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Modeling the Baltic Sea Eutrophication in a Decision Support System

SANBALTS (Simple As Necessary Baltic Long-Term Large-Scale) is a model of the coupled nitrogen and phosphorus cycles. This model has been developed as an integral part of the decision support system Marine Research on Eutrophication's Nest with the overall aim to evaluate management options for reducing Baltic Sea eutrophication. Simulated nutrient and oxygen concentrations as well as transport flows and major biogeochemical fluxes can be analyzed in many different ways, including construction of detailed nutrient budgets and tracing the fate of nutrient inputs. The large amounts of data that exist for this sea makes it possible to validate model results with observations. Major biogeochemical properties of the Baltic Sea are discussed through an analyses of model sensitivity to external forcing and internal parameterizations. Model results emphasize two features that are especially important for ecosystem management: *i)* impacts of local measures would always be modified by the long-range transports from other regions and *ii)* the response to significant changes in loads would only be seen after several decades.

INTRODUCING "WORKING HORSE"

The decision support system (DSS) Nest developed within the MARE (Marine Research on Eutrophication) program is a tool aimed at a search of cost-effective nutrient reductions necessary to improve the state of the Baltic Sea (1, 2). To relate nutrient inputs to nutrient concentrations and other ecological quality indicators, Nest should have a marine model that is:

i) fast enough to serve as a part of the interactive use of DSS Nest;
ii) reliable enough in the description of nutrient dynamics in the entire Baltic Sea, based on our current knowledge; and
iii) plausible enough for modeling scenarios of nutrient load reductions and climatic variations.

Because of the geographical and ecosystem characteristics of the Baltic Sea, with long nutrient residence times and strong interconnectivity of its subbasins, the DSS must be able to simulate decadal to centennial responses of the entire Baltic Sea, from the Bothnian Bay to Kattegat. The implementation for these tasks of high resolution three-dimensional (3D) ecosystem models (3, 4, 5) would demand massive computer resources and very long computational times. For the MARE program this is not necessary because the large-scale dynamics of nutrients in the Baltic have already been plausibly described by rather aggregated models (6–8). A further development of such integral approaches is the SANBALTS model that we are now using as a "working horse" in the MARE's Nest.

The primary goal of SANBALTS is to simulate the interplay between nutrient sources and sinks within the seven major basins of the Baltic Sea (Fig. 1A). Each basin is treated as a homogeneous box except for the Baltic Proper basin, which is split along the halocline into surface (BPs, 0–60 m) and deep (BPd, below 60 m) boxes. The model aims to describe interactions between annual integrals of external inputs, interbasin transports, and internal biogeochemical fluxes. Correspondingly, the nine model state variables represent annual averages of their natural prototypes: dissolved inorganic nitrogen (DIN) and phosphorus (DIP); nitrogen (ONL) and phosphorus (OPL) content in all the labile organic fractions—dead and alive, dissolved and particulate; and nitrogen (ONS) and phosphorus (OPS) in refractory fractions of dissolved organic matter. Benthic nitrogen (BEN) and phosphorus (BEP) comprise bioavailable fractions only. In the deep Baltic Proper box, an average oxygen concentration (OX) is simulated as a regulator of nutrient cycles subject to redox alterations.

Simultaneous interactions of inputs, transports, and transformations that drive nutrient cycles in eight boxes ($i \neq j = 1, \ldots, 8$) are described by a system of ordinary differential equations in the general form:

$$\frac{dC_i}{dt} = BG(C_i)_i + L_{C_i} + A_{Ci} + \sum C_j Q_{ji} - C_i \sum Q_{ij};$$
$$\frac{dBC_i}{dt} = BG(BC_i)_i\,, \qquad \text{Eq. 1}$$

where L_C and A_C are inputs of variable C from the land and atmosphere, respectively; Q_{ij} is a water flow from basin i to basin j, including the water exchange with the Skagerrak; $BG(C_i)_i$ and $BG(BC_i)_i$ represent internal biogeochemical processes in the water column and sediments, respectively (Fig. 1B).

To obtain a quantitative solution of this system, we must prescribe numerical values of both the parameters describing biogeochemical processes and the boundary conditions representing external nutrient inputs and water flows between boxes. Although being mechanistic in a sense that it is based on mass balances and describes interactions of first-order processes, SANBALTS heavily relies on subjective comparison with empirical information in a tuning of basin-specific constants in basin-independent parameterizations of biogeochemical processes. This approach has been possible because of the wealth of data on hydrography, nutrient concentrations, and inputs that are available for the Baltic Sea. Details of parameterizations and tuning are given elsewhere (9, 10). Depending on the objectives of a particular model analysis, boundary conditions can be prescribed either as time-series or as constants. In the former case, a solution of the system of equations shows how the concentrations and processes vary in time (10). In the latter case, also used in this study, the system of equations is numerically integrated until the solution reaches a steady state that corresponds to a given combination of invariable external forces (4, 11).

