 1.3 | 1.5 | 0.7 | 1.7 | 3.6 | 4.1 | 2.2 | 1.5 |
| Atmospheric load (kt N y-1) | up to 2005 | 154 ± 12 | 9 ± 2 | 29 ± 5 | 28 ± 2 | 17 ± 2 | 12 ± 1 | 25 ± 3 | 275 ± 22 |
| | 2005-2016 | 135 ± 12 | 8 ± 1 | 25 ± 3 | 27 ± 2 | 15 ± 2 | 10 ± 1 | 22 ± 2 | 241 ± 21 |
| Atmos. load (t N km$^{-2}$) per sea surface area | up to 2005 | 0.7 | 0.3 | 0.4 | 1.4 | 0.6 | 0.6 | 1.1 | 0.7 |
| | 2005-2016 | 0.6 | 0.2 | 0.3 | 1.3 | 0.5 | 0.4 | 1.0 | 0.6 |

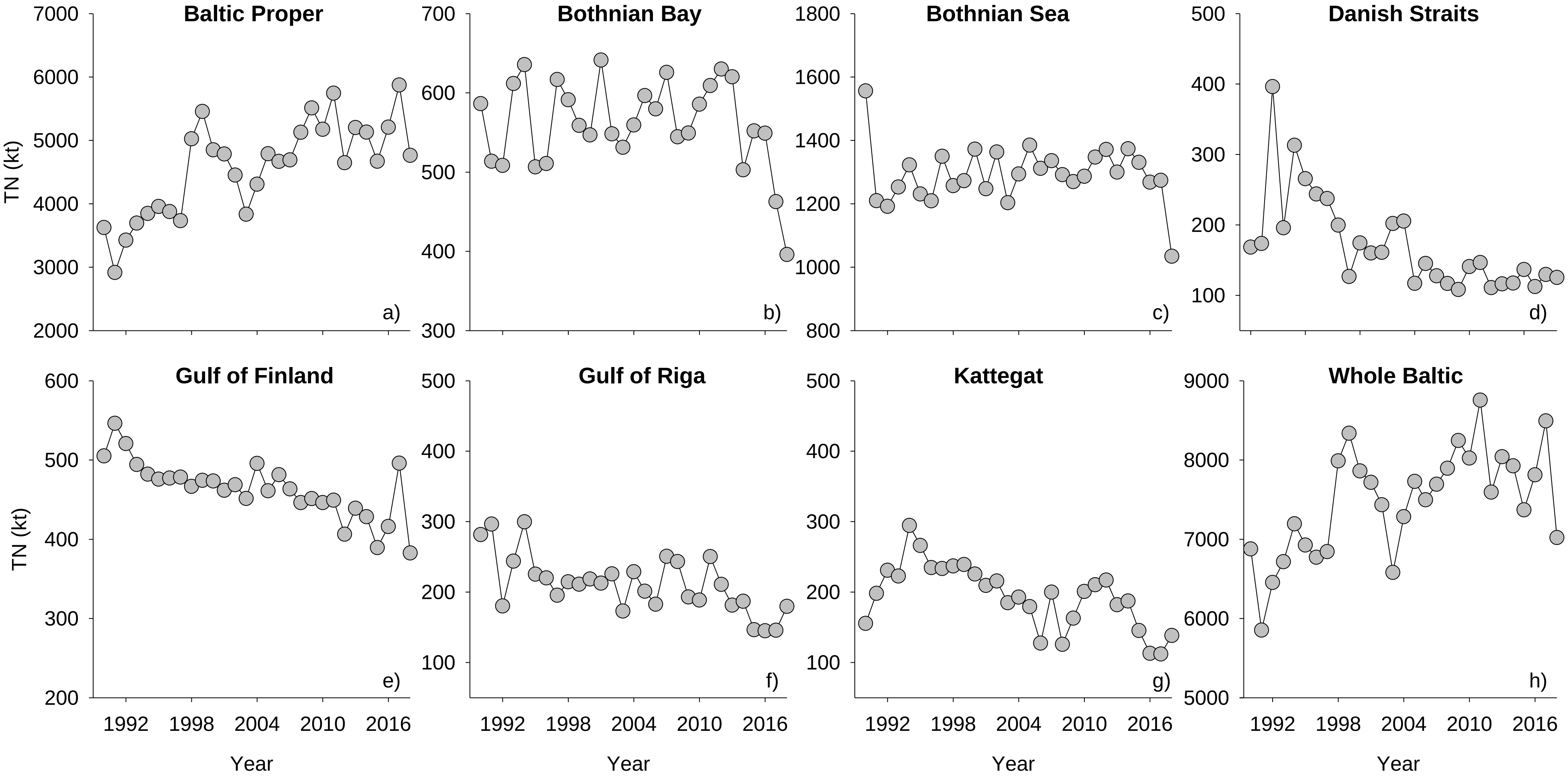

**Figure 3**. Trends in yearly averaged total nitrogen (TN) pools for the period 1990 to 2018 in the basins, a) Baltic Proper, b) Bothnian Bay, c) Bothnian Sea, d) Danish Straits, e) Gulf of Finland, f) Gulf of Riga, g) Kattegat and for h) the whole Baltic Sea.

River inputs have been shown to constitute around 70% of the TN input, with natural sources contributing around 30%, while the remaining is of anthropogenic origin, mainly from agriculture (HELCOM 2018). The largest fraction of TN in rivers is found as DIN (approximately 65%), while the DON pool dominates the organic fraction (roughly 1/3 of TN). The compiled river load dataset showed that generally the highest average TN river loads were found in the period prior to 2005 (Table 2). In the period between 2005 and 2016 highest river loads were found in the Baltic Proper (262 kt $y^{-1}$), and the lowest in the Danish Strait (37 kt $y^{-1}$; Table 2). Normalising the river