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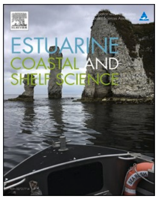

Increased nutrient retention and cyanobacterial blooms in a future coastal zone

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ABSTRACT

Climate change and coastal management directly affect the magnitude of nutrient loads and the functioning of the coastal zones. In this novel approach, a coastal-zone-model was used to study future retention capacity of nitrogen and phosphorus loads and changes in cyanobacterial blooms in an archipelago in a eutrophied coastal sea. By conducting projections under the combined impact of changing climate and nutrient loads we demonstrate that i) future filter efficiency of the archipelago increases compared to present day regardless of the nutrient load projection, ii) the cyanobacteria biomass increased 5-fold in a worst-case nutrient load projection and iii) resulting in an increased spread of bottom anoxia and hypoxia. However, the phytoplankton biomass and hypoxia/anoxia will remain stable if the planned mitigation is successfully implemented. This study highlights the importance of nutrient load management and the need to understand more about the complex interactions taking place in the coastal systems.

1. Introduction

Anthropogenic pressures and climate change are increasingly affecting all ecosystems on Earth, not least the coastal zones (Steffen et al., 2015). With an increased input of nutrients to the ocean during recent decades, many seas are now highly eutrophic (Maure et al., 2021; Nixon, 1995) and thus, also suffering from an increasing spread of bottom hypoxia (Almroth-Rosell et al., 2021; Breitburg et al., 2018). However, not all nutrients released from land reach the open sea as estuaries and archipelagos in the coastal zone are efficient nutrient filters retaining a large proportion of the land loads (Edman et al., 2018; McGlathery et al., 2007). The coastal zone's efficiency to remove nutrients, (i.e., the level of retention) is important to impede coastal sea eutrophication and is controlled by processes such as denitrification, nitrogen fixation (N_2-fixation) and sediment burial.

The Baltic Sea, located in northern Europe, is one of the world's largest brackish seas suffering from eutrophication. Regional projections for the Baltic Sea climate in the 21st century include warmer water, decline of sea ice cover and mean sea level rise (Meier et al., 2022b). In detail, recent scenario simulations project an increase of the Baltic Sea wide averaged sea surface temperature between 1 and 3 °C by the end of this century compared to 1976–2005, depending on the applied greenhouse gas emission scenario (Meier et al., 2021). In the northern Baltic Sea, the rising mean sea level will to a large part be counteracted by land uplift, while sea level rise affects the southern Baltic Sea to a larger extent as the land up lift is smaller in that area. These changes may also have a profound impact on the coastal zone. For instance, coastal hypoxia is assumed to occur more frequently in future climate, changing the coastal filter capacity (Johansson et al., 2014; Meier et al., 2022b; Nordman et al., 2020). However, it has been shown that changes in oxygen condition, primary production and N_2 fixating cyanobacteria are more dependent on the supply of nutrients than on the climate scenario (Meier et al., 2021). Further, long-term monitoring of filamentous cyanobacteria in the Baltic Sea recently revealed an increase in abundance, especially in the northern regions where recent decades of decreased salinities benefit freshwater taxa (Olofsson et al., 2020). Their development for the future in coastal zones is not fully understood, as those regions cannot be directly compared to open sea due to high local

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variation in abiotic factors such as light, nutrients, and salinity. Biogeochemical models have projected a decrease in primary production and N_2-fixation under future climate conditions if nutrient loads are significantly reduced (Saraiva et al., 2019). In summary, climate change is a threat to marine ecosystems of the same magnitude as all current pressures combined (Wåhlström et al., 2022).

During recent decades the nutrient loads to the Baltic Sea have decreased after a century of increase. This is primarily the result of better and more efficient removal of nutrients at the major sewage treatment plants (Gustafsson et al., 2012). To continue to reduce nutrient loads, the Baltic Sea countries signed a plan known as the Baltic Sea Action Plan (i.e. BSAP; HELCOM, 2007; 2021), however, the plan does not include the effect of climate change.

In the Baltic Sea, dense blooms of diazotrophic cyanobacteria are formed almost every summer. By performing N_2-fixation, they contribute to the nitrogen (N) availability to surrounding organisms, and their contribution to the internal loads are equal to the total amount of external N from rivers and atmospheric deposition in the Baltic Sea area (Larsson et al., 2001; Olofsson et al., 2021; Wasmund et al., 2001). As they can utilise dissolved nitrogen from the water they are controlled mainly by the availability of phosphorus (P) derived from for example land loads and of stored P in the sediment. However, despite load reductions during recent decades, filamentous cyanobacteria are still partly increasing (Kahru and Elmgren, 2014; Olofsson et al., 2020). This increase may be due to lingering effects from eutrophication, such as the internal phosphate release from anoxic sediments (Conley et al., 2009).

Sweden has a long and complex coastline with a coastal zone consisting of archipelagos, islands and estuaries in the Baltic Sea, where a large part of the nutrient runoff from land is retained in a more or less effective way (Edman et al., 2018). The filter efficiency of an ecosystem is an important function both in the coastal zone but also in the open sea, as it retains and removes nutrients from the system. Increased filter efficiency of nutrients in the coastal zone means less supply to the open sea in relation to the load.

Denitrification is highest in lagoons and inner parts of the coastal system, as these regions receive large input of organic matter and nitrate (Carstensen et al., 2020; van Helmond et al., 2020). In archipelagos, burial of P is highest when sediment rates are high (Carstensen et al., 2020). Asmala et al. (2017) estimated that 16% of N and 53% of P inputs from land was retained in the entire Baltic Sea coastal zone, and that P burial was most effective in archipelagos, accounting for 45% of the total removal. However, denitrification in the archipelagos was only 9 % with higher values in lagoons (40 %) and at the open coast (36%). Edman et al. (2018) estimated slightly higher values with the average filter efficiency of 54% for N and 70% for P. They also concluded that the long-term nutrient removal depends mainly on the physical characteristics of the system and is most efficient in the inner parts and decreases towards the open coastal sea. In the largest archipelago in Sweden, the Stockholm archipelago, the present filter efficiency of nutrients was estimated to be 72% for N and 65% for P (Almroth-Rosell et al., 2016). This means that much of the supplied nutrients from land is retained in the coastal zone and is not transported downstream to the already eutrophied open sea. The burial rate of P is high and denitrification is the major benthic nitrate-reducing process (van Helmond et al., 2020).