Driving Forces and Data for Comparison

The Baltic Sea nutrient dynamics strongly depend on long-term and interannual variations of driving forces caused by natural processes (e.g., 12–14) and by anthropogenic impacts. Thus, the prescription of boundary conditions determining some typical state is not a trivial task and can be made in different ways, depending on objectives (11). To describe the trophic state corresponding to the times of transition from the last century, we have chosen the following boundary conditions.

The riverine transports and coastal point sources of organic and inorganic nutrients are given as averages for 1997–2003 based on the data provided by the Helsinki Commission (HELCOM). This time interval includes such remarkable events as extremely wet and dry years of 1998 and 2003 as well as the elevated river discharge to the Gulf of Bothnia in 2000. These interannual differences resulted in a rather high variability of nutrient loads (Table 1). In the model, inputs of organic nutrients are split into labile and refractory fractions, assuming the labile fractions are smaller in the nitrogen input from northeastern forested watersheds (20%–30%) than in the inputs from southwestern agricultural and urbanized areas (30%–40%) (15, 16). The labile fraction of the organic phosphorus is given as invariable (90%).

Basinwise estimates of the inorganic nitrogen atmospheric deposition have been obtained from the cooperative program for monitoring and evaluation of the long range transmission of air pollutants in Europe (EMEP) and given in the model as averages for 1997–2002. Inputs of labile organic nitrogen from the atmosphere were assumed to be 20% of inorganic nitrogen inputs, while for phosphorus the atmospheric deposition is assumed to deliver 15 kg P km^{-2} y^{-1} (17) as phosphate over all basins according to their surface areas.

Nutrient imports from the Skagerrak were calculated as a product of the water inflow and annually averaged concentrations, computed with the SwingStations and data assimilation system (DAS) tools on data extracted from the Baltic Environment database (BED) (18, 19).

The steady state water flows between basins, including the exchange with the Skagerrak, were calculated from hundreds of thousands salinity measurements with the Knudsen approach as long-term means for 1991–1999, the time interval covering quite different states of the Baltic Sea and considered representative of the contemporary hydrographic conditions (17).

To ensure comparability between simulated and observed characteristics, actual measurements were aggregated with the same spatial and temporal resolutions as were used in the model. Time series of annual basinwide volume-weighted averages of nutrient and oxygen (below 60 m in BP) concentrations as well as the area of sediments covered by the waters containing less than 2 mL L^{-1} of oxygen (hypoxic area) were calculated from 3D fields reconstructed with DAS from the data in BED. These annual mean concentrations were calculated as averages of all the measurements made within each year and pooled. The correction of these values for seasonal variations was made by factors estimated as a ratio between two sets of annual averages. One set was calculated from long-term monthly means for 1991–1999, another set as all-year-round averages for the same period.

The transparency of natural waters is determined by the concentration of particles, including plankton, and of dissolved substances such as humic acids, and can be considered as a combined result of both the intensity of autochthonous primary production and the contribution of allochthonous matter. Therefore, in the Nest, the water transparency is used as one of environmental indicators, which describe the state of eutrophication in the different subbasins. Empirical relationships between water transparency and nutrient concentration have been developed on the base of simultaneous measurements of Secchi depth, total N, and total P in offshore waters (20). The slopes of the basin-specific relationship between Secchi depth (SCD, m) and concentration (C, μM):

$$\log_{10}(\mathrm{SCD}_i^{\mathrm{C}})_i = a_i^{\mathrm{C}} \log_{10} \mathrm{C}_i + b_i^{\mathrm{C}} \qquad \text{Eq. 2}$$

are assumed basin-invariant ($a_i^{TN} = -1.5, a_i^{TP} = -0.7$), while the intercepts are given lower values in the gulfs affected by the major river inputs of humic substances, with the ranges of 2.7–2.8 for b_i^{TN} and 0.3–0.7 for b_i^{TP}. Assuming that it is the limiting nutrient that predicts the highest water transparency, the deeper Secchi depth is chosen from values calculated by basin-specific regressions with simulated TN and TP. Note, however, that Secchi depth is not a model variable, i.e., there is no feedback between changes in the water transparency and annual rates of primary production.