loads in the same period to the size of the catchment the TN loads were largest in the Danish Strait (1.3 t $km^{-2}$ $y^{-1}$) and lowest in the Bothnian Sea (0.2 t N $km^{-2}$ $y^{-1}$; Table 2). On the other hand when normalising the river loads to sea surface areas of the Basin's, the largest inputs were found in the Gulf of Riga (4.1 t N $km^{-2}$ $y^{-1}$) and lowest in the Bothnian Sea (0.7 t N $km^{-2}$ $y^{-1}$), showing that the Gulf of Riga receives most TN per sea surface area. The average total river load in the period 2005 to 2016 to the Baltic Sea was 640 ± 84 kt N $y^{-1}$, which is similar to other estimates (average 819 kt N $y^{-1}$; range 640-1109 kt N $y^{-1}$) (Granéli and Granéli 2008; Gustafsson et al. 2017; Murray et al. 2019; Savchuk 2005; Savchuk et al. 2008; Voss et al. 2005; Wulff and Stigebrandt 1989). Analysing the long-term trends in yearly averaged river loads for the whole Baltic Sea showed a general decrease from 1995 to 2016 (4.8 kt $y^{-1}$), with a larger decrease per year in the period between 1995 and 2010 (9.4 kt $y^{-1}$) and a potential minor increase since 2014 (Fig. 4).

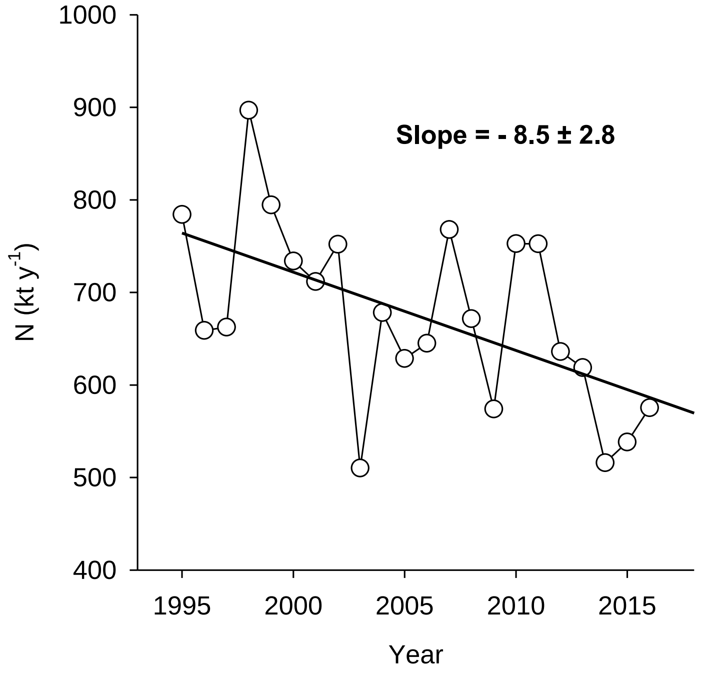

**Figure 4**. Long term trends in yearly averaged river loadings (kt N) to the Baltic Sea over the period between 1995 and 2016. Solid lines represent the linear regression line and the slope of this line represents the reported yearly decrease.

