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Climate change effects on denitrification and associated avoidance costs in three Baltic river basin - coastal sea systems

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Abstract To fight ongoing eutrophication of the Baltic Sea, major international directives and agreements, like the EU Water Framework Directive or the Helcom Baltic Sea Action Plan, aim at a reduction of nutrient loads to the Baltic Sea. These external nutrient load reductions interact with retention and removal processes (ecosystem services) in coastal and marine waters. Beside sedimentation, denitrification is the most important regulation ecosystem service provided by the sea, because it removes nitrogen (N) to the atmosphere and controls eutrophication. Denitrification is a spatially and temporally highly variable process and largely depends on temperature and N concentrations in the water. Climate change will have strong effects on denitrification. Increasing temperatures favour denitrification and changes in precipitation and discharge will alter the availability of N, with strong differences between river basins. We combine a 3D–ecosystem model of the Baltic Sea with economic marginal cost functions for three major Baltic river basins: Odra, Vistula and Neva. Objective is to calculate the monetary consequences of climate change (scenario A1B) for the implementation of water quality objectives, taking into account both, spatial changes in N loads and denitrification. In all regions over 90% of the entering N loads are subject to denitrification mainly in coastal waters. For the climate change scenario (A1B), our approach suggests reduced riverine N-loads of 7690 t/a (Odra), 6410 t/a (Vistula) and increased loads of 3200 t/a for the Neva. At the same time our model results suggest an increased denitrification of N-loads by 9.1% (Odra) and 9.9% (Neva) and minor changes with respect to the Vistula loads. In combination, in all three regions climate change helps to reach policy targets (lower N concentrations in the sea) at lower costs. The monetary benefit of load reduction measures that do not have to be implemented because of climate change are 11,270 million €/a (Odra), 2000 million €/a (Vistula) and 92 million €/a (Neva). The valuations strongly depend on the assumed climate change scenario and the economic approach, but indicate that climate change effects differ much between river basins and should be taken into account in nutrient load reduction management plans.

Keywords Ecosystem services · Water framework Directive · Baltic Sea · Szczecin lagoon · Odra · Neva · Vistula

Introduction

Eutrophication is still one of the major problems in the Baltic Sea and during summer in the open Baltic Sea and most inner coastal waters, nitrogen is the limiting element for algal development. About 75% of nitrogen (627,000 t total N in 2006) enters the Baltic Sea through rivers (HELCOM 2009). The availability of nitrogen in the water largely depends on denitrification. Denitrification means that nitrate is reduced to nitrogen (N) gas by bacteria in several steps and released to the atmosphere. Deutsch et al. (2010) estimated that 48% to 73% of the annual N loads into the Baltic Sea can be removed by denitrification. The retention and transformation of nutrients are regarded as major regulating ecosystem services provided by surface waters, especially burial in the sediments and denitrification (e.g. Maes et al. 2016).

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Climate change has multiple and strong effects on the Baltic Sea ecosystems and its coastal waters (HELCOM 2007a). Effects on water quality are significant and have been projected based on ecosystem models (Meier et al. 2012; Friedland et al. 2012). As stated in the guidance document for river basin management in a changing climate (European Communities 2009) and the Baltic Sea Region adaptation strategy, it is important to consider climate change in the implementation of long-term plans and directives, e.g. the Water Framework Directive (WFD), the Marine Strategy Framework Directive (MSFD 2008) and the Baltic Sea Action Plan (BSAP, HELCOM 2007b). Climate change alters the release, transformation and retention of nutrients and pollutants. Quantitative changes of these processes due to climate change will have immediate consequences on the state of eutrophication and on eutrophication abatement programs, like the BSAP. Meier et al. (2012) suggest an increase of denitrification in the Baltic Sea by 30% in a future climate (2070–2100). An increasing denitrification rate at higher temperatures is supported by data in Silvennoinen et al. (2008) and Nowicki (1994). Climate change induced modifications of denitrification can be re-calculated in monetary values, based on marginal cost approaches. Marginal costs functions describe the costs to reduce nitrogen emissions per weigth uni. They largely depend on the state of pollution and the efforts that already took place to reduce emissions. Gren et al. (1997) and Gren (2008, 2009) already provide marginal cost functions different Baltic drainage areas.

