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Reduction of Baltic Sea Nutrient Inputs and Allocation of Abatement Costs Within the Baltic Sea Catchment

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Abstract The Baltic Sea Action Plan (BSAP) requires tools to simulate effects and costs of various nutrient abatement strategies. Hierarchically connected databases and models of the entire catchment have been created to allow decision makers to view scenarios via the decision support system NEST. Increased intensity in agriculture in transient countries would result in increased nutrient loads to the Baltic Sea, particularly from Poland, the Baltic States, and Russia. Nutrient retentions are high, which means that the nutrient reduction goals of 135 000 tons N and 15 000 tons P, as formulated in the BSAP from 2007, correspond to a reduction in nutrient loadings to watersheds by 675 000 tons N and 158 000 tons P. A cost-minimization model was used to allocate nutrient reductions to measures and countries where the costs for reducing loads are low. The minimum annual cost to meet BSAP basin targets is estimated to 4.7 billion €.

Keywords Nutrient reduction · Nitrogen · Phosphorus · Retention · Management · Cost minimization

INTRODUCTION

The Baltic Sea has suffered from severe effects of eutrophication for many decades. The Baltic Sea Action Plan (BSAP) of the Helsinki Commission (HELCOM) was adopted by all the coastal countries of the Baltic Sea and by the European Community in November 2007 (HELCOM 2007). The eutrophication section of the BSAP is commonly considered as its most important component, since it presents very specific goals in terms of nutrient reductions (in tons of nitrogen and phosphorus) for the various sub-basins in order to achieve a "healthy" Baltic by 2021 (Backer et al. 2010). Moreover, these nutrient reduction goals are allocated to the countries around the sea. Models and datasets covering the entire sea and catchment were used in these calculations (Wulff et al. 2007).

The novelty of the approach used in the HELCOM action plan (BSAP) is that it puts the ecosystem at the center, defining the status of the sea as we want it to be in the future, and focusing management decisions on this goal instead of taking the traditional approach of addressing pollution sources on a sector-by-sector basis, without directly linking abatement measures to the status of the Baltic Sea (Pyhälä 2012).

When the BSAP was adopted, it was recognized that the calculated maximum allowable nutrient loads and the country-wise allocations of nutrient reductions were based on the best knowledge available, but that revised estimates would be necessary as soon as updated data and more advanced models became available. These revisions have now been made (late fall 2013), but have not yet been approved by all HELCOM member countries.

The economic cost of implementing nutrient reductions is not addressed in the BSAP, but is estimated to be high (Elofsson 2010a). Policymakers are likely to be concerned with the costs incurred within their respective countries, and well-founded estimates of nutrient reduction costs and their distribution could serve as a basis for negotiations among countries as well as for the selection and design of economic incentives.

The BONUS research project RECOCA (*Re*duction of Baltic Sea Nutrient Inputs and *Co*st Allocation in the Baltic Sea *Ca*tchment) was specifically designed to improve our

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understanding of processes in the catchment, compared to those used in the original BSAP, by using improved models and datasets. The key objectives of RECOCA were to (1) simulate possible future riverine nutrient loads to the Baltic Sea, (2) estimate cost-effective reductions of those loads, and (3) suggest cost allocation schemes for the countries in the drainage basin. In this paper, we describe a multi-model approach to characterize the nutrient loads, the retentions that occur between these sources and the Sea, and the effects of various management strategies to reduce loads. An advantage of the approach, in which models of different levels of complexity and spatial resolution are applied to the basin (see Electronic Supplementary Material, Fig. S1), is that it provides more robust insights into patterns of loading and response when the models yield similar results and provides insight into priorities for additional research when they disagree.