Atmospheric N is primarily derived from fossil fuel combustion releasing NO/$NO_2$, and agricultural emissions releasing principally $NH_3$ (Jickells et al. 2017). Estimates suggest that the TN deposition in the Baltic Sea has most likely doubled to tripled compared with the middle of the 20th century (Granat 2001), but more recently there has been an overall decrease in N deposition (Gauss et al. 2018). Contrary to riverine inputs which are geographically focused at particular locations, atmospheric TN inputs reach all areas of the Baltic Sea, although at lower rates. Moreover, as the atmospheric N inputs occurs directly at the sea surface, a smaller fraction will be caught in the coastal zone, compared to river borne N. The atmospheric TN deposition data was derived from the HELCOM database and covers the period from 1995 to 2016[5]. The combined atmospheric TN deposition dataset showed that from 1995 to 2016 there was a clear spatial difference, with generally elevated depositions in southern parts. The long-term analysis showed that yearly averaged atmospheric TN depositions to the whole Baltic Sea decreased from 1995 to 2016 with a rate of 3.4 kt $y^{-1}$ (Fig. 5). The dataset also showed that generally the highest average TN atmospheric depositions were found in the period prior to 2005 (Table 2).

Minimum depositions rates in the period after 2005 were found in the Bothnian Bay (8 kt $y^{-1}$) while the highest in the Baltic Proper (133 kt $y^{-1}$) (Table 2). Considering the surface areas of the basins, largest inputs were found in the Danish Strait (1.3 t N $km^{-2}$ $y^{-1}$) and lowest in the Bothnian Bay (0.2 t N $km^{-2}$ $y^{-1}$; Table 2). Using these values, we obtained total atmospheric TN inputs for the whole Baltic Sea of 240 kt $y^{-1}$ (Table 2; Fig. 6) in the period 2005 to 2016, which is similar to previous estimates (average 300 kt N $y^{-1}$; range 220–330 kt N $y^{-1}$), and suggests that atmospheric TN is around 3.6 times lower than the riverine input (Hertel et al. 2003).

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[5] http://maps.helcom.fi/website/mapservice/

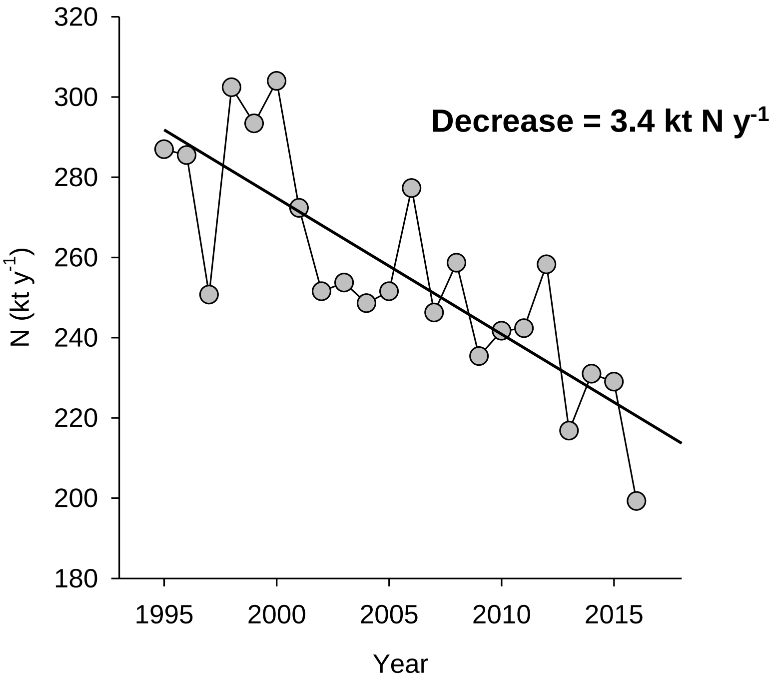

**Figure 5**. Long term trends in atmospheric nitrogen (N) depositions (kt y $^{-1}$) to the Baltic Sea in the period from 1995 to 2016. Solid line represents the linear regression line and the slope of this line represent the yearly decrease in deposition.