Usually ecological and economic approaches are linked in a straightforward way to answer questions like: To what extend do we need to reduce nutrient loads to reach a desired ecological status and what does it cost or what is the economic benefit of a good status of the sea? (Söderqvist 2000; Gren et al. 2008). Usually the results do not reflect the full potential of linking spatially resolved models, regional ecological and economic specifics and interactions.

We apply a 3D ecosystem model for the Baltic Sea and simulate denitrification rates for the present situation and for a future climate. We focus on three major, contrasting river basins, namely Odra, Vistula and Neva. By linking the ecological model with regional economic calculations, we assess how changing river loads in a future climate interact with changing denitrification in the sea, calculate the monetary consequences for river basin management approaches and discuss the management implications.

Study area & methods

Study areas

According to HELCOM (2011) the Baltic Sea has a total catchment area of 870,870 km^2 and the long-term mean flows of the seven largest rivers discharging into the Baltic Sea is 6670 m^3/s. We focus on three of the most important rivers, Neva, Vistula, and Odra. The Neva (Russia) has a length of only 74 km, but is with respect to catchment area (271,800 km^2) and discharge (2278 m^3/s) the most import Baltic river. It is followed by the Vistula (Poland) with a length of 1047 km, a catchment area of 194,420 km^2 and a discharge of 1047 m^3/s. The Odra (Poland) has a length of 854 km, a catchment area of 118,840 km^2 and a discharge of 574 m^3/s (Fig.1). Its discharge is smaller compared to the Daugava (1036 m^3/s) but similar to other major Baltic rivers like Nemunas, Göta Älv and Kemijoki.

The average total N concentrations in the rivers (2004–2008) are about 1.2 mg/l (Neva), 2.7 mg/l (Vistula) and 3.7 mg/l (Odra). The Odra has the highest N concentrations of the 7 most important rivers (HELCOM 2011). Natural concentrations assuming minor anthropogenic influence (reference conditions according to the European Water Framework Directive, assuming a period around 1880–1900) for all three rivers are very likely below 1 mg/l total N (Hirt et al. 2014). The total waterborne N-loads to the Baltic Sea (including monitored rivers, unmonitored areas and direct point source inputs) in 2006 were 638,000 t. About 24% of these loads enter with the Odra and Vistula into the southern Baltic Sea. The area specific load is about 0.42 t/km^2 (HELCOM 2011). The most important source of N are diffuse loads from agricultural land (about 75%). However, altogether about 40% of the gross riverine N loads are subject to retention in the river basins.

Odra and Vistula basins can be mainly assigned to Polish territory (89% resp. 87%). The Polish river basins are populated

Fig. 1 The Baltic Sea drainage area and the location of Odra, Vistula and Neva river basins

by 13.1 million (Odra) and 22.3 million inhabitants (Vistula). More than half of the area is used for agriculture, 29% are covered by forests and 6% represent urban areas, leading to a high contribution of diffuse sources (HELCOM 2004).

The Neva drains into the Gulf of Finland, which is heavily eutrophied (HELCOM 2009). The total drainage basin is 271,800 km^2 and has a high share of forests with 55%, followed by lakes (17%), peat lands (13%), farmland (12%) and urban areas (2%). 79% of the basin are located in Russia and are populated by 8 million. The riverine load of the Neva is assumed to be 52,500 t N/a (HELCOM 2004). Major nitrogen source are largely untreated municipal and industrial discharges from the city of St. Petersburg.