KEY RESEARCH AND RESULTS

New Catchment Database

We have assembled datasets from many sources and then compiled gridded data with high spatial resolution over the entire Baltic watershed. These can then be used in watershed-scale nutrient accounting tools and models. These gridded data are now available via the Nest decision support system (Fig. 1). Data sources include the EU Joint Research Centre (fertilizer use, crop types), EUROSTAT (livestock data), HYDE database (population), CORINE (land cover), and SMHI (hydrological and climate forcing). For further details, see Hong et al. (2012). These data have been compiled for all the 117 watersheds that comprise the Baltic Sea drainage area (82 major watersheds and 35 coastal areas) as well as for 8 "type watersheds," and are

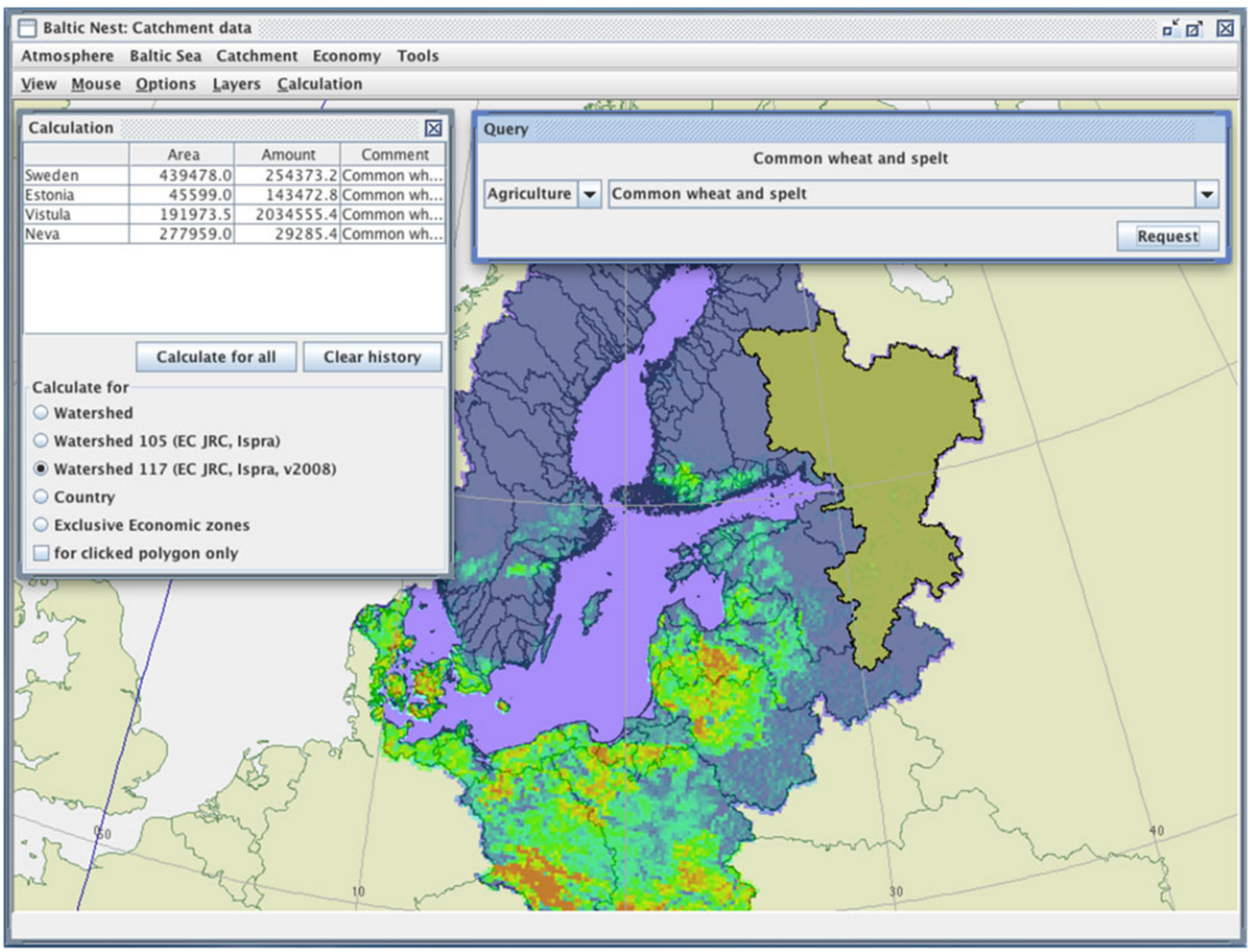

Fig. 1 The new catchment database accessible via the decision support system Nest (www.balticnest.org). This example shows agricultural data, specifically the distribution of cultivation of common wheat and spelt. The Nest interface allows the user to make various calculations, in this case aggregate data for countries or sub-catchments