Biological nitrogen fixation (i.e. transformation of $N_2$ gas to biologically available N forms) has previously been suggested to sustain 30–90% of the open water production in the Baltic Sea during the summer (Larsson et al. 2001). For our N analysis we compiled $N_2$ fixation rates from across the Baltic Sea using the $^{15}$N technique. We did not include earlier estimates which concentrated samples and excluded pico- and nanoplankton (Wasmund et al. 2001). Overall there is a poor spatial coverage of measured rates and thus the estimates are highly uncertain. For the whole Baltic we found that 223 kt N $y^{-1}$ of atmospheric N is fixed annually (Fig. 6), which is within previous estimates varying widely from 100 kt N $y^{-1}$ (Niemisto et al. 1989), to nearly 400 kt N $y^{-1}$ (Wasmund et al. 2001).

Water exchange with the North Sea constitutes both a source and a sink of TN. Balancing water exchanges in the Baltic Sea have shown that river inflow exceeds evaporation by 500 $km^3$ $y^{-1}$ and that around 1000 $km^3$ $y^{-1}$ of surface water is transported to the North Sea, meaning that 500 $km^3$ $y^{-1}$ of saltier North Sea water enters the Baltic Sea from deeper levels (Stigebrandt 2001). This exchange has been shown to account for a net loss of around 10% of the total N inputs (rivers, atmosphere and $N_2$ fixation) to the Baltic Sea, meaning that 90% of the total inputs are retained in the Baltic Sea (Granéli and Granéli 2008). For our N analysis we used the inflow/outflow values provided by (Stigebrandt 2001) and average surface and bottom water TN values for the outflow area of the Baltic Sea (Kattegat area) resulting in an outflow of 246 kt N $y^{-1}$ and an inflow of 122 kt N $y^{-1}$ (Fig. 6). This results in a net outflow of N to the North Sea of 123 kt N $y^{-1}$, similar to previous values which vary between 100 and 198 kt N $y^{-1}$ (Granéli and Granéli 2008; Gustafsson et al. 2017).

Sediments in the Baltic Sea contain higher TN concentrations than the water column, but precise, large-scale estimations are difficult. Using the average concentration obtained from 250 independent sediment samples we estimate, assuming that the top 25 cm of the sediment are the active layer, a total sediment TN pool of 158.058 kt N, which is 18 times higher than in the water column (Fig. 6). There is a constant exchange of N with the overlaying water column. Sedimentation of particles add N to the sediment pool and after remineralisation DIN is often leaving the sediment due to diffusion, particularly during hypoxia. Sediments also introduce TN to the water column during sediment resuspension events, but also acts as a sink (e.g. burial). Sediment resuspension has been suggested to impact at least once a year the entire Baltic Sea at locations with a water depth down to 80 m (Jönsson et al. 2005) which last about 22 h (Danielsson et al. 2007). For the purpose of our N analysis we did not directly consider sediment resuspension as these events are highly variable and current evidence suggest a minor or no clear effect on N levels (Almroth et al. 2009). Permanent burial of N in sediment has been suggested on a yearly basis to account for between approx. 30 and 50% of the riverine TN inputs (Granéli and Granéli 2008; Jansson 2001). In our calculations we consider storage and transformations in the active sediment layer (top 25 cm), which represents the horizon that receives most of the fresh organic material and is most likely transferring material back to the water column (Bunke et al. 2019). Using available literature values we calculate a N burial rate of 318 kt N $y^{-1}$ (Fig. 6), which is comparable to estimates used in other N budget studies (300 kt N $y^{-1}$; Granéli and Granéli 2008).

Organic bound N is partly lost as $N_2$ in anoxic parts of sediments and water columns by denitrification and/or anammox. In the Baltic Sea, denitrification is the main removal process while anammox has not been detected (Dalsgaard et al. 2013). Overall there is a poor spatial coverage of measured rates and thus estimates are highly uncertain. However, one estimate suggests that denitrification removes around 65% of the external TN load (1250 kt N $year^{-1}$; Granéli and Granéli 2008). In our analyses we included denitrification data from the literature and other sources determined by the $^{15}N$ isotope pairing method in a total of 450 estimates. Data based on acetylene method was not used since it has shortcomings such as the blocking of the coupled nitrification-denitrification process (Seitzinger et al. 1993). Our dataset showed a large variability ranging from non-detectable to 11391 µmol N $m^{-2}$ $d^{-1}$ with an overall average of 1064 ± 1811 µmol N $m^{-2}$ $d^{-1}$. In our calculations we calculate an average value for the whole Baltic Sea of 668 kt $y^{-1}$ (Fig. 6), showing that 54% of the N inputs (atmosphere, rivers, inflow and $N_2$ fixation) is removed by denitrification, which is comparable to previous values reported (Deutsch et al. 2010; Gustafsson et al. 2012).