SANBALTS Performance

The solution obtained from SANBALTS computations gives us both the annual mean concentrations of nutrient and oxygen variables, and the annual rates of transport flows and biogeochemical fluxes, all of them interdependent and mutually consistent. Depending on objectives and user, the simulation results can be presented in different ways and analyzed from different perspectives.

Generally, the concept of nutrient concentration as an indicator of water quality is easily comprehended by a wide audience, from scientists to laymen, and the elevated concentrations have for long time been considered as an important indicator of aquatic eutrophication (e.g., 21, 22). Concentrations have also been extensively measured in the Baltic Sea by comparable methods over almost half a century, and the information is invaluable for both the representation of recent eutrophication history and for validation of models (e.g., 10). In this study, the period of 1991–2002, which spans rather different hydrographic and biogeochemical situations, including several saltwater inflows, is chosen as characteristic of contemporary conditions. Interannual variations of different variables over this period differ from basin to basin (Fig. 2), but generally the coefficients of variation (CV) are smaller for total nitrogen (CV = 4%–12%) and phosphorus (CV = 8%–19%) than for dissolved inorganic nitrogen (CV = 5%–29%) and phosphorus (CV = 12%–29%), most likely due to a smaller variability of the refractory fractions of organic nutrients.

A comparison to the statistics of nutrient concentration for the years 1991–2002 shows (Fig. 2) that the steady-state version of SANBALTS reproduces both interbasin and vertical (BP) gradients of nutrient concentrations that are generally larger than intrabasin temporal variations, represented by the standard deviation of observations. The simulated oxygen concentration of 3.5 mL L^{-1} and the area of hypoxic sediments of 42×10^3 km^2 are also well comparable to the corresponding statistics (mean ± sd for 1991–2002) of 3.4 ± 1.0 mL L^{-1} and 44.4 ± 14.1 10^3 km^2, estimated from observations. Concentration can also be used in empirical regressions to estimate other ecological indicators, for instance, the chlorophyll α level (23) and the water transparency (20). In the case of SANBALTS,

Table 1. Land loads (thousand tonnes) of total nitrogen (TN) and phosphorus (TP) into major basins of the Baltic Sea in 1997–2003 (mean ± sd)

Basin	BB	BS	BP	GF	GR	DS	KT
TP	51 ± 13	57 ± 15	320 ± 74	120 ± 11	78 ± 19	46 ± 16	65 ± 17
TN	2.6 ± 0.7	2.5 ± 0.8	17.9 ± 3.8	7.1 ± 0.8	2.2 ± 0.5	1.4 ± 0.3	1.6 ± 0.4

BB = the Bothnian Bay; BS = the Bothnian Sea; BP = the Baltic Proper; GF = the Gulf of Finland; GR = the Gulf of Riga; DS = the Danish Straits; KT = the Kattegat.

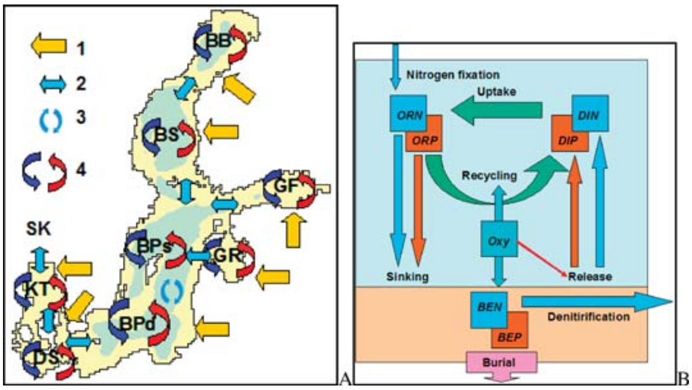

Figure 1. Basic principles of SANBALTS. (A) Nutrient dynamics in the major basins of the Baltic Sea (BB = the Bothnian Bay; BS = the Bothnian Sea; BP = the Baltic Proper; GF = the Gulf of Finland; GR = the Gulf of Riga; DS = the Danish Straits; KT = the Kattegat; Ska = the Skagerrak boundary) is driven by continuous interaction of (1) the inputs from land and atmosphere, (2) the water transports due to horizontal advection and (3) vertical exchange between surface BPs and deep BPd boxes, and (4) biogeochemical processes. (B) Biogeochemical fluxes between pelagic and sediment nitrogen and phosphorus variables.