Baltic Sea ecosystem model

The ecosystem model ERGOM-MOM (Ecosystem Regional Ocean Model) is an integrated biogeochemical model coupled to a three-dimensional (3D) circulation model and covers the entire Baltic Sea. The circulation model is an application of the Modular Ocean Model (MOM) (Pacanowski and Griffies 1998). A thermodynamic ice model is included to simulation ice cover. The horizontal resolution is 3 nautical miles; vertically the model is resolved into 77 layers with a layer thickness of 2–3 m for the upper 100 m and a constant thickness of 6 m at greater depths. For detailed studies, a higher spatial model resolution of 1 nm is used (Fig. 5). The bio-chemical state variables describe the nitrogen and phosphorus cycle. The dissolved inorganic nutrient state variables are ammonium, nitrate, and phosphate. Three functional phytoplankton groups, representing diatoms, flagellates, and cyanobacteria allow calculating primary production. Cyanobacteria are able to fix atmospheric nitrogen. Therefore, their growth is limited by phosphorus only. A dynamically developing bulk zooplankton variable represents grazing pressure. The detritus state variable describes the accumulation of dead organic particles. Detritus sinks down and is mineralized to dissolved ammonium and phosphate. Detritus that reaches the bottom is partly buried, mineralized or re-suspended (Neumann 2000; Schernewski et al. 2008). Detritus mineralization in the sediment takes place at a temperature-dependent rate. Nitrogen is removed by denitrification. The oxygen cycle is coupled to all biogeochemical processes. A detailed description is given in Neumann (2000). The model has been used for various applications (Neumann et al. 2002; Neumann and Schernewski 2005; Neumann and Schernewski 2008; Schernewski et al. 2008).

Meteorological forcing

CLM is the climate version of the operational weather forecast model of the German Weather Service model. Neumann (2010) applied the regional meteorological data of CLM (CLM Community 2008) in ERGOM to simulate differences of ecosystems due to climate change in the Baltic Sea. The mean data on denitrification for a reference period from 1990 to 2009 and future period from 2080 to 2099 are used in this study, to reflect possible changes. The greenhouse gas emission scenario A1B by the Intergovernmental Panel on Climate Change (IPCC), which is a more progressive scenario (IPCC 2007) is applied.

CLM has a horizontal resolution of 18 km and time resolution of 1 h for wind components and 3 h for other meteorological variables. Large-scale controlling conditions are derived from transient climate-change simulations performed with the ECHAM5/MPI-OM of the Max-Planck-Institute of Meteorology. Mean annual cycles of nutrient concentrations are estimated for each of the rivers based on the present nutrient load. For runoff in the different sub-catchments, data from observations and downscaling simulations are used in a statistical model STAT. CLM includes a land surface and soil model, where surface and groundwater runoffs are applied (Neumann 2010).

Changes of denitrification attributed to river-borne nitrogen

Processes in the Baltic Sea show a high spatial and temporal variability. Depending on prevailing currents processes may take place in different areas. To determine the exact areas in the Baltic Sea where denitrification of river-borne nitrogen takes place is a major challenge. In ERGOM-MOM simulations, river-borne nitrogen inputs were labelled and tracked to be able to analyse the spreading and residence time within the Baltic Sea. Details are described in Radtke et al. (2012). This approach allows the estimation where and how much denitrification takes place in the Baltic Sea during defined time periods. With this tracking method, spatial denitrification pattern of nitrogen loads entering with the rivers Odra, Vistula and Neva where calculated and averaged over the period 1976 to1996. Because of computation time limitations, these spatial pattern where applied in the climate change simulation, as well.

To assess denitrification quantities of river-borne nitrogen for the climate change scenario the model studies from Radtke et al. (2012) and Neumann (2010) are combined. In the first step, mean denitrification rates are obtained for the reference period and for the future climate change scenario, based on simulations of Neumann (2010). The model provides denitrification rates for each model grid in the Baltic Sea. In the next step, denitrification rates are attributed to the river-borne nitrogen, which is denitrified in the Baltic Sea. For each model grid cell the share of river-borne nitrogen of the total denitrified nitrogen amount, is calculated based on mean distribution pattern. This is separately done for the rivers Odra, Vistula and Neva. The shares are multiplied with

denitrification rates from climate change simulations of Neumann for the chosen periods to attribute denitrification rates to river-borne nitrogen. The total amount of river-borne nitrogen, which is denitrified in the Baltic Sea for each river and period, can be calculated by integrals. The boundaries of the integrals are set by the Baltic Sea. The average river loads in the corresponding periods are calculated as the product of mean nitrogen concentrations and water discharge.