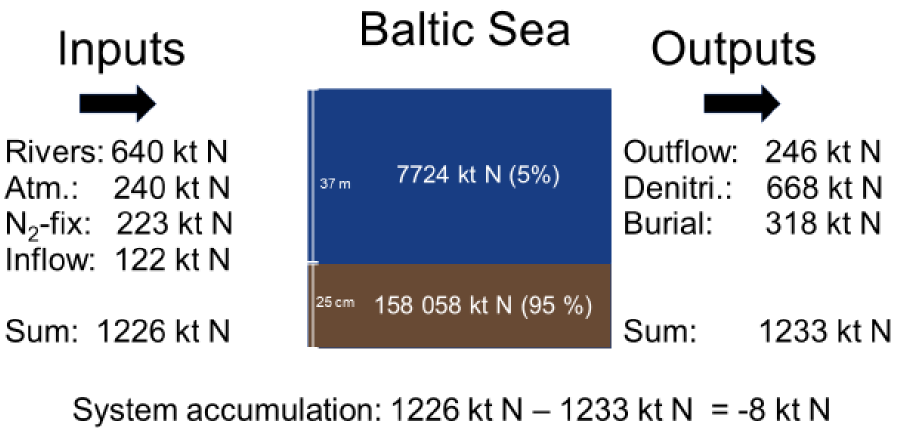

**Figure 6**. Simplified view of the Baltic Sea total nitrogen (TN) budget for the period 2005 to 2018. Inflows and outflow as well as standing stocks in the water column and sediment are shown. The standings stock is calculated using an average water depth of 37 m and assuming that the top 25 cm of the sediment is the active layer.

Considering the variability in the different inputs and outputs our TN budget shows that the Baltic Sea is in near balance, with a decline of around 8 kt N pr. year in the period from 2005 to 2018 (Fig. 6). This finding corresponds well to the stable water column TN pool calculated from field data during the same period (Fig. 3h). This comparability between our budget and the field data gives us assurance that the fluxes and pools in our TN mass budget are on the right magnitude and provides confidence in the scenarios presented below.

*Time lags and future scenarios* – We used our TN budget to: 1) predict the time lag for a TN decline in the system in a scenario when external loads are declining; 2) test how two different proposed nutrient mitigations strategies, reestablishing seagrass meadows and establishing commercial mussel farms, could influence the overall N budget of the Baltic Sea.

In order to calculate the time lag of TN decline in the Baltic Sea following declines in loading we assume that sources both include a natural background and inputs from anthropogenic sources. In our calculations we assume that the manageable part ("anthropogenic sources"), constitute 60% of river load. For the atmospheric deposition we use a anthropogenic fraction obtained from the difference between deposition in year 1900 and those measured in 2000 (Engardt et al. 2017). This difference is about 67%. Further assuming that part of the atmospheric deposition in year 1990 also was anthropogenic, we reach 80% as the manageable part of the present atmospheric deposition.

Previous research has demonstrated that $N_2$ fixation in the Baltic Sea is partly regulated by the availability of phosphorus (Moisander et al. 2007), and we therefore assume that the manageable part of phosphorus could influence these rates. In our calculations the manageable part of $N_2$ fixation is therefore set to 30%. The N inflow from the North Sea to the Baltic Sea mainly contains N from the deeper parts of the

North Sea, but also a fraction originating from anthropogenic N inputs to the North Sea, particular through the Jutland current that flows northward along the West coast of Jutland bringing N from the Rhine and Elbe into Skagerrak. In addition is part of the N entering the Baltic Sea with inflowing deep water coming from sedimentation of N in the outflowing surface waters (Jørgensen et al. 2013). Thus, a lowering of TN concentrations in the Baltic Sea and of anthropogenic inputs to the North Sea will also reduce the N inflow. We have assumed this part is 30% of the present N inflow. As the sinks (burial, outflow and denitrifications) also dependent on the TN concentrations, we assume that these losses also decline, but at a rate ten times less than the inputs.