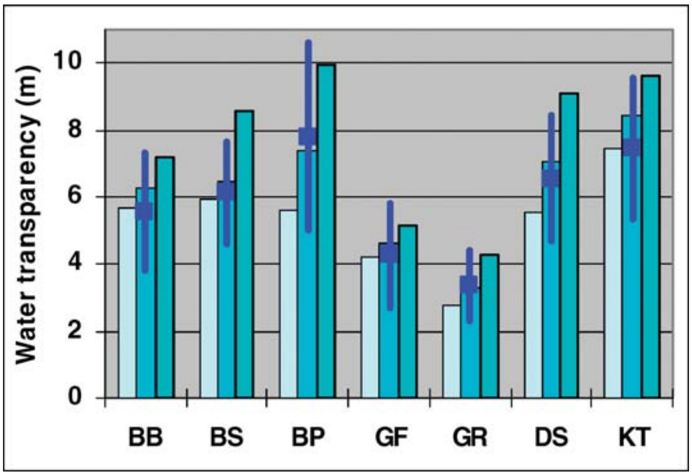

Figure 3. Contemporary distribution of the water transparency reconstructed from observations (symbols, mean ± deviation for 1985–2000, [23]) and estimated by empirical regressions from nutrient concentrations (Eq. 2) simulated for average (1997–2003, central columns), "average + sd" (left columns), and "average – sd" (right columns) land loads.

Secchi depths calculated on simulated concentrations with empirical regressions (Eq. 2) correspond well to the ranges observed in both the present (Fig. 3) and a century ago (10, 18).

On the other hand, however important the concentrations are as indicators of the water quality and the characteristics of the trophic status of aquatic systems, the comparability of simulated values to observations as a criterion for the model validation should be considered with caution. Concentration represents the total amount (pool) of nutrient in aquatic systems that is the net result of an interplay between nutrient sources and sinks. Simulated concentrations may be tuned to a specific level by differing combinations of positive and negative terms. Therefore, independent estimates of the biogeochemical processes described by the terms in Eq. 1 are more important for validation of this semiempirical model than the similarity between simulated and observed concentrations. Moreover, because the trophic status of aquatic systems is determined by the balancing of nutrient cycling and fluxes, the most important scientific outcome of the SANBALTS model is the annual nutrient budgets that describe mechanisms of eutrophication (oligotrophication) and indicate the relative significance of its driving forces (Fig. 4). Such budgets are also a convenient presentation of results to the decision makers as a clear demonstration of the cause–effect relationships that determine consequences of different management scenarios. In a research process, the budgets can also be used as a common platform for a consistent integration of results obtained in separate hydrographic, chemical, and biological studies. Unfortunately, there are only a few published estimates of biogeochemical fluxes, especially those that have been really scaled up to annual and basinwide values as shown in Fig. 4. To make the comparison to empirical estimates easier, we present in Table 2 simulated fluxes recalculated by simple transformations into more commonly used units.

Simulated annual primary production is presented as a sum of DIN uptake and nitrogen fixation, multiplied by 6 for conversion to carbon units and divided by the areas of the basins. The simulated values correspond to net primary production, while measurements are somewhere between gross and net production rates (25). Within these assumptions, simulated values are quite comparable to published estimates (see Table 2).

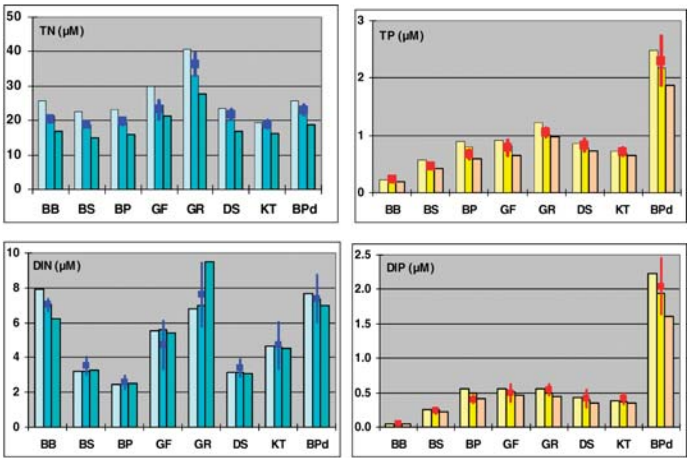

Figure 2. Average concentration (μM) of TN, DIN, TP, and DIP in the major basins of the Baltic Sea reconstructed from observations (symbols, mean ± sd for 1991–2002) and simulated by SANBALTS for average (1997–2003, central columns), "average + sd" (left columns), and "average – sd" (right columns) land loads. Note differences in scale.