Like many other coastal areas, the Stockholm archipelago suffers from a long history of eutrophication and as a consequence, severe algal blooms and periodical oxygen deficiency (Brattberg, 1986; Walve et al., 2021). However, since the 1970s the water quality has improved due to the improved removal of nutrients (Lücke, 2022; Walve et al., 2018). The Stockholm archipelago is an important and unique area used for tourism, recreation and as a nature reserve. Thus, it has a high economic value but as it is situated near the capital of Sweden, the anthropogenic impact is high. Dense blooms of filamentous cyanobacteria during summer do cause problems for tourism and ecosystem services, due to surface accumulations and beach fouling. Also, high biomass of filamentous cyanobacteria may enhance anoxic bottom waters when degrading at the end of a bloom (Carstensen et al., 2014; Conley et al., 2009; Paerl and Huisman, 2008; Vahtera et al., 2007).

Only 1% out of 832 scientific publications about coastal eutrophication investigated how both the land- and open sea net links affect the eutrophication in coastal water at the same time (Vigouroux and Destouni, 2022). This is a major research gap for the coastal waters and points out the need to investigate the land-coast-open sea continuum as they affect each other. In the present study, we contribute to bridging this knowledge gap by investigating the retention and exchange of nutrients across the land-coast-open sea continuum, identifying the current situation but also in a future climate. For this aim, a coastal zone model was driven with data from future climate and nutrient load projections from a three-dimensional coupled physical-biogeochemical model for the open Baltic Sea. We investigated how retention and removal of nutrients as well as the magnitude of cyanobacterial blooms in the coastal zone are affected by future climate change and different nutrient loads.

2. Method

2.1. Study site

The brackish Stockholm Archipelago consists of many sub-basins (Fig. 1) and is the largest archipelago in Sweden and the second largest in the Baltic Sea, situated in Northern Europe. Most freshwater and nutrients enters the archipelago in the innermost basin, from lake Mälaren and from wastewater treatment plants and industries, further described in Almroth-Rosell et al. (2016). The concentrations of total N and total P in the Stockholm archipelago have north-south increasing gradients and the outer archipelago is influenced by the relatively high concentration of nutrients in the open Baltic Sea (Svealandskustvattenvårdsförbund, 2022).

The model set-up includes 86 coupled sub-basins, divided into three sub-areas in accordance with Almroth-Rosell et al. (2016); the inner (16 sub-basins), intermediate (44 sub-basins) and outer archipelago (26 sub-basins; Fig. 1). The division into three sub-areas was to estimate the transport of nutrients from land, atmosphere and point sources through the coastal archipelago into the open Baltic Sea. The natural borders between the inner and intermediate archipelagos consist of several large islands where the water exchange is limited to five narrow sounds with shallow sills. The border between the intermediate and the outer archipelagos follows a chain of islands in the north–south direction, with several sounds between the two areas. The area of the entire archipelago is 3228 km^2 (inner 109 km^2; intermediate 759 km^2 and outer 2360 km^2).

2.2. Experimental strategy of retention

Retention is the withholding of matter within a region and also includes internal removal or additions. Retention of N and P can be calculated as the difference between the total nutrient loads from land and atmosphere ($Load_{total}$) and the outflow to/from an ambient area (Almroth-Rosell et al., 2015, 2016; Hayn et al., 2014; Johnston, 1991). The $Load_{total}$ of nutrients is here defined as the sum of loads from rivers, land runoff, point sources and atmosphere. The outflow of nutrients is the net export from the area to an ambient sea, another basin or the open coastal sea.

Total retention (R_{tot}) is estimated as the sum of temporary and permanent retained N and P (Almroth-Rosell et al., 2016). Permanent retention is defined as the removal of nutrients from the nutrient pool in the model system. For P this is burial. For N it is burial, pelagic and benthic denitrification minus N_2-fixation, where the latter reduces the retention as N is added to the water column. The temporary retention is defined as the change in the benthic and pelagic storage (pools) of inorganic and organic nutrients, which can be both negative and positive depending on the sign of the nutrient inventory change. The pelagic temporary retention of N and P is affected by the supply of nutrients from land, the export of organic matter to the sediment, the release of

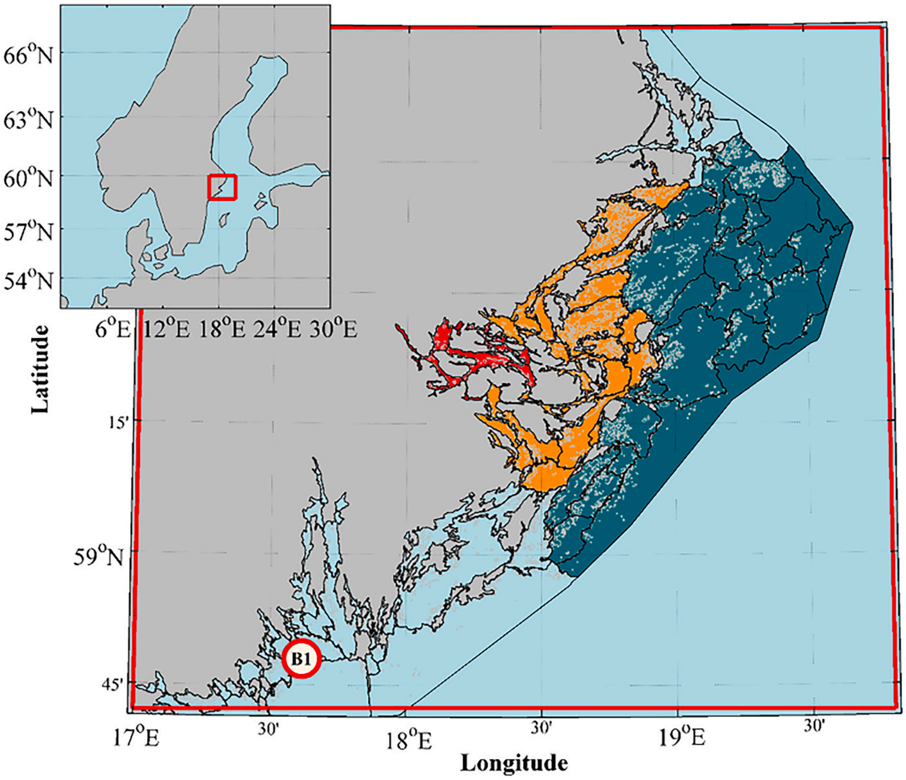

Fig. 1. Map of the Stockholm Archipelago with an insert of Sweden, located in Northern Europe. The Stockholm Archipelago is divided into inner (red), intermediate (orange) and outer (green) archipelago. The sub-basins are marked with black contours and the positions for the coastal monitoring station B1 in a red/white circle. The figure is modified from Almroth-Rosell et al. (2016). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

nutrients from the sediment to the water column, and the net export of nutrients to the ambient sub-area. The benthic N and P pools are affected by: sedimentation of organic material from the water column, the release of inorganic nutrients back to the water column, burial of nutrients and, for N, also denitrification.