Setting a target for TN levels below which the Baltic Sea is unaffected by eutrophication is challenging. According to (Gustafsson et al. 2012) the TN pool in the water column in the early 20th century, were about 39% lower than in the period 1997 to 2006. Contrary, nitrate concentrations in Danish waters were in the early 20th century around 77% lower than current measured values (0.5 vs. 2.5 µmol $l^{-1}$). Also in a study which reconstructed the N loadings for Danish Waters 100 years ago, it was shown that TN values in marine waters were around 70% lower than those, measured currently (8 vs. 24 µmol $l^{-1}$). So if the Baltic Sea was to reach "pristine levels" estimates of the necessary reduction varies between 39 and 77%. In the HELCOM nutrient reduction scheme a decline of 36% is suggested as the level when the Baltic Sea is unaffected by eutrophication. In our scenarios we use a conservative value and assume that a reduction of 33% in TN concentrations is needed for the Baltic Sea to bring the system in a condition that comply with the definition of GES and the targets in MSFD. Here we assume, that a deviation from pristine condition of 60% is in accordance with GES and that a number of positive feed-back loops in the ecosystem will help to improve the conditions, e.g. a better filtering effect in estuaries and coastal areas, once the overall pressure from nutrients are reduced.

In our scenario we assume an immediate reduction of all manageable parts of current TN inputs (river load, atmospheric deposition, inflow from the North Sea and $N_2$ fixation) into the Baltic Sea in steps of 10% compared to current values and thereafter calculate the time it would take for TN in the water column to decline by 33% (Table 3).

**Table 3.** Calculated time lags (years) for when the pool of total nitrogen (TN) will reach the reduction target of 33%, depending on the different scenarios descried. NA – indicated that it is not possible to achieve the target with the proposed reduction in inputs.

a)

| **Water column** | **Scenario nr.** | | | | | |
|---|---|---|---|---|---|---|
| **Reduction in inputs:** | 1 | 2 | 3 | 4 | 5 | 6 |
| **10%** | 37 | 44 | NA | NA | 16 | 10 |
| **20%** | 20 | 24 | 65 | NA | 12 | 8 |
| **30%** | 13 | 16 | 25 | 244 | 9 | 7 |
| **40%** | 10 | 12 | 16 | 35 | 7 | 6 |
| **50%** | 8 | 10 | 11 | 19 | 6 | 5 |

b)

| **Sediment + water column** | **Scenario nr.** | | | | | |
|---|---|---|---|---|---|---|
| **Reduction in inputs:** | 1 | 2 | 3 | 4 | 5 | 6 |
| **10%** | 780 | 1046 | NA | NA | 377 | 240 |
| **20%** | 410 | 556 | 1519 | NA | 271 | 192 |
| **30%** | 278 | 379 | 593 | 5738 | 212 | 161 |
| **40%** | 211 | 287 | 368 | 831 | 174 | 138 |
| **50%** | 169 | 231 | 267 | 448 | 148 | 121 |

**Explanation of scenarios:**

| |
|---|
| **Scenario 1:** All inputs are reduced, while outputs are unaffected. |
| **Scenario 2:** Both inputs and outputs are reduced. |
| **Scenario 3:** Initial inputs are 100 kt larger and all inputs are reduced, while outputs are unaffected. |
| **Scenario 4:** Initial inputs are 200 kt larger and all inputs are reduced, while outputs are unaffected. |
| **Scenario 5:** Initial inputs are 100 kt lower and all inputs are reduced, while outputs are unaffected. |
| **Scenario 6:** Initial inputs are 200 kt lower and all inputs are reduced, while outputs are unaffected. |

The results show that if all inputs (scenario 1) to the Baltic Sea are reduced by 10% it would take between 37 and 44 years before the TN levels in the water column would be reduced by 33% (Table 3). While if both the sediment and water column TN pools are considered the timescales are around 20 times longer. Overall these calculations show that recovery of the Baltic Sea is possible within a decadal timescales but that to reach this target input reductions of 10% or more are needed (Table 3).

The variables included in our TN budget are associated with uncertainty. The size of the sediment TN pool, which is the largest TN pool in our budget, is highly uncertain due to lack of spatial coverage and long term datasets. Also burial, denitrification and $N_2$ fixation rates are due to lack of geographical and long-term coverage associated with an unknown uncertainty. To test the uncertainty of our simple TN budget we changed the inputs by +/- 100 and 200 kt N. This demonstrates that if our estimates are erroneous with 100 kt N then the estimated time lags are still generally comparable, on the other hand if the inputs/outputs are indeed 200 kt N lower or higher the time lags vary up to 10 times (Table 3).