Table 1 An example of datasets compiled for the Baltic Sea catchment (Hong et al. 2012)

Item	Bothnian Bay	Bothnian Sea	Gulf of Finland	Gulf of Riga	Kattegat	Baltic Proper	Danish Straits
Area (km^2)	269 576	230 953	418 980	136 179	90 081	573 368	27 357
Population density (persons km^{-2})							
Total	4.9	11.5	26.7	27.7	36.2	94.5	172.7
Urban	3.2	8.1	18.9	18.5	29.4	61.5	148.2
Rural	1.7	3.4	7.8	9.2	6.8	33.0	24.6
Livestock density (animals km^{-2})							
Cattle	1.1	1.5	2.6	7.4	12.2	13.1	32.1
Pigs	1.0	2.7	3.3	8.3	62.5	37.5	150.9
Poultry	30.0	28.3	130.4	73.5	94.1	357.2	341.1
Sheep	0.1	0.4	0.2	0.5	2.0	1.3	6.9
Crop production (kg km^{-2} year^{-1})							
Barley	2047	4245	2248	5093	19 035	10 988	58 853
Wheat	63	1796	1204	6674	25 990	23 140	120 255
Maize (green)	0	0	2902	1883	8856	25 061	126 952
Oats	1120	2386	1202	1331	5578	3736	3759
Rye	20	140	177	1937	1683	9048	9237
Other cereal	32	238	68	1287	1909	13 573	4662
Potatoes	1344	1468	2908	12 709	8671	36 478	21 013
Rape and turnip	88	222	172	985	2146	3915	18 184
Sugar beet	103	3193	410	3831	6582	27 811	150 296
Fodder roots	0	0	21	1930	4071	6932	5966
Pulses	3	13	8	116	79	309	203
Leguminous plants	339	88	960	4653	360	6620	2577
Fruits and berries	17	24	67	469	223	5996	2499

organized into fertilizer use, atmospheric deposition, biological N-fixation, crops, livestock, and human population distributions.

Furthermore, data from EUROSTAT and the EU Farm Accounting Data Network were used to estimate costs of reducing livestock production, fertilizer inputs, and changing land use. A detailed description of the distributions of point sources of nutrient pollution, i.e., municipal wastewater treatment (WWT) systems, including estimates of the populations connected and not connected to sewage systems, was also created (Table 1).

Nutrient Accounting Tools and Nutrient Retention in Catchments

Net Anthropogenic Nitrogen Inputs (NANI), first introduced by Howarth et al. (1996) for North Atlantic watersheds, represent human-induced nitrogen inputs to a watershed and have been shown to be a good predictor of riverine nitrogen export on a large-scale, multi-year average basis (Howarth et al. 2012). A corresponding approach for phosphorus (NAPI) accounts for major P inputs in a similar manner as with N, excluding terms for crop fixation, which do not exist for P, and atmospheric deposition, which is generally negligible (see Electronic Supplementary Material).

NANI, NAPI, and their components exhibited substantial variations among the Baltic Sea catchments (Fig. 2). Agricultural N-fixation in Baltic Sea catchments was estimated to be much lower than that in the US (Hong et al. 2011), reflecting relatively small areas of N-fixing crops in this region, unlike the US where soybean is one of the major crops. Nitrogen fluxes in net food and feed imports were often negative (i.e., positive net export of N as food or feed), although the magnitude of the negative values was again much smaller than in the US, for example, compared to the areas of the Corn Belt (Hong et al. 2011). Phosphorus fluxes generally showed a similar spatial pattern to nitrogen fluxes, although N fluxes were much higher in magnitude than the P fluxes.