Monetarization

N marginal avoidance cost functions for all river basins are taken from Gren (2009). Data for the cost functions and nutrient loads under business as usual are based on an existing static programming model of the Baltic Sea (Gren et al. 2008). In this approach the entire basin of the Baltic Sea is divided into 24 drainage basins and specific N emission avoidance costs functions are given for each of these drainage basins considering different nitrogen reduction measures (Gren 2009). For the Neva basin cost functions from the drainage basin of St. Petersburg and its surroundings are taken as it shows the highest overlap to the river basin of the Neva. The functions are shown in Fig. 2.

C expresses the reduction costs in millions of Euros (recalculated from Swedish crowns). N represents kilotons of nitrogen reduction from the river basins to the Baltic Sea per year.

Results

Validation of the Baltic Sea ecosystem model

Spatially integrated monitoring data of the Baltic Sea (e.g. winter concentrations of all N compounds), does not show strong changes in the Baltic Sea total nitrogen content, even over a decade. We assume that the monitoring data, which is based on a large number of data, is correct and that denitrification field
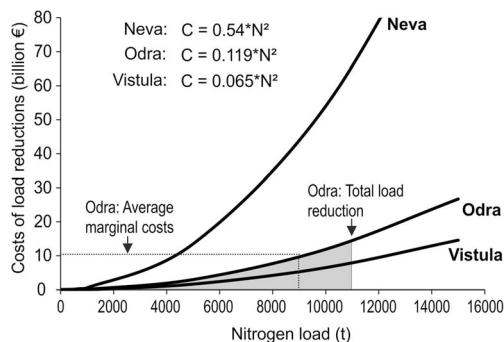
studies underestimate the total denitrification in the Baltic Sea. ERGOM represents the total amount of nitrogen in the Baltic Sea and its changes very well. Figure 3 a comparison between model and data long-term changes. We used relative changes because total N-compounds in the model are different to those derived from monitoring data. The model data is lower because it only takes into account compounds which are actively involved in processes, while total N data includes e.g. resuspended material and in-active components.

To ensure that the long-term development of total N amounts in the Baltic Sea are correctly reflected in the model, ERGOM requires a higher total annual denitrification in the Baltic Sea compared to data from field studies e.g. Stockenberg and Johnstone (1997), Deutsch et al. (2010), Tuominen et al. (1998), Hietanen and Kuparinen (2008) and Jäntti et al. (2011). Neither assuming a lower annual N-fixation rate in our Baltic Sea model, nor assuming lower N load from atmospheric deposition would solve this problem. Therefore, the denitrification data provided by the model simulations are used as a basis for our calculations.

Spatial denitrification pattern in the Baltic Sea

Figure 4 shows where the denitrification of river-borne N takes place in the Baltic Sea. Our model suggests that nearly all river-borne N entering the Baltic Sea is subject to denitrification. The concrete numbers slightly differ between the three rivers: 96% of Odra N-loads, 93% of Vistula loads and 91% of Neva loads are denitrified in the Baltic Sea. The numbers refer to the period 1987 to 1996.
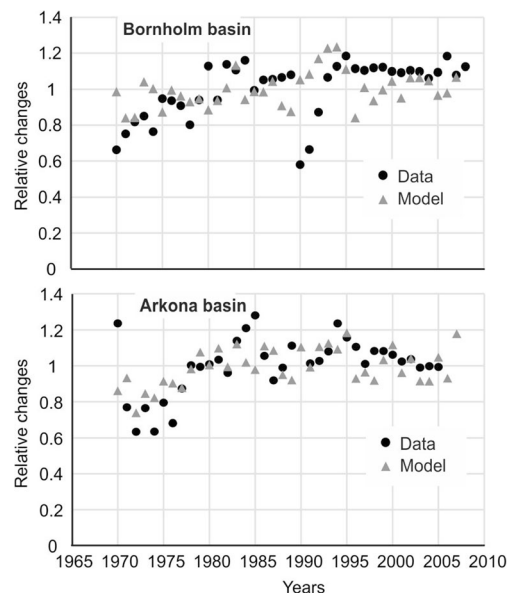

Fig. 3 Comparison between data and model simulation: Relative long term (1965–2010), depth integrated total nitrogen concentrations in the Arkona Sea and the Bornholm Sea