The Baltic Sea Action Plan (BSAP) include a maximum allowable N input of 792 kt N year$^{-1}$ for riverine and atmospheric inputs and a present loading for 2017 of 859 kt N year$^{-1}$ (HELCOM 2017). Thus present loadings are 12% above the target in BSAP. According to Table 3 this result in time frame of 30 to 40 years for reaching GES, only considering the N pool in the water column. Including the entire sediment pool the time lag is about 700 years. It is unlikely, that the entire sediment pool is active but on the other hand will the sediment act as a source – or less of a sink for N - once the TN concentrations in the water column starts to decline. Hence, the most likely time lag for GES is higher than 40 years with the present maximum allowable input in BASP and most likely hundreds of years. A more ambitious targets is needed to achieve GES in this century. A reduction of the manageable N inputs of 30%, which include a reduction of P inputs as well in order to reduce $N_2$ fixation, might bring the Baltic Sea in a significantly better condition within a time scale of 20 to 40 years.

### Other mitigation measures

Seagrass meadows are highly productive ecosystems, able to assimilate large amounts of N. As organic matter produced by seagrass is more recalcitrant than e.g. phytoplankton cells, the degradation of this organic matter takes place over longer time scale leading to a temporary retention of nitrogen (on the order of weeks to months); (Banta et al. 2004). In addition, the uptake of N by seagrass can limit phytoplankton growth that otherwise could shade the seagrass (Aoki et al. 2020; Gurbisz et al. 2017). Furthermore, sediment burial and denitrification rates are 21 and 4 times higher in seagrass meadow compared to bare sediments (Aoki et al. 2020). Overall burial seems to be the major component of N removal, accounting for 90% of the total loss (Aoki et al. 2020). Taken together, the enhanced burial and denitrification have been suggested to act as a “filter” slowing the movement of N inputs from watersheds to the open ocean, and has been coined the “coastal filter effect". In our scenario, we determined the impact of reestablishing seagrass meadows assuming the areas covered would increase with 10, 25, 50 and 100% compared with the current estimated value (2500 km$^2$; (Bostrom et al. 2014; Staehr et al. 2019). In table 4 we present different scenarios calculated for N removal considering specific areas are reestablished in the Baltic Sea. Finally, the calculated values were compared to the yearly amounts of nutrients the Baltic Sea receives from rivers.

**Table 4.** Calculated nitrogen (N) yearly removal by reestablishing Seagrass meadows. The removal per square kilometer (ton N km$^{-2}$ y$^{-1}$) and the total amounts of N removed by Seagrass meadows with different coverage of the whole Baltic Sea are also shown for reference, together with a comparison with the total riverine inputs.

| Seagrass cover | Area | Denitrification | Sediment Burial | Removed - Baltic Sea | % of River input |
|---|---|---|---|---|---|
| | km$^2$ | ton N km$^{-2}$ y$^{-1}$ | ton N km$^{-2}$ y$^{-1}$ | ton N km$^{-2}$ y$^{-1}$ | |
| Current | 2500 | 10.220 | 18.477 | 28.697 | 4.5 |
| + 10% | 2750 | 11.242 | 20.325 | 31.567 | 4.9 |
| + 25% | 3125 | 12.775 | 23.096 | 35.871 | 5.6 |
| + 50% | 3750 | 15.330 | 27.715 | 43.045 | 6.7 |
| + 100% | 5000 | 20.440 | 36.954 | 57.394 | 9.0 |

The results show that if the areas covered with seagrass would double these could remove approximately 9% of the N transported to the Baltic Sea by rivers. Planting such areas artificially has large economical costs limiting the use of this measure, while the natural reestablishment of seagrass meadows would not have any direct costs but would take years.

The mussel *Mytilus edulis* is native to the Baltic Sea where it can occupy large areas of hard substrate down to approximately 30 m of water depth (Stadmark and Conley 2011). The establishment of mussel farms benefits the ecosystem by reducing particulates in the water column and increasing light availability (Kotta et al. 2020; Schröder et al. 2014). Establishing commercial mussel farms to mitigate impacts of excess nutrient run-off from land has been intensively investigated (e.g. Taylor et al. 2019). This interest derives from the capacity of mussels to incorporate N – and P - into their tissue, which is removed from the system once the mussels are harvested. Rates of N removal have recently been reported when growing mussel using two different cultivation technics (longline and net) in the Baltic Sea (Table 5; Taylor et al. 2019). In our calculation we did not include the possible stimulation of sediment denitrification rates below the mussel rafts as previous studies have found highly variable impacts with stimulations between 25 and 260% (e.g. Carlsson et al. 2012; Christensen et al. 2003). In table 5, we have illustrated the potential of this measure to remove nutrients when growing mussels using the two different cultivation technics mentioned above (longline and net). We show scenarios of N removal when mussels grow with different spatial coverage and compare these values with the yearly amounts of nutrients the Baltic Sea receives from rivers.