Nutrient retention is the permanent removal or storage of nutrients and other biogenic elements within a system, i.e., the difference between nutrient inputs to a watershed and its riverine exports over the timescale considered (von Schiller et al. 2008). Conceptually, total retention within a catchment can be sub-divided into retention in soils, groundwater, and surface waters. Catchment processes

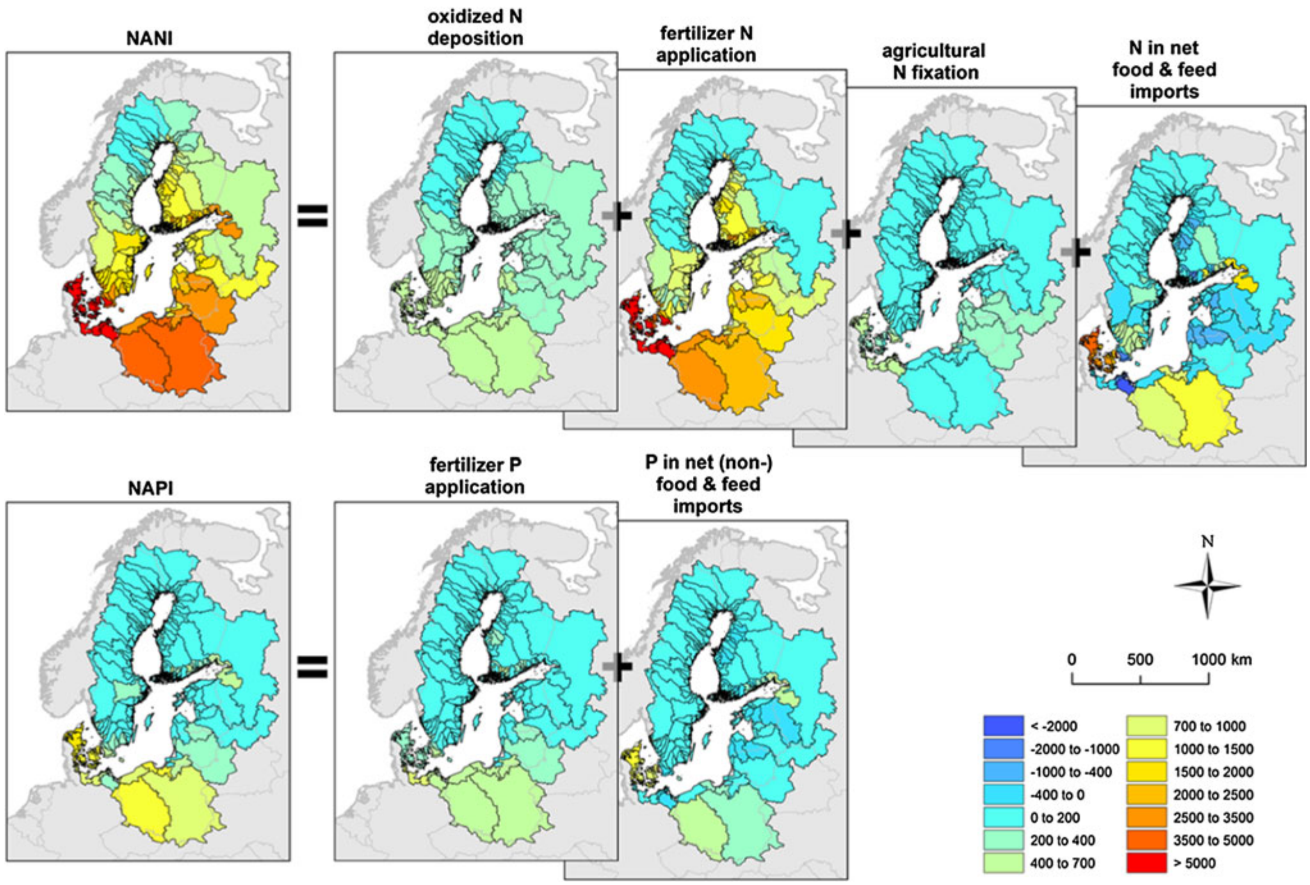

Fig. 2 NANI (kg-N km^{-2} year^{-1}) and NAPI (kg-P km^{-2} year^{-1}), and their components in the Baltic Sea catchments (redrawn from Hong et al. 2012). The "P in net (non-)food & feed imports" includes human P consumption for both food and non-food use (e.g., detergents). *Positive numbers* mean net addition of nutrients to the catchments (e.g., import of food and feed), whereas *negative numbers* mean net removal of nutrients from the catchments (e.g., export of food and feed)