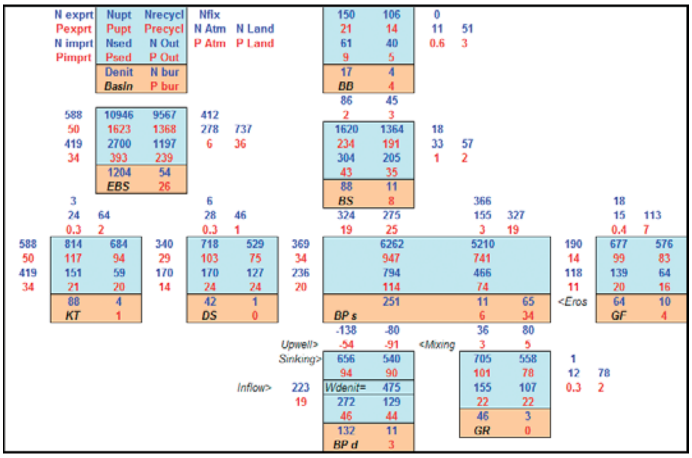

Figure 4. Coupled budgets of nitrogen and phosphorus in the major basins and entire Baltic Sea (EBS) representing contemporary conditions. The key in the top left corner indicates position of nutrient fluxes (10^3 t y^{-1}) corresponding to Figure 1. In the BPd box, nutrient uptake is replaced by sinking (*Sinking*) from BPs box, while the overall nutrient budget includes advection from DS (*Inflow*), the upwelling to (*Upwell*) and mixing with (*Mixing*) BPs, as well as erosion (*Eros*) of sediment nutrients from BPs into the BPd waters.

Table 2. Major biogeochemical fluxes simulated for contemporary conditions: primary production (PP, g C m^{-2} y^{-1}), nitrogen fixation (NF, 10^3 t N y^{-1}), and denitrification (Den, mmol N m^{-2} d^{-1}).

Basin	BB	BS	BP	GF	GR	DS	KT
PP_{est}*	17 (30)–28 (25)	52 (30)–113 (25)	165 (25)–200 (30)	80 (30)–128 (26)	200–260 (27 and references therein; 30)	200 (32)–250 (28)	150 (29,32)–200 (31)
PP	25	124	188	141	259	216	223
NF	0	17.5	366.2	18.1	1.3	6.1	3.0
Den	0.09	0.22	1.66†	0.43	0.55	0.41	0.78

BB = the Bothnian Bay; BS = the Bothnian Sea; BP = the Baltic Proper; GF = the Gulf of Finland; GR = the Gulf of Riga; DS = the Danish Straits; KT = the Kattegat. * PP_{est}–contemporary estimates from different sources. Reference numbers are given in parentheses. † Sum of fluxes in the surface and deep boxes, including water denitrification.

Nitrogen concentrations in most of the Baltic basins are today to a large extent governed by a balance between nitrogen fixation and denitrification, and less by variations in inputs (33). Therefore, independent large-scale estimates of these processes are especially important for a model validation. Nitrogen fixation simulated for the Baltic Proper under contemporary forcing is well within the most recent estimates of 180×10^3–430×10^3 t N y^{-1} (34), 370×10^3–434×10^3 t N y^{-1} (35, 36). Likewise, simulated sediment denitrification, downscaled to areal units and daily rates, fits into a range of scattered measurements of 0.1–1.8 mmol N m^{-2} d^{-1} (37–40). Denitrification below 70 m in the Gotland deep was estimated in a range of 220–340 mmol N m^{-2} y^{-1} (41), which is expectedly lower than 452 (354 in the water column, 98 in the sediments) mmol N m^{-2} y^{-1} modeled for a larger domain, below 60 m in the Baltic Proper. Simulated water denitrification of 475×10^3 t N y^{-1} occurred within a hypoxic volume of about 1260 km^3, which is equivalent to about 1.0 mg N m^{-3} d^{-1}. This is within a range of 0.62–1.54 mg N m^{-3} d^{-1} reported from two expeditions in 1986 and 1987 at the Gotland Deep (42).

Total mineralization in the Eastern Gotland basin below 70 m was estimated as 4.4–4.7 mol C m^{-2} y^{-1} (41). Total nitrogen mineralization simulated with SANBALTS under contemporary forcing in the Baltic Proper deep box corresponds to 5.5 mol C m^{-2} y^{-1} if the molar ratios of POC : PON = 8.4 for the water column (41) and TC :TN = 10.8 for the sediments (43) are applied for conversion from nitrogen to carbon units. In the Baltic Proper, the total volume and sediment area situated below 60 m exceed those below 70 m by 17% and 29%, respectively, which explains the 17%–25% difference between simulated and estimated mineralization rates.