The filter efficiency (E_F) is examined according to Almroth-Rosell et al. (2016) and defined as the proportion (%) of the total nutrient load ($Load_{total}$) retained within a sub-area (eq. (1)):

$$E_F = \frac{R_{tot}}{Load_{total}} * 100\% \tag{1}$$

All calculations are based upon data from the Swedish Coastal zone Model, described below.

2.3. Model description

The Swedish Coastal zone Model (SCM) is a one-dimensional physical multi-basin model based on the equation solver PROgram for Boundary layers in the Environment (PROBE; Svensson and Omstedt, 1998) coupled to a biogeochemical model; the Swedish Coastal and Ocean Biogeochemical model (SCOBI; Eilola et al., 2009; Marmefelt et al., 1999).

PROBE calculates vertical advection, mixing and horizontally averaged concentration profiles of all state variables, including temperature and salinity as well as transports between basins (Omstedt, 2015; Svensson and Omstedt, 1998). The vertical grid resolution is 0.5 m in the uppermost layers, 1 m from 4 to 70 m and 2 m between 70 and 100 m. The dynamic biogeochemistry is described by SCOBI, which includes three phytoplankton groups (diatoms, flagellates and others, and cyanobacteria), one zooplankton group, one pool for detritus and three inorganic nutrients pools (nitrate+nitrite, ammonium and phosphate) in the pelagial and the amounts of stored N and P as benthic variables (Eilola et al., 2009). N_2-fixation by cyanobacteria adds bioavailable N to the system, which in the model occurs with salinity below 10 and temperature above 10 °C. The N_2-fixation capacity is highest at low N:P ratio and decreases with increasing N:P ratio. N_2-fixation and cyanobacterial growth is also positively related to light and phosphate availability.

Burial of nutrients is parameterized from the concentration of nutrients using a burial rate constant, defining how large a fraction of the sediment nutrient content (mmol/m^2) that is buried in each time step. Denitrification occurs in both the water and in the benthic layer and is regulated by the redox state and available nitrate, and for the benthic N, mineralization of organic material. There is also an additional burial of N due to a small amount of N-adsorption to sediment particles. SCM has been used in several studies and more detailed descriptions can be found in Almroth-Rosell et al. (2016), Edman et al. (2018) and Eilola et al. (2009).

2.4. Model validation

Data from the Swedish Marine Environment Monitoring program, which includes monthly sampling of physical, chemical and biological parameters along the coastline of Sweden, were used for the evaluation of the model results. These data are hosted by The national archive for oceanographic data at the Swedish Hydrological and Meteorological Institute (SMHI), and are freely available. Due to the lack of long-term monitoring data for cyanobacteria within the Stockholm archipelago, data for evaluation of the model was used from the nearby monitoring station B1, situated south of the Stockholm archipelago (Fig. 1). Modelled physical and biogeochemical parameters were evaluated for the control period, using modelled monthly averages for 1999–2012 in the basin where B1 is positioned, as well as model results averaged over the entire Stockholm archipelago. Monitoring data used were cyanobacterial carbon biomass (μg C L^{-1}), salinity, temperature, dissolved inorganic nitrogen (DIN) and phosphorus (DIP), and DIN:DIP ratios. In the monitoring dataset, microscopy-derived biovolume of filamentous cyanobacteria is calculated to carbon biomass based on Menden-Deuer and Lessard (2000).

2.5. Future climate and nutrient load scenarios

In the present study, the climate and nutrient load projections for the future Swedish coastal zone is restricted to the Stockholm Archipelago where the scenario simulations were performed for the period 1985–2098 with an initial five-year spin-up.

The future projections were produced with the Rossby Centre Ocean model (RCO) coupled to the SCOBI (see section 2.3) model (RCO-SCOBI) and simulated for the time period 1961–2100. The RCO model is a three-dimensional regional coupled ice-ocean model for temperature, salinity, velocity, sea level and sea ice with a horizontal and vertical resolution of 3.6 km and 3 m, respectively (e.g. Meier et al., 2003). The climate simulations were based on two Intergovernmental Panel on Climate Change (IPCC) greenhouse gas emission scenarios: the moderate SRES scenario A1B and the high emission SRES A2 scenario (Nakicenovic et al., 2000) run with two different global general circulation models (GCMs). In addition, the A1B scenario was simulated with two different sets of initial conditions to assess how natural variability impacts the climate in the long-term evolution after the preindustrial period. We consider the two initial condition simulations as two different possible realisations for the future climate. In this study, Baltic Sea projections downscaled from global climate models presented in the fourth IPCC assessment report were used (Meier et al., 2012a, 2012b).

Three nutrient load scenarios were performed and for each of the three nutrient load scenarios, an ensemble average over the four climate projections was calculated and averaged over two twenty-five-year periods, the future climate (2074–2098) and the present-day climate (1990–2014, hereafter called the control period), which are compared. The calculations of the ensemble average follow earlier approaches based on an equal weighting of the two GCMs (Meier et al., 2012a). The spread of the ensemble averages illustrate uncertainties in global climate models and the assumptions about socio-economic future developments with impact on greenhouse gas emissions. The various ensembles of future projections differ in the nutrient loads from land and atmospheric deposition. The nutrient load scenarios are:

1) BAU - Business-As-Usual is increased nutrient concentrations in rivers and current atmospheric deposition assuming a growth of agriculture around the Baltic Sea following HELCOM (2021),
2) REF - The reference nutrient scenario is based on nutrient concentrations in rivers and atmospheric deposition from the period 1969–1998 (Eilola et al., 2009),
3) BSAP - The reduced nutrient load scenario according to the Baltic Sea Action Plan (HELCOM, 2007) and 50 % reduced atmospheric deposition, For further information see Meier et al. (2012b).

The coastal open sea boundary forcing of the SCM model was extracted from the ensemble of future projections as described and validated in detail by Wåhlström et al. (2017). The SCM forcing, i.e. the forcing from land, the atmospheric deposition of nutrients and the state variables of the planetary boundary layer, were extracted at matching model grid points from the forcing of the RCO-SCOBI climate simulations. The forcing from land includes discharge of water and nutrients from both rivers and point sources and the atmospheric forcing includes air temperature, wind, relative humidity and cloudiness. Radiation and fluxes of heat and momentum across the water–air interface were calculated by the SCM model.