Fig. 2 Marginal cost functions for an N-loads reduction to the Baltic Sea in three river basins Odra, Vistula and Neva. The figure exemplary indicates for the Odra how average marginal cost functions were calculated (see Table 1)

Fig. 4 Model simulated spatial denitrification pattern of the nitrogen loads entering the Baltic Sea with the Odra **a**, Vistula **b** and Neva **c** river discharges. Shown are averaged denitrification rates covering the period from 1987 to 1996. It includes denitrification in the sediments and in the water column
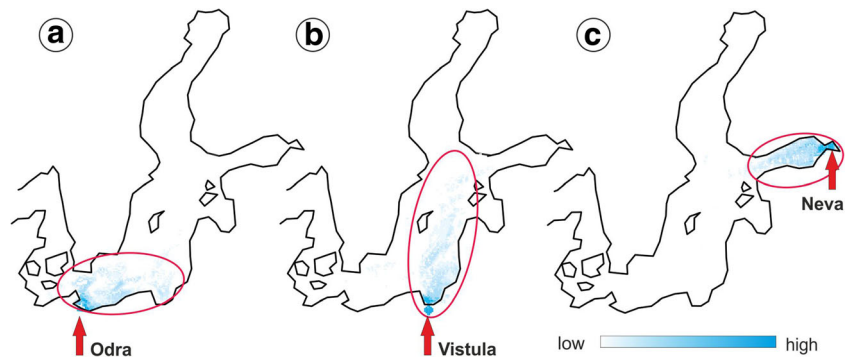
Already in coastal waters, most of the entering N is denitrified and removed from the water body. With respect to the Odra the vast majority is removed in the Odra Lagoon, the Bay of Pomerania and along the western part of the Polish coast (Fig. 5). Denitrification in the Oder/Szczecin Lagoon removes about 28% of the Odra river N load and another 15% are removed in the coastal Pomeranian. Only smaller amounts are removed in open Baltic Sea. The denitrification rate in the Oder/Szczecin Lagoon is about 10 times higher compared to the Bay of Pomerania and about 50 times higher than in the Bornholm Sea (Fig. 5). These number refers to the removal of Odra borne N.

N entering with the Vistula is transported relatively fast towards the open Baltic Sea (Gotland Basin) and is denitrified in a large sea areas. However, the most important sink is the western part of the Gulf of Gdansk, the Puck Bay. Altogether 19% of the riverine nitrogen loads are removed in the Gulf of Gdansk. Smaller amounts of N are removed in the Gdansk Basin and along the coast of the Courland Spit. The mean denitrification rates of Vistula borne N are more than 10 times higher in the Gulf of Gdansk compared to the Gotland Basin.

With respect to the nitrogen load of the Neva, most denitrification takes place in the Gulf of Finland and only few N reaches the central Baltic Sea (Gotland Basin). However, 35% of the nitrogen loads are removed already near the coast, in the Neva Estuary. The mean denitrification rates in the Neva Estuary are about 24 times higher compared to the western part of the Gulf of Finland.

Climate change induced differences in denitrification

The denitrification rates of riverine load in the Baltic Sea for the two periods, the present situation (1990–2009) and under a future climate (2080–2099), are compared (Fig. 6). In general, gradients in denitrification rates between coast and open sea exist. Denitrification rates depend on temperature and the availability of inorganic N. Higher water temperatures along the coast in the future scenario cause up to $0.5 \, \text{mmol N m}^{-3}\text{d}^{-1}$ higher denitrification rates in lagoons and close to the coast. As consequence, less nitrogen is transported to and available in the open sea, causing reduced denitrification rates in the open sea in a future climate.

The model suggests an increase of the total denitrification in a future climate by 9.1% for the Odra N loads and by 9.9% for Neva N load. With respect to Vistula nitrogen loads, the model simulations show a slight decrease of total denitrification by 0.14%. These changes are largely a result of increasing denitrification rates due to higher water temperatures. However, climate change not only affects water temperatures, but also has multiple consequences in the river basin.