**Table 5.** Calculated nitrogen (N) removal by two types of mussel cultivation types (longline and net). The minimum and maximum N removal per square kilometer of mussel farm (ton N km$^{-2}$) and the total amounts of N removed by mussel farms with different coverage of the whole Baltic Sea are also shown for reference, together with a comparison with the total riverine inputs.

| | ton N km$^{-2}$ | | | ton N removed - Baltic Sea | | % of River input | |
|---|---|---|---|---|---|---|---|
| Cultivation type | min* | max* | | min | max | min | max |
| Longlines | 60 | 127 | 0,001% of Baltic covered (4,12 km$^2$) | 247 | 523 | 0.04 | 0.08 |
| Nets | 163 | 200 | | 672 | 824 | 0.10 | 0.13 |
| | | | 0,01% of Baltic covered (41,2 km2) | 2.472 | 5.232 | 0.4 | 0.8 |
| | | | | 6.716 | 8.240 | 1.0 | 1.3 |
| | | | 0,1% of Baltic covered (412 km2) | 24.720 | 52.324 | 4 | 8 |
| | | | | 67.156 | 82.400 | 10 | 13 |
| | | | 1% of Baltic covered (4120 km2) | 247.200 | 523.240 | 39 | 82 |
| | | | | 671.560 | 824.000 | 105 | 129 |

*Source: Taylor et al. Production Characteristics and Optimization of Mitigation Mussel Culture. Frontiers in Marine Science 6:698. doi: 10.3389/fmars.2019.00698

Our results show that between 0.1 and 1% of the Baltic Sea would need to be covered with mussel farms to substantially reduce N levels. However, appropriate locations for a mussel farm close to the coast are also often areas used for recreational purposes (e.g. recreational sailing, fisheries, protected areas), questioning if such large areas would be available for mussel farming. For example, mussel farming should occur close to a port and in sheltered waters, and such areas are often also the most import recreational areas. The success of mussel farming also depends on factors such as water depth, food concentrations, water currents, temperature, predation on mussels – particular from eiders and recruitment (Kotta et al. 2020). On the other hand, there may also be negative effects through increased sedimentation below the farms, decreasing oxygen availability and changing the sediment chemistry (Christensen et al. 2003). Furthermore, the low salinities found in the Baltic Sea would result in high physiological stress and thus a slow growth rate of mussels, with decreased nutrient uptake efficiency (Hedberg et al. 2018). Therefore, the values used in table 5 above are likely an upper limit. Overall on local scales, mussel farms might help mitigate impacts of excess nutrient run-off from land. However, these measures would not solve the eutrophication problems without a large reduction in external nutrient loads to the whole of the Baltic Sea.

## 4. Conclusion

In this study, we demonstrate that in the Baltic Sea:

1) The long-term trends in yearly averaged river loads show a general decrease from 1995 to 2016.
2) The average TN pools size has been fairly stable since 2005, following the decline in inputs.
3) Our TN budget shows that the Baltic Sea is in near balance, with a decline of around 8 kt N pr. year in the period from 2005 to 2018.
4) If all TN inputs to the Baltic Sea are reduced by 10% - as in the current BSAP - there is a time lag of between 37 and 44 years before the TN levels in the water column would be reduced by 33%. These calculations show that recovery of the Baltic Sea is possible within a decadal timescales but that to reach this target input reductions of 10% or more are needed.
5) A reduction of the manageable N inputs of 30%, which include a reduction of P inputs as well in order to reduce N fixation, might bring the Baltic Sea in a significantly better condition within a time scale of 20 to 40 years.
6) Seagrass meadows could remove N from the system by increasing denitrification and sediment burial. Our calculations show that seagrass areas would need to double in order to remove approximately 9% more of the N transported to the Baltic Sea by rivers.
7) Mussel farms might help mitigate impacts of excess nutrient run-off from land on local scales. However, this measure would not solve the eutrophication problems without a large reduction in external nutrient loads to the whole of the Baltic Sea.

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