3. Results

3.1. Model validation

It has previously been shown that the SCM model realistically represents the Stockholm archipelago (Almroth-Rosell et al., 2016). In the present study, both model results from the control period at station B1 and average values from the entire Stockholm Archipelago during the control period were in good agreement with observations (Fig. 2). Salinity and temperature were especially close to observations in the model, while DIN and DIP values differed more from the observations, where the observed values were higher than model output at station B1, while observed and simulated DIN values for the entire archipelago were close. DIN was very low for both model and observations during summer, when also DIP was low, and with overlapping standard errors. The DIN:DIP ratios from model and observations at station B1 were similar during the early season, but higher for the entire archipelago due to relativ higher DIN concentrations. Cyanobacteria biomasses at the seasonal maximum were of the same magnitude, but simulated values occurred later in August or September instead of July as observed (Fig. 2).

3.2. Total nutrient load and total net exchange of nutrients

The main part of the land-derived nutrient loads to the Stockholm Archipelago enter the inner archipelago. The weighted ensemble average of the future nutrient load decreased in the BSAP load scenario compared to the control period, but increased in both the REF and BAU load scenarios, due to increased freshwater supply in a future climate (Meier et al., 2012a). In REF, total nutrient loads to the entire archipelago increased by 11% for P (from 276 t yr^{-1} to 307 t yr^{-1}) and 7% for N (from 9143 t yr^{-1} to 9825 t yr^{-1}) in a future climate (Table 1). For BAU, the corresponding increases were 34 % and 40 % for P and N, respectively. In contrast, a decrease for BSAP of 16% and 22 % for P and N, respectively (Table 1).

The net transport of N and P (total net exchange) between the three sub-areas, flows from the inner archipelago downstream to the intermediate archipelago, and then further to the outer archipelago, after which the net transport continues out towards the open coastal sea (Fig. 3). This pattern was true for all but REF and BAU in the outer archipelago, where the negative values imply a net import of P from the open coastal sea to the outer archipelago instead of vice versa (Table 2). Overall, there was a decrease in the outflow of both N and P to the open coastal sea in all three nutrient load scenarios compared to the control period.

3.3. Future retention

The future total retention in the entire Stockholm Archipelago increased compared to the control period for both N and P in the BAU and REF nutrient load scenarios, but only for P in the BSAP scenario. The relative changes in total retention for the entire Stockholm Archipelago for P in BAU, REF and BSAP in comparison to the control period amounts to 125, 68 and 5%, respectively, and for N; 60, 20 and −17%, respectively (Table 1).

When examining the three areas separately, the total retention in the BAU and REF scenarios increased for both P and N in the intermediate and outer archipelago, but decreased for P in the inner archipelago. In contrast, the total retention in BSAP decreased for both P and N, with the exception of P in the outer archipelago where it increased with 18%. The increase was largest for BAU and also increased seaward indicating that a larger proportion of nutrients was withheld closer to the open sea. Thus, the relative change was largest in the outer area, which also has the highest retention (Table 1 and 2).

The total retention of N and P was larger in the outer compared to the inner and the intermediate archipelago (Fig. 3, Table 2). In the outer and

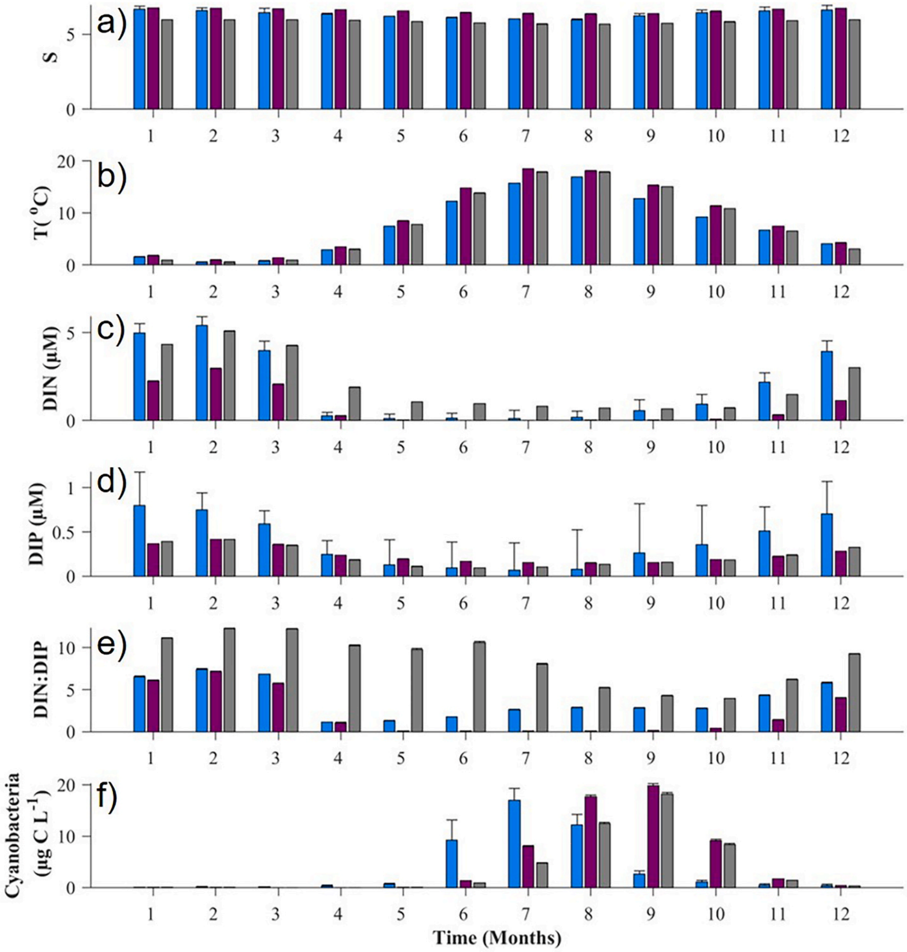

Fig. 2. Seasonal variation of surface (0–10 m), monthly average of a) salinity, b) temperature, c) dissolved inorganic nitrogen (DIN), d) phosphorus (DIP), e) DIN:DIP ratio and f) cyanobacterial carbon biomass of observations (blue) and model (purple) results at the station B1 and for the entire Stockholm archipelago (grey) during the control period 1999–2012. Error bars indicate standard error. Note: error bars for the model are too small to be visible. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Relative changes (%) of the total retention (permanent and temporal retention) and total nutrient load (Load$_{total}$; rivers, land runoff, point sources, atmosphere) of P and N compared to the control period, for the nutrients loads scenarios Business-As-Usual (BAU), Reference (REF), and Baltic Sea Action Plan (BSAP) in the inner, intermediate, outer and entire archipelago. Negative values are decreased total retention or load in the future climate compared to the control period (1990–2014).