Fig. 5 Model simulated spatial denitrification pattern of the nitrogen loads entering the Baltic Sea with the Odra river. **a** Average total annual denitrification (t N a^{-1}) and relative denitrification of Odra river loads. **b** Annual area specific denitrification rates (g N $m^{-2}a^{-1}$). All numbers are related to an average annual Odra river N load of 55,000 t/a and include denitrification in the sediments and in the water column
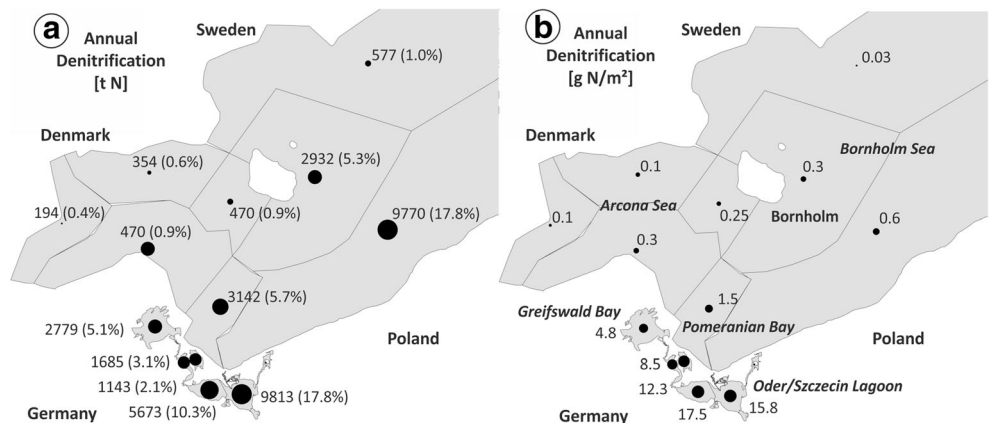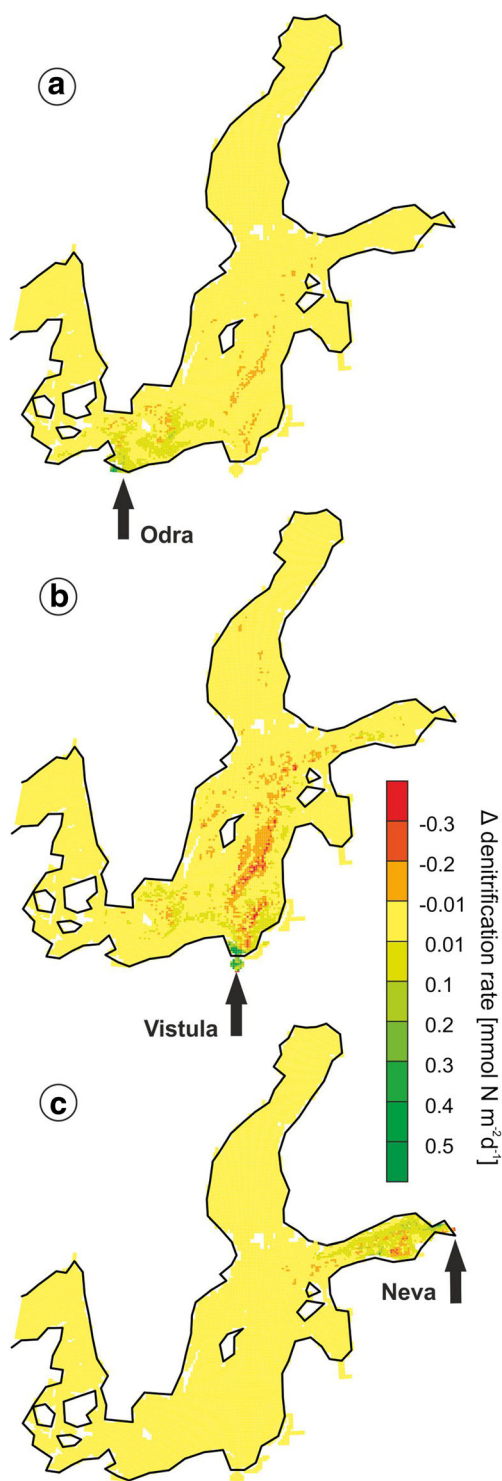
Fig. 6 Changes in denitrification of riverine nitrogen from the Odra **a**, Vistula **b** and the Neva **c** in the Baltic Sea. Differences are calculated considering mean data of the reference period (1990–2009) and future (2080–2099)