As this analysis shows, the rates of the major internal biochemical processes simulated with SANBALTS fit reasonably within the ranges of empirical estimates. In other words, there are no suspicious deviations in any of the critical terms of Eq. 1 large enough to significantly compromise other terms and make basinwise budgets questionable. Therefore, we may assume that simulated budgets are representative for the turn of twentieth century and use them as a point of reference in eutrophication studies and scenario simulations (11).

A comparison of these detailed and coupled nutrient budgets to much more aggregated and uncoupled empirical nitrogen and phosphorus budgets built independently for the same seven basins on over 30 000 oceanographic stations made in 1991–1999 (17) reveals one distinction important for the objectives of Nest. Generally, a similarity between interbasin exchanges of nutrients in simulated and empirical budgets can only be expected because the values of water flows are the same in both cases and the simulated concentrations (Fig. 2) are tuned close to the averages estimated from observations (see Table 1 in Ref. 17). However, the nutrient exports from the Baltic Proper into neighboring basins are systematically smaller in simulated budgets compared with empirical budgets. The reason is in the different partitioning of the Baltic Proper: for empirical budgeting, the entire Baltic Proper basin was assumed homogeneous, while in the SANBALTS model, a two-layer structure was adopted. As a result, the simulated concentrations in the surface Baltic Proper box are lower than the whole-basin concentrations used in empirical budgets—by 10% for nitrogen and by over 20% for phosphorus. Apparently, the two-layer structure with its lower surface concentrations more realistically reproduces nutrient exports from the Baltic Proper across shallow sills, i.e., into the Gulf of Riga and the Danish straits. In the case of the Bothnian Sea and the Gulf of Finland with their deep entrances, the SANBALTS model neglects a fraction of inflowing waters originated in the deep layers and to that extent underestimates an import of nutrients from the Baltic Proper, which counteracts the reductions of nutrient loads to these particular basins.

The compensatory role of such advective transports can be quantified for every basin by the network analysis tools (e.g., 17, 44) that are also included in DSS Nest. For example, the

Table 3. Origin of nitrogen inputs to the Baltic Sea basins: fraction (%) of total (sum of external loads and advective transports) nitrogen input into "column" basin that entered the sea as external load into "row" basin.

Basins	BB	BS	BP	GF	GR	DS	KT
BB	63	14	3	1	1	2	1
BS	12	29	7	3	2	5	2
BP	19	45	71	32	20	48	24
GF	2	6	9	59	2	6	3
GR	1	3	5	2	73	3	2
DS	1	2	3	1	1	17	8
KT	1	2	3	1	1	19	60

BB = the Bothnian Bay; BS = the Bothnian Sea; BP = the Baltic Proper; GF = the Gulf of Finland; GR = the Gulf of Riga; DS = the Danish Straits; KT = the Kattegat.

Table 4. Origin of phosphorus inputs to the Baltic Sea basins: fraction (%) of total (sum of external loads and advective transports) phosphorus input into "column" basin that entered the sea as external load into "row" basin.

Basins	BB	BS	BP	GF	GR	DS	KT
BB	56	5	2	1	1	1	0
BS	8	17	6	4	3	4	1
BP	22	48	57	34	33	40	6
GF	6	12	14	49	8	10	2
GR	2	5	6	4	46	4	1
DS	1	2	2	1	1	5	1
KT	5	11	13	8	8	35	90

BB = the Bothnian Bay; BS = the Bothnian Sea; BP = the Baltic Proper; GF = the Gulf of Finland; GR = the Gulf of Riga; DS = the Danish Straits; KT = the Kattegat.