		Inner		Intermediate		Outer		Entire	
		P	N	P	N	P	N	P	N
Relative changes of total retention	**BAU**	−18	67	80	58	192	59	125	60
	REF	−17	34	42	15	107	18	68	20
	BSAP	−23	−2	−4	−18	18	−20	5	−17
Relative changes of total nutrient load	**BAU**	40	51	28	30	1	2	34	40
	REF	13	9	11	8	0	1	11	7
	BSAP	−20	−15	−11	−26	0	−49	−16	−22

intermediate archipelago, the total retention of both N and P increased the most for BAU nutrient load scenario followed by REF and BSAP (Table 2). In the inner archipelago, the total retention of N had the same pattern, whereas there was a decrease in P for all three nutrient scenarios compared to the control period. These patterns were consistent with the permanent retention (Fig. S1). Changes in the temporary retention were more diverse, with smaller changes in the inner archipelago's nutrient pools with a seaward increase in the pools (Fig. S1).

3.4. *Future coastal filter*

The filter efficiency of N in the control period, i.e. the fraction of total nutrient load withheld in the area, was 17% in the inner coastal zone and 77% in the entire coastal zone (Fig. 4). For P, these values were slightly lower, 14% and 69%, respectively. In the future projections, the net import of P from the open coastal sea to the outer archipelago in REF and BAU (Table 2) causes the filter efficiency (E_F) to be higher than 100%, 104% and 117% for REF and BAU, respectively (Fig. 4). Hence, the outer Stockholm archipelago acts as a filter not only for the nutrients from the inner sub-areas, but also for the nutrients from the open, eutrophied

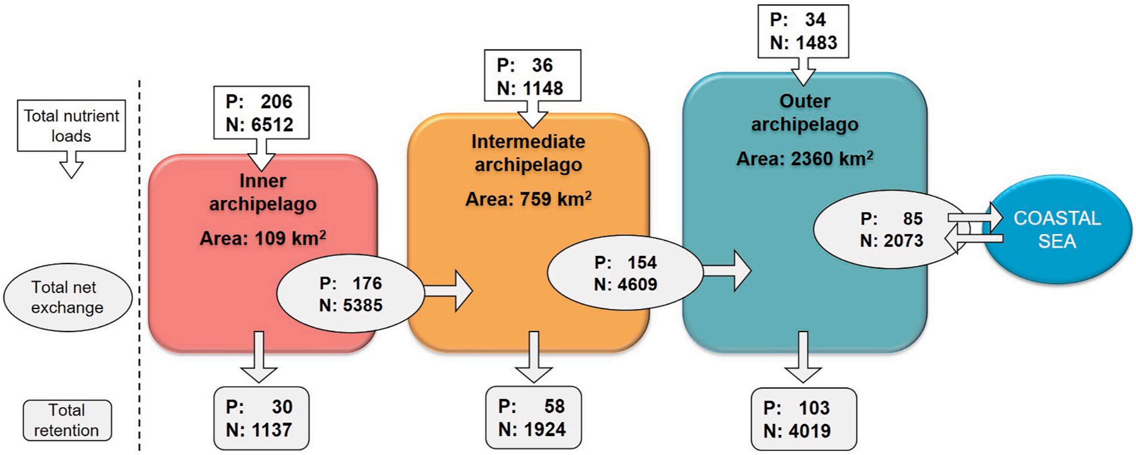

Fig. 3. A schematic view of the Stockholm archipelago with the inner (red), intermediate (orange) and outer (green) archipelago in the three squares and the open coastal sea (blue circle). The ensemble average transports of P and N (t yr^{-1}) for the control period into (total nutrient loads, top, boxes), between adjacent sea areas and with the open coastal sea (total net exchange, ellipses), and out of the system (total retention, lower squares). The total nutrient loads are the sum of rivers, land runoff, point sources and atmosphere; total retention is the sum of temporal and permanent retention. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 2
The ensemble average of total nutrient loads, total net exchange and total retention of P and N (t yr^{-1}) for the future nutrient scenarios; Business-As-Usual (BAU), Reference (REF) and Baltic Sea Action Plan (BSAP).

	BAU			Ref			BSAP		
Phosphorus (t yr^{-1})	Inner	Intermediate	Outer	Inner	Intermediate	Outer	Inner	Intermediate	Outer
Total nutrient loads	288	46	34	233	39	34	165	32	34
Total net exchange	263	204	−62	209	166	−13	142	118	30
Total retention	25	105	300	25	82	213	23	56	122
Nitrogen (t yr^{-1})									
Total nutrient loads	9820	1496	1506	7098	1236	1490	5552	850	761
Total net exchange	7942	6405	1501	5617	4633	1370	4448	3729	1263
Total retention	1878	3033	6410	1481	2220	4753	1104	1569	3227

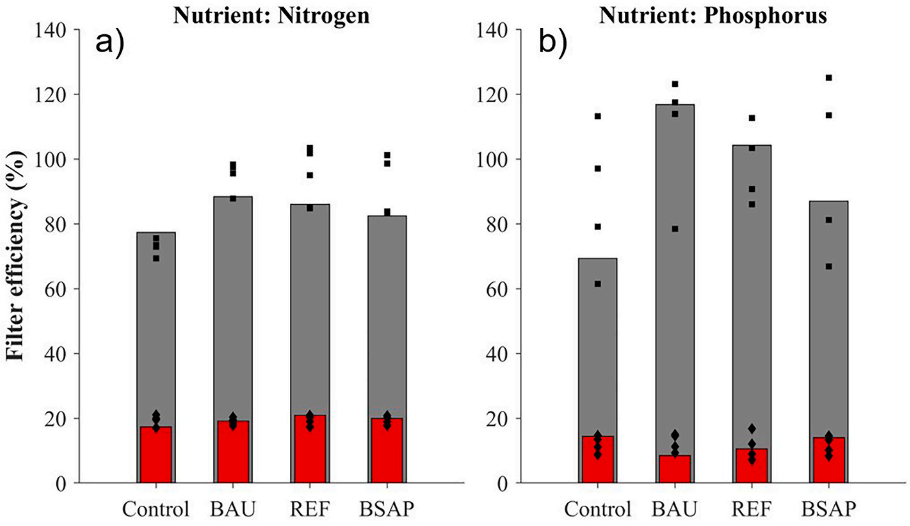

Fig. 4. The ensemble average of the filter efficiency (E_F) of N and P for control period (1990–2014) and future nutrient load scenarios Business-As-Usual (BAU), Reference (REF), and Baltic Sea Action Plan (BSAP) for the inner (red) and entire (grey) Stockholm archipelago. The dots are the results from the different climate projections and their spread is a measure of uncertainties. As the ensemble average of the four climate scenarios are weighted, the average values are not in the centre of the dot values. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Baltic Sea water.