According to our model input data, the concentrations of N all three rivers are very similar for both scenarios, the situation today and in a future climate. But the riverine water discharge specific runoffs show strong differences between both

periods. Following the approach by Neumann (2010), riverine water discharges were estimated from runoff data provided together with the CLM data. For the future climate scenario A1B, the water discharge in Odra and Vistula are decreasing while an increase is projected for the Neva. As consequence, the nitrogen load of the Odra (Vistula) is lower in a future climate by 14.5% (5.9%) (Fig. 6). In contrast, higher N loads of 5.9% are projected for the Neva River.

The strongly increased total denitrification of Neva N loads in a future climate is a result of higher water temperatures and higher concentrations of N due to increased loads. The slight decrease of total denitrification in the Vistula is a result of reduced future N loads that over-compensate temperature effects. Changing ventilation of the bottom waters may play a role, as well. In case of the Odra, the Szczecin Lagoon, plays a modifying role that has to be explored in more depth. The highest increase of mean denitrification rates are observed in the coastal areas, which show the highest denitrification.

Economic valuation

In a future climate (scenario A1B) increased denitrification reduces the pollution deriving from Odra loads by 3250 t N per year and in case of the Neva 3670 t N/a. The denitrification of Vistula N loads will decrease by 310 t N/a. Nutrient concentrations are indicators for water quality in the WFD. Enhanced denitrification means an improved water quality in the Baltic Sea and is beneficial for reaching the environmental quality targets of the WFD and the BSAP. The BSAP defines nutrient load reduction targets for each country. In our river basins, climate change helps us to reach these targets easier and at lower coast. This benefit can be expressed in monetary terms based on marginal cost approaches. The costs of reducing the riverine loads by 1 t N depend e.g. on the structure of the river basin, the considered nutrient retention measure or the state of pollution. In the Vistula basin reduction measures can be implemented at lowest costs, in the Odra basin the costs are nearly twice as high and for the Neva basin the costs are nearly 8 times higher (Gren 2009) (Fig. 2).

The average costs of N reductions per river basin (Tab.1) result from the integral under the marginal cost function between zero and the total amount of N changes. With respect to the Odra the average costs of 1.03 million €/t N results from the averaged integral between 0 and 10,940 t N/a (Fig. 2). The monetary benefit of increased denitrification, reduced riverine loads and both in combination are shown in Table 1. It further shows the background data for the calculations and the results based on our model simulations.

In the Neva region, climate change increases denitrification strongly and this cleaning effect has a monetary benefit of 724 million Euros/a, but this effect is compensated by climate change induced higher river loads which increase cost by 632 million Euros/a. As a consequence the benefit is only 92

Table 1 Effects of climate change on riverine loads and denitrification in three river basins, Odra, Vistula and Neva as well as monetary consequences and total economic benefits

	Odra	Vistula	Neva
River loads 1990–2009 [t N/a]	53,100	108,900	54,800
River loads 2080–2099 [t N/a]	45,400	102,500	58,000
Change in river load [t N/a]	-7700	-6400	3200
Change in denitrification of river-borne N [t N/a]	−3300	0,100	−3700
Total changes [t N/a]	−10,900	−6300	−0.500
Average costs of N reductions [€/t N]	1,029,885	318,548	197,297
Monetary benefits of changes in load [million €/a]	7920	2042	−632
Monetary benefits of changes in denitrific. [million €/a]	3351	−42	724
Total monetary benefits of changes [million €/a]	11,270	2000	92

million Euros/a. For the Odra region, the situation is very different: an increased denitrification meets reduced riverine loads and both result in high monetary benefit in a future climate of 11,270 million Euros/a. For the Vistula we see minor climate change effects on denitrification as a result of the specific natural setting of the coastal waters. Climate change induced reduced riverine loads alone are responsible for benefit of 2000 million Euros/a.