contributing to retention are of vital importance for the economic evaluation performed in RECOCA (see below); retention is critical to finding a cost-optimal solution when the aim is to model cost-effective nutrient load reductions to the sea, as the effectiveness of abatement measures differs between source locations and target waters. Depending on the hydrological pathways, catchment retention processes may significantly alter elemental concentrations before they reach the sea (Stålnacke et al. 2003). For instance, wastewater treatment plants (WWTPs) discharge nutrients directly into surface waters, whereas agricultural nitrate losses normally leach from the root zone and are transported by groundwater to streams.

The differences between net anthropogenic inputs and observed riverine nutrient exports to the sea from catchments are an expression of catchment-scale retention. Nutrient loads and fluxes of water (average values for the period 1994–2006) were here taken from the ongoing HELCOM pollution load compilation PLC-5 (http://www.helcom.fi). The dataset covers almost 400 rivers and coastal regions, aggregated into 117 watersheds in which 78 major monitored rivers were identified, draining approximately 1 487 700 km^2 (86 % of the total catchment area), as well as 29 coastal areas, draining approximately 227 800 km^2 (13 %).

Riverine exports of N and P in the watersheds of Baltic Sea catchments correlate well to the NANI/NAPI loadings, with R^2 values between 0.66 and 0.97 (Fig. 3). Statistical analyses of the data show that across the Baltic catchments, N retention amounts to 72–88 % of NANI and P retention 85–96 % of NAPI. Knowing overall retention patterns for various watersheds is of obvious practical relevance, because this allows the country-wise required nutrient load reductions at the river mouth as formulated in the BSAP (HELCOM 2007) to be scaled to produce the required nutrient reductions at source, i.e., upstream in the watersheds. Overall, under the existing spatial distribution of nutrient loads across catchments, to reach the nutrient reduction goals of 135 000 tons N and 15 000 tons P as formulated in the BSAP from 2007 would require a