Hence, the filter efficiency of both N and P increased in the entire archipelago during all three nutrient load scenarios; most for BAU, and least for BSAP and was most pronounced for P. However, the uncertainties are larger for P than for N, shown by the spread in results from the individual climate projections (Fig. 4). In the inner archipelago, the development was different. The filter efficiency of P decreased for BAU, and also to some extent for REF, but remained on the same level for

BSAP. The filter efficiency of N in the inner archipelago increased slightly for all scenarios, more for BSAP and REF than for BAU.

3.5. Future cyanobacterial biomass and nitrogen cycling

Future projections of the ensemble average, annual cyanobacterial biomass and N_2-fixation showed an increase in BAU and REF as compared to the control period (Fig. 5a and b). The results imply that in the entire archipelago the increase in cyanobacterial carbon biomass may be more than 5-fold under BAU conditions as compared to the control period (12.1 and 2.3 μg L^{-1}, respectively, Fig. 5a). In contrast, the cyanobacteria biomass would remain stable if the BSAP is accomplished. The inner archipelago is projected to undergo only minor changes in the future scenarios, while the effects would be largest for the intermediate and outer archipelago.

The Baltic Sea filamentous cyanobacteria have the ability of performing N_2-fixation, and while almost no fixation rates were observed in the innermost archipelago, the outer archipelago, especially under BAU, had a large input of N from this process. The lower N_2-fixation in the inner archipelago is supposedly due to higher concentrations of available dissolved N in the water resulting in a high DIN:DIP ratio (Fig. 5c), while relatively lower in the outer and thus, more beneficial for N_2-fixation (Fig. 5b). Both DIN and DIP increased in the whole archipelago during BAU as compared to the control period (Fig. S2), but without shifting DIN:DIP ratios (Fig. 5c). In contrast, the ensemble average annual denitrification rates during the control period were 10–20 times higher than N_2-fixation (Fig. 5d), and for the inner archipelago outcompeting N_2-fixation by orders of magnitude. Further, denitrification was almost 100% higher under BAU conditions as compared to the control period, potentially coupled to the increased anoxia in the bottom waters (Fig. 5f).

4. Discussion

The environmental conditions in the coastal zone are impacted by human pressures and are strongly connected with the conditions in the atmosphere, on land and in the open coastal sea as well as the extensive transports across these boundaries. Therefore, it is important to simultaneously investigate the net exchange of water and its content along the land-coast-open sea continuum and consequently, how much of the nutrient loads from land and open coastal sea stay (retained) within the coastal zone. This is important both now and in a future climate as eutrophication is a severe marine environmental problem causing for example deoxygenation (Breitburg et al., 2018; Rabalais et al., 2014), as shown in the present study when the future supply of nutrients increases.

The total retention is important both for the coastal zones and for the open coastal seas as well as further out into the oceans as it retains

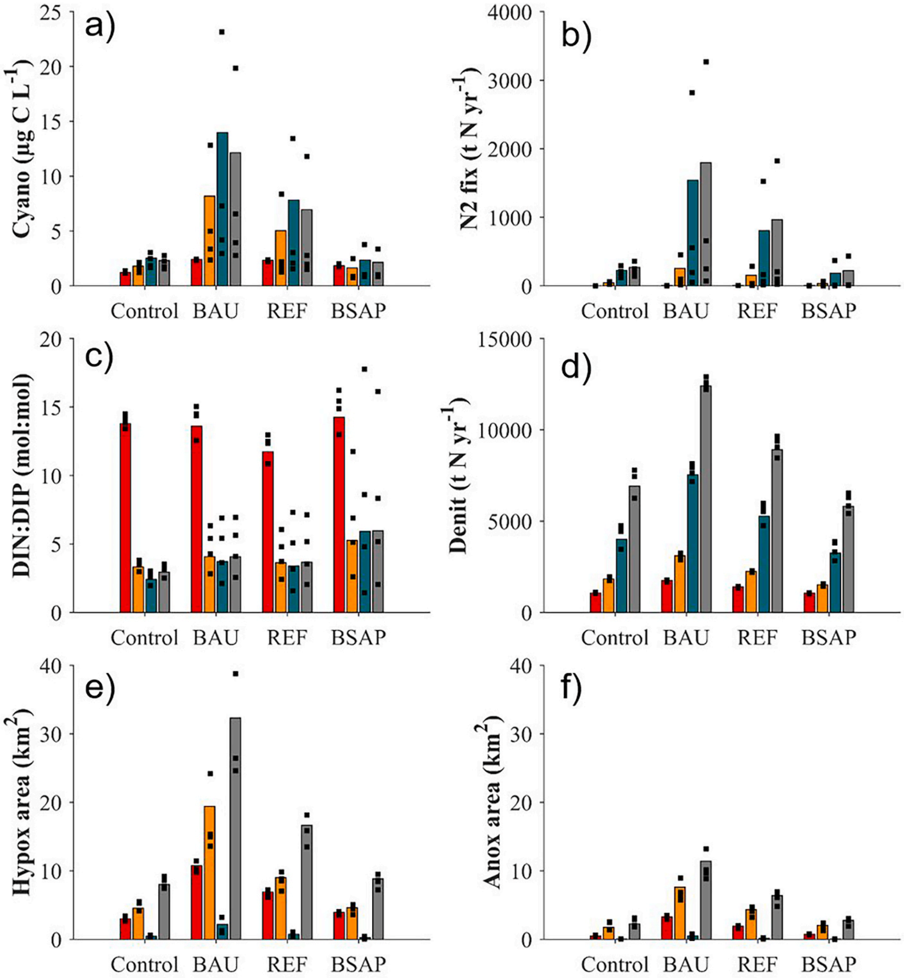

Fig. 5. The ensemble average, volume weighted annual values integrated for the whole water column for a) the biomass of filamentous cyanobacteria (μg C L^{-1}), b) N_2-fixation (t N yr^{-1}), c) DIN:DIP, d) denitrification (t N yr^{-1}), and the ensemble average sum of e) hypoxic bottom area (km^2) and f) anoxic bottom area (km^2) in the inner (red), intermediate (orange), outer (green), and entire (grey) archipelago for the control period (1990–2014), and for the three future nutrient load scenarios: Business-As-Usual (BAU), Reference (REF), and Baltic Sea Action Plan (BSAP). The dots are the results from the different climate projections and their spread is a measure of uncertainties. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

nutrients from the water column. The greater the proportion of the supplied nutrient loads that are retained, the greater the filter efficiency (percentage of the total nutrient load retained). If this is high in the coastal zones, a large part of the supplied nutrients from land stay within the coastal zone and consequently, less nutrients reach the open coastal sea or oceans and vice versa. Potentially, it reduces eutrophication in the waters outside the coastal zone resulting in an improved oxygen situation.