Discussion

The horizontal model grid resolution of 3 nautical miles does not fully resolve the coastal waters (Friedland et al. 2012), may underestimate the quantitative role of processes in coastal waters and may cause inaccuracies in the flow and transport pattern. Transport pattern are important for the spatial distribution of denitrification and may the different under a future climate. This is neglected in our approach. Using only one climate change scenario is a simplification that does not sufficiently provide information on regional differences and uncertainties (Meier 2006). Uncertainties linked to the economic approach are discussed in Gren et al. (2008).

The denitrification rates used by our model are higher than extrapolated field data for Baltic Sea basin sediments of Stockenberg and Johnstone (1997), Tuominen et al. (1998), Hietanen and Kuparinen (2008) and Jäntti et al. (2011). Deutsch et al. (2010) calculated average denitrification rates in the Baltic Sea between 0.2 and 0.31 mmol N m^{-2} d^{-1} for the year 2008. ERGOM calculates an average denitrification rate of 0.5 mmol N m^{-2} d^{-1} in the Baltic Sea for the period 1990–2009. This may lead to an overestimation of the N-removal (Radtke et al. 2012). However, the high rates observed in the model are supported by few studies. Eiola and Stigebrandt (1999), for example, suggests a mean denitrification rate of 0.59 mmol N m^{-2} d^{-1} for the entire Baltic Proper basin. In Baltic coastal waters much higher rates have been observed, like 1.0 mmol N m^{-2} d^{-1} in Bassholmen Bay (Sundbäck and Miles 2002), 3.2 mmol N m^{-2} d^{-1} in Randersfjord (Nielsen

et al. 2001) or 0.28–1.55 mmol N m^{-2} d^{-1} in the Curonian Lagoon (Zilius 2011). It is known that denitrification field data shows a strong spatial and temporal variability (e.g. Dahlke et al. 1998). Field data depends on the methodological set-up and the specific site. The few data available hardly allows a reliable extrapolation to the Baltic Sea level. The extrapolated denitrification field data according to Deutsch et al. (2010) would cause a strong annual accumulation of nitrogen in the Baltic Sea of at least 475,000 t N/a. However, a relatively good spatial correlation ($r^2 = 0.67$) between observed (Deutsch et al. 2010) and simulated data exists. For us it was important to keep the long-term N budget in the model stable and close to nutrient balances calculated based on N monitoring data. One needs to keep in mind that denitrification rates bear uncertainties when interpreting our results.

An increase of denitrification in the Baltic Sea due to climate change is supported by several papers (e.g. Friedland et al. 2012). Meier et al. (2012) suggested an increase of denitrification by 30% in the Baltic Sea related to present load scenarios applying different regional climate change models and greenhouse gas emission scenarios. An increase of denitrification due to temperature increase in coastal areas is also supported by Dahl et al. (2012).

Altogether we can conclude that our approach suffers from several uncertainties, but successfully links economic and dynamic marine ecosystem modelling and provides a spatially explicit view. We can provide consistent estimates how much of riverine N-loads are subject to denitrification as well as where spatially and in which season this takes place. We were able to combine these results with a future climate simulation that gives us insight into how denitrification is affected by changing riverine nitrogen loads. The dominating near-shore denitrification show the importance of coastal waters for providing this regulating ecosystem service and underline their outstanding role for providing services for human-welfare (e.g. Costanza et al. 1997). However, most important are the implications for river basin management. The European Water Framework Directive (2000/60/EC) aims at a good ecological status of surface waters and the Baltic Sea Action Plan (BSAP,

HELCOM 2007b) is a programme to restore this good ecological status in the Baltic. Nutrient load reduction targets in every river basin play a major role to reach this goal. According to HELCOM (2010) the total costs of achieving the BSAP target regarding eutrophication in the entire Baltic Sea region are estimated to be 2.5–3.0 billion Euros per year. The total benefits are assumed to be 2.5–4.8 billion Euros per year. Compared to our results these numbers are lower because of different approaches. However, for the central Baltic (Baltic Proper) the BSAP demands a 25% of nitrogen load reduction. According to our results, climate change alone may cause 20% a load reduction in the Oder/Odra river basin system (including denitrification effects) and would strongly reduce the required high investment costs. The benefits of climate change strongly differ between river basin-coastal water units and potentially can be opposite in some regions.

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