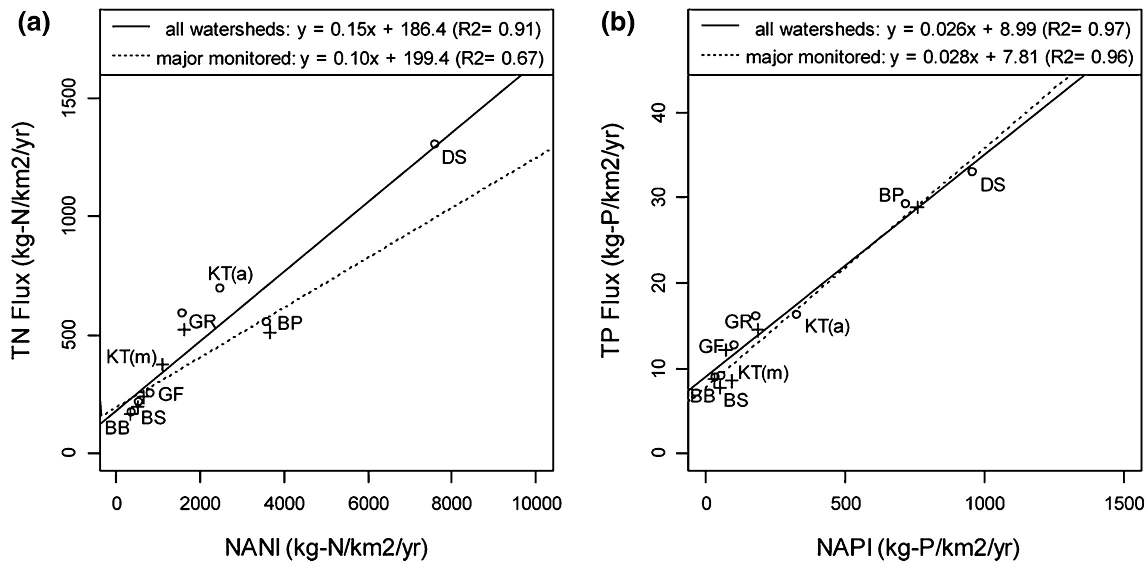

Fig. 3 Relationships between NANI and riverine TN fluxes (**a**) and between NAPI and riverine TP fluxes (**b**) in seven regions of Baltic Sea catchments. NANI and NAPI are calculated with spatially uniform parameters. *Open circles* represent regional averages calculated from all watersheds with estimates of riverine TN and TP fluxes (107 watersheds); *plus symbols* from monitored watersheds only (78 watersheds). *BB* Bothnian Bay, *BS* Bothnian Sea, *GF* Gulf of Finland, *GR* Gulf of Riga, *KT* Kattegat, *BP* Baltic Proper, and *DS* Danish Straits. No monitored data were available in the DS region. Only the KT region showed a substantial difference between all watersheds and monitored watersheds only, and is thus separately labeled as "KT(a)" and "KT(m)," respectively

reduction in nutrient loadings to the watersheds by 675 000 tons N and 158 000 tons P, respectively, assuming current estimates.

It is important to understand where nutrient retention is occurring within catchments in order to manage nutrient loads more effectively. MESAW, a statistical model developed by Grimvall and Stålnacke (1996) for source apportionment and retention of riverine loads of pollutants, has been applied to calculate nutrient retention (N and P) in surface water bodies within the Baltic Sea river basins. Input data consisted of land use (distinguishing cultivated areas, wetlands, lakes, and others), total drainage area, and point source emissions (from both waste water and industry). Results obtained for the same drainage basins as those used in the NANI/NAPI calculations have shown that the MESAW model was able to predict riverine loads of nitrogen very accurately; coefficients of determination between the observed and modeled data varied between 0.94 and 0.99. The estimated retention parameters were not statistically significant for the phosphorus model.

The MESAW calculations indicate that around 380 000 tons of nitrogen is retained annually in surface waters (streams, rivers, reservoirs, and lakes). In comparison, the total riverine load to the Baltic Sea for the 117 river basins was estimated to 570 000 tons N year^{-1}, which amounts to an overall *surface* water nitrogen retention value of around 40 %. The three largest river basins (Neva, Vistula, and Oder) accounted for 50 % of the total retention. Results for phosphorus indicate retention of 12 000 tons compared to an estimated river load of 18 000 tons P year^{-1} for 76 Baltic drainage basins with measured P load, and thus an overall surface water P retention that is also around 40 %, but these P results are highly uncertain and should be used with caution. The values of nutrient retention in surface waters are understandably lower than the total catchment retention estimated from the NANI and NAPI analyses. Together, the NANI budget approach and the MESAW approach indicate that half of the total N retention on a Baltic-wide catchment scale occurs in surface waters, i.e., in watercourses and lakes, whereas the residual losses occur in groundwater and soils. For P, an even higher amount is retained in soils and groundwater, but estimates of surface water retention remain uncertain.

Budget Calculations and Scenarios for Future Loads

The NANI budget calculations have been coupled to the catchment model CSIM as run in the NEST decision support system in order to undertake scenario analyses of possible future nutrient loads to the Baltic Sea. The various NANI components were distributed to CSIM land use categories (Fig. 4a). Such models have been used for exploring the effect of, e.g., different agricultural practices (BNI 2007; Hägg et al. 2010). With the new databases and models described here, we explored a possible scenario where fertilizer use in the transitional countries (Poland, Russia, and the Baltic States) increased to the levels now used in Germany, using overall nutrient retention