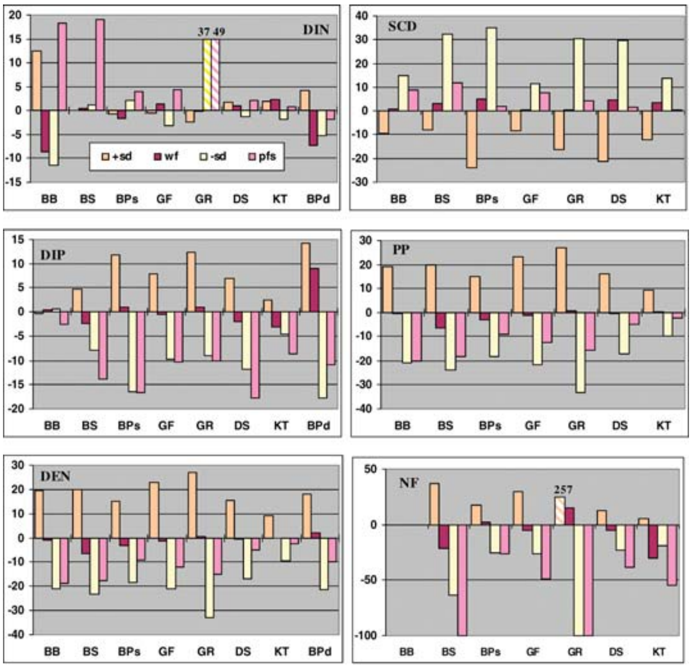

Figure 5. Relative deviations (%) of simulated dissolved inorganic nitrogen (DIN) and phosphorus (DIP), Secchi depth (SCD), primary production (PP), nitrogen fixation (NF), and release (Den) from the reference steady state (Figures 2 and 3, Table 2) obtained in numerical experiments. +sd and −sd, land loads are given as average for 1997–2003 plus and minus standard deviations, respectively (see Table 1); wf = water flows between basins are calculated for the period 1998–2002; pfs = no phosphorus deposition from the atmosphere. Note differences in scale and outliers in the Gulf of Riga indicated by numbers.

total annual input of nitrogen into the Gulf of Finland is composed of 146 × 10^3 t entering directly into the Gulf (113 × 10^3 t discharging from land, 15 × 10^3 t depositing from atmosphere, 18 × 10^3 t fixed by cyanobacteria) and of hefty 118 × 10^3 t being imported from the Baltic Proper (Fig. 4). As shown by the network analysis, 59% of the total input of 264 × 10^3 t are generically related to the Gulf itself as external loads, nitrogen fixation, and a fraction of 190 × 10^3 t exported from the Gulf that returns back with inflowing waters (Table 3). Of the remaining 41% portion of total input, the major part, 32%, is generated within the Baltic Proper, while contributions from the remote basins are much smaller. Similarly, only 49% of total phosphorus input into the Gulf of Finland is generated within the Gulf and its drainage basin area, while the rest originates from other basins, even as remote as the Kattegat (Table 4). Recalling that the import from the Baltic Proper might be somewhat underestimated, these fractions, 59% for N and 49% for P, represent the upper bounds of self-generated contributions. In other words, only about a half of the present trophic status of the Gulf of Finland is determined by the conditions in its watershed and the situation in the Gulf itself, while another half is induced from elsewhere. Similar proportions are also seen in such "dead-end" basins like the Bothnian Bay and the Gulf of Riga. From an ecosystem management perspective, the situation in the "flow-through" basins is even worse. The total inputs of nitrogen and phosphorus into both the Bothnian Sea and the Danish Straits are to a lesser degree determined by direct nutrient loads than by imported nutrients originally entering other basins.

SANBALTS Sensitivity

The main objective of SANBALTS is to study how the trophic status of the sea, for example, the contemporary status, would