Our results of the filter efficiency (77% for N, 69% for P) shows that less than one third of the land loads of N and P reach the open eutrophied coastal sea. These results are 1.3 and 4.8 times higher, respectively, than those of Asmala et al. (2017). They estimated the filter efficiency of the entire Swedish coastline from upscaled observations of denitrification for N and burial of P, together with basin wise river loads, which makes these data not directly comparable. In addition to this difference, we also include the burial of N to estimate the total retention. Our results are also slightly higher than the maximum value (30–65% for N, 10–55% for P) previously estimated for the land-sea margins of the North Atlantic Ocean by Nixon et al. (1996). Although the Baltic Sea was included in their study, other types of systems, i.e. eutrophied, not-eutrophied and even pristine, might have dominated their estimates of the filter efficiency. However, our estimations agree with earlier studies using the SCM model (Almroth-Rosell et al., 2016; Edman et al., 2018). The small difference can be explained by the different forcing's of the SCM model, where the forcing at the open Baltic Sea, which in the present study is from the dynamic three-dimensional RCO-SCOBI model, while Almroth-Rosell et al. (2016) used vertical mean profiles from monitoring stations situated outside the Stockholm archipelago.

The future filter efficiency increases if the nutrient supply of N and P increases (BAU) or remains at present values (REF). This is due to the increased nutrient content in the entire system (Figs. S3–S4), especially in BAU, compared to the control period caused by increased nutrient loads from both land and the open coastal sea. Consequently, with the elevated nutrients in the coastal ecosystem, the archipelago becomes more eutrophic and enabling phytoplankton to increase. A decrease in the DIN:DIP-ratio, on the other hand, provides N_2-fixing cyanobacteria a competitive advantage in relation to other phytoplankton, which is clearly seen in the intermediate and outer archipelago, where cyanobacteria increased (Fig. 5).

The increased nutrient content also affects the net exchange of N and P between the areas and the retention within the areas as well as the decreased oxygen content of the bottom water. The retention of both N and P (REF and BAU), especially in the outer archipelago, increases at the same time as open coastal sea nutrients increases (Meier et al., 2012b), resulting in a decreased net exchange with the open coastal sea. Under certain circumstances (BAU and REF), there is a net import of P from the open coastal sea into the coastal zone, creating a filter efficiency over 100% (Fig. 4) and thus, the coastal zone also acts as a P filter for the eutrophied, open coastal water.

The occurrence of cyanobacteria blooms is perhaps the most visible evidence of human perception of eutrophication and will probably influence the ecosystem services such as tourism and other human activities. This N_2-fixation increases when N is limiting the growth and phosphate is still available (Fig. 5). Higher levels of phytoplankton may lead to increased oxygen consumption, reduced oxygen levels in bottom waters when they sink and decompose, which might be problematic in shallow coastal bays, creating bottom water with low oxygen concentrations or even dead zones. This is visible in the present study were both anoxic and hypoxic areas increased, mostly in the BAU scenario and less in the BSAP (Fig. 5e and f).

Denitrification is the most important process retaining N and where burial removes only about 7 % of the N. Although burial is a small part of the retention of N, it is the only process retaining P, which is strongly connected to the sedimentation rate and bottom water oxygen condition (Mortimer, 1941; Viktorsson et al., 2013). Denitrification is to a large extent regulated by the oxygen concentration, which is affected by properties such as the water's residence time (Almroth-Rosell et al., 2016; Nixon, 1995). The denitrification rates during the control period for the inner and intermediate area, scaled up to the area of the regions, are in good agreement to measurements from van Helmond et al. (2020), ~1100 t N yr^{-1} in our study versus ~1000 t N yr^{-1} in their study in the inner archipelago, and ~1800 t N yr^{-1} in our study versus on average 1700 t N yr^{-1} in their study in the intermediate archipelago. When normalising the denitrification rates per area unit, the highest rates were in the inner archipelago, decreasing towards the open coastal sea also shown by van Helmond et al. (2020). For several Baltic Sea archipelagos, the denitrification rate was estimated to on average 0.9 t N km^{-2} yr^{-1} (Asmala et al., 2017), while for Himmerfjärden (a fjord south of Stockholm) the estimated denitrification rate was about 1.3 t N km^{-2} yr^{-1} (Bonaglia et al., 2014). These estimates are somewhat lower than our denitrification rate during the control period of 2.1 t N km^{-2} yr^{-1} for the entire Stockholm archipelago, of which the latter varied from 9.8, 2.4 to 1.7 t N km^{-2} yr^{-1} from the inner to the intermediate and outer archipelago, respectively. These results indicate higher denitrification rates in the Stockholm archipelago, and especially in the inner archipelago, compared to other Baltic Sea areas. Denitrification rates have been shown to have a large variability, also between adjacent basins, not only due to residence time but also due to organic matter deposition to the sediment varying between basins and the consequently varying oxygen consumption (van Helmond et al., 2020). In addition, these observations are limited in both spatial and temporal resolution while the resolution in the model are high in both which can be used as argument to be careful when comparing scarce observations with model results (Skogen et al., 2021).

There are sparse studies including measurements of filamentous cyanobacteria in the Stockholm archipelago, but the biomass at station B1 used in the present study was in the same range as the control period (Fig. 2). In general, the modelled cyanobacterial biomass was lowest in the innermost archipelago and increased towards the open coastal sea. Regional difference are most likely due to the higher DIN:DIP-ratio closer to the coast, related to a high N availability (Fig. S3), which hampers their N_2-fixation as they can grow on nitrate (Mohlin and Wulff, 2009). However, other groups of phytoplankton are favoured by high DIN concentrations, and might therefore out-compete the cyanobacteria, possibly explaining the relatively small increase in cyanobacterial biomass in the inner archipelago (BAU), despite more nutrients available. In addition, less light availability has a negative effect on phytoplankton growth rate, which decreases closer to the coast (Svealandskustvattenvårdsförbund, 2022).

Due to lack of empirical N_2-fixation rate measurements within the archipelago, we cannot compare the model results to observations from within this area, but only from a monitoring station (B1) in the southern archipelago (Fig. 1). Since cyanobacteria biomass is highly dependent on local environmental factors the observations and horizontally integrated model results cannot be directly compared but used as an indicator of similar levels (Fig. 2). The modelled magnitude of cyanobacteria carbon biomass was in the same range as observations, but with a temporal delay as the modelled cyanobacteria bloom did not peak until early fall, which is later than in observations (Karlson et al., 2022; Olofsson et al., 2021). The delayed bloom is the result of in situ temperatures between 10 and 15 °C, which previously was demonstrated to lower the N_2-fixation rates. This is now corrected by using a cyanobacteria life cycle model application (Hieronymus et al., 2021), not yet available for the current model setup. With the high cyanobacteria biomass in future BAU conditions, high total N_2-fixation-based loads are anyhow expected as long as DIN:DIP ratios are low and beneficial to the cyanobacteria.

For the Baltic Sea, several ensembles of scenario simulations based upon the fourth and fifth IPCC assessment report and even earlier projections are available and have been thoroughly assessed (Meier et al., 2018, 2022a). The projections based on the IPCC's fifth assessment report, using the representative concentration pathways RCP4.5 and

RCP8.5 (Moss et al., 2010), were not available for the Baltic Sea when the present study was performed and therefore are the SRES scenarios from the fourth IPCC assessment report used. However, in future studies the more recent climate scenarios will be used for the coastal zone model and also include the entire Swedish coast. The RCP's for the Baltic Sea have become available after this study (Meier et al., 2021; Saraiva et al., 2019) and the basic conclusions about the model response to warming do not change. Differences between the two sets of scenario simulations for the Baltic Sea, based upon the fourth and fifth IPCC assessment report, respectively, have been discussed by Meier et al. (2022a) and includes for example assumptions of the not well-known fraction of bioavailability of the river nutrients loads, global sea level rise and regional water cycle. Both SRES and RCP scenarios rely on plausible narratives of future socioeconomic developments. The here employed moderate A1B and high emission A2 SRES scenarios are nearly identical to RCP4.5 and RCP8.5 at the end of the century (Fig. 1.15 in Cubasch et al., 2013). Notable deviations are visible in the historical period and for RCP8.5 vs A2 up to ~2080. Thus, the increase in radiative forcing from historical times is somewhat stronger in the SRES family. However, the conclusions and results of this study assess the response of the coastal filter to climate warming in a physically consistent and plausible way in addition to the chosen eutrophication scenario.

From the weighted ensemble averages we do not investigate the impact of a specific socioeconomic scenario or differences between those. Instead, we admit the fact that it is highly unknown which of the various socioeconomic pathways will become real and thus, consider this as an additional source of uncertainty in our analysis. Since we only had two global models (ECHAM and HadCM3) at hand, we weighted the realisations in a way that both models are equally accounted for when building the average across the models (Meier et al., 2012a).

The open boundary forcing of the SCM is given by climate and nutrient projections from a three-dimensional model (RCO-SCOBI, Meier et al., 2012b), which has a less complex description of the coastal zone. Hence, in our scenario simulations nutrient transports between the two models, RCO-SCOBI and SCM, might be biased. However, the results from this investigation highlights the importance of the coastal filter. In a future approach we suggest two-way nesting should be carried out to investigate systematic changes in the coastal filter capacity for the entire Baltic Sea system. This is important as there is no uniform answer to how the coastal filter will respond to climate change (Kulinski et al., 2022), but it will affect the amount of nutrients available to phytoplankton. On a global scale, coastal phytoplankton blooms have increased over the last 20 years, both in spatial extent and frequency, along with ocean warming and anthropogenic impact (Dai et al., 2023). The same study also acknowledges the need of policy decisions to reduce nutrient input to these vulnerable and important ecosystems.

5. Conclusions

The approach of the present study and its results form a basis for understanding how important the coastal zone is for the uptake of nutrients and how the future nutrient loads and climate change may affect the future retention of N and P as well as possible cyanobacteria bloom situations in coastal archipelagos.

Archipelagos work as efficient filters for nutrients that enter the coastal zone from land and atmosphere but also from the open coastal sea. The future filter efficiency increases compared to present day, regardless of the nutrient load projection. This means that not all the nutrients from land reach the open coastal sea but instead are retained within the archipelago. The intermediate and outer coastal zones have the most effective filtering roles along with increasing nutrient loads.

The increased filtering has an effect on the ecology of the coastal zone, through changes in the nutrient concentrations and ratios: as a consequence, the cyanobacterial biomass increases in the nutrient load projections with increased (BAU) or todays (REF) supply of nutrients but remains stable if a reduction in nutrients supply (BSAP) is accomplished. This increase is most pronounced in the outer coastal zone.

Our study efficiently exemplifies how an attained nutrient management plan can maintain the cyanobacteria biomass at the same level as today even under future climate change projections. If this plan is not followed, cyanobacteria biomass might increase by a factor of five, with potentially negative effects on the tourism in this well-used region. Further, an increased phytoplankton biomass under especially BAU conditions, elevates the spread of anoxia/hypoxia bottom water.

Coastal cities have a large impact on the aquatic environment because of their large human population and therefore, plays an important role by providing a large amount of ecosystem services, both recreational and professional activities. Coastal managers and decision makers therefore need to account for the combined impact of climate change and anthropogenic effects, including nutrient supplies, in the coastal zone planning. It is important to have a good understanding of the complex interactions taking place in the coastal systems. Globally, experiments with coupled biogeochemical and physical models in combination with representative scenarios may support future ecosystembased management with decision support.

CRediT authorship contribution statement

Iréne Wåhlström: Writing – original draft. **Elin Almroth-Rosell:** Writing – original draft. **Moa Edman:** Writing – review & editing. **Malin Olofsson:** Writing – original draft. **Kari Eilola:** Writing – review & editing. **Vivi Fleming:** Writing – review & editing. **Matthias Gröger:** Writing – review & editing. **Lars Arneborg:** Writing – review & editing. **H.E. Markus Meier:** Writing – review & editing.

Declaration of competing interest

The authors declare no conflicts of interest.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecss.2024.108728.

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