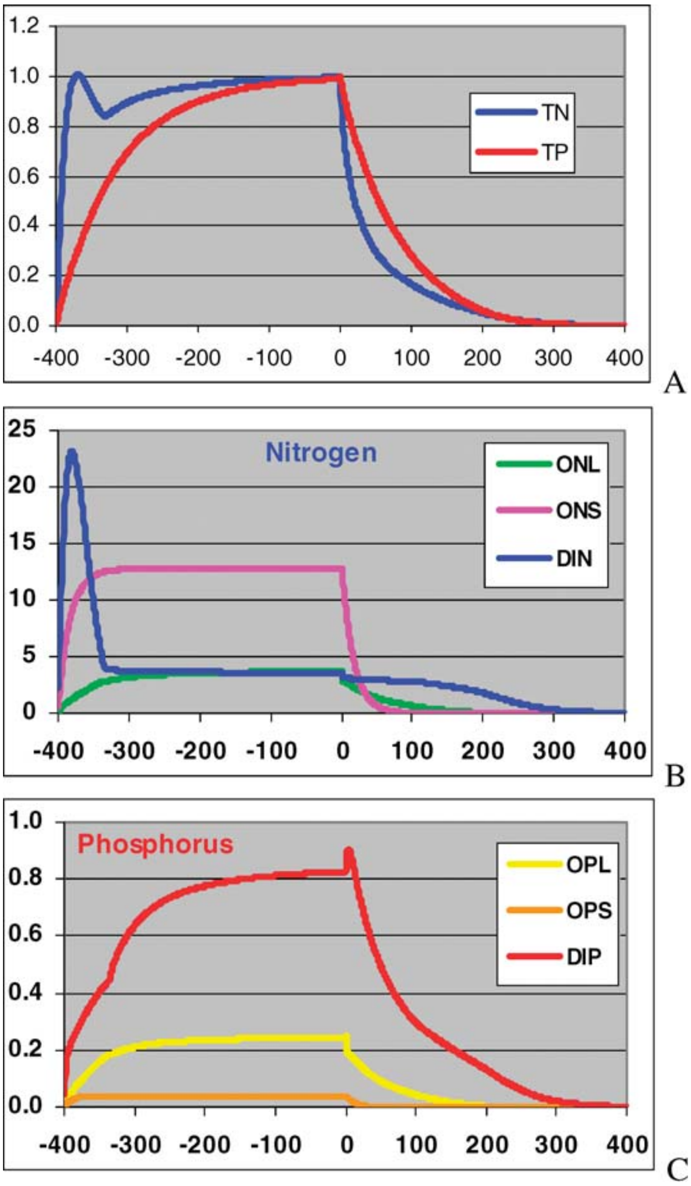

Figure 6. Simulated "filling up" (–400 to 0 years) and "flushing out" (0 to 400 years) evolution of nitrogen and phosphorus in the Baltic Sea. (A) The evolution of total amounts of nitrogen and phosphorus in the entire Baltic Sea shown as deviation from the contemporary steady state pools of 12.5 × 10^6 t N and 3.7 × 10^6 t P. The evolution of (B) pelagic nitrogen and (C) phosphorus variables (μM) in the Baltic Proper as volume-weighted average of the surface and deep boxes.

change in response to perturbations in the boundary conditions. As shown in Table 1, the contemporary nutrient inputs are subject to substantial interannual fluctuations, with coefficients of variation of about 25%. While prescribing the boundary conditions, we also made some assumptions that affect the simulated state. To demonstrate how responsive the simulated state is to alterations in the boundary conditions, several numeric experiments have been performed. All the experiments were run in a single-factor sensitivity mode, i.e., in each experiment only a limited number of similar parameters have been changed, while all the other parameters were kept the same as in the standard run (St. Run) described previously.

In two numerical experiments both nitrogen and phosphorus land loads used in the St. Run were simultaneously either increased ("+sd" experiment) or decreased ("–sd" experiment) by its standard deviations estimated for the period 1997–2003 (cf. Table 1). In contrast to other scenarios (4, 5), where only the inputs of bioavailable fractions were altered, the perturbations in +sd and −sd experiments were proportionally applied to all fractions, thus mimicking wetter or drier climatic conditions. For the wf-experiment, the steady-state water flows between basins have been calculated with the Knudsen approach on the salinities and freshwater inputs, averaged for 1998–2002. These calculations resulted in a reduced water exchange between basins compared with the period 1991–1999 because of increased freshwater inputs to the northeastern gulfs and the lower salinity in them. The exception was the increased water exchange of the Bothnian Bay. However, the changes were small, less than 10% in all the straits except at the Skagerrak boundary, where the calculated water exchange was intensified by a third to maintain a higher observed salinity in the Kattegat. Our estimate of phosphorus atmospheric deposition is within the range of 4–33 kg P km^{-2} y^{-1} compiled from observations for northern Europe (45–47). In spite of these measurements, phosphorus deposition has often been deemed insignificant in the Baltic Sea studies and, for instance, was not covered by the recent HELCOM publications. Therefore, it seemed instructive to test the importance of this phosphorous source in the phosphorus-free sky (pfs) experiment, where phosphorus deposition from the atmosphere was set equal to zero. Finally, two experiments were run to test the significance of our assumptions on nitrogen sources. In one of them, the atmospheric deposition of organic nitrogen was ignored, while in another all the nutrients discharged from point sources directly into the sea were assumed to be bioavailable. However, the differences between St. Run and the solutions obtained in these two later experiments were less than 5%, i.e., far smaller than the deviations that emerged from other experiments (Fig. 5) and are not presented here in further detail.

In sd experiments, the increased and decreased nutrient inputs resulted in changes of primary production and all other related fluxes, from sedimentation and recycling to denitrification. However, these changes are not linearly related to the load alterations because the sinks and sources were differently affected in different basins. As a result, the differences in concentrations are even more pronounced than the differences in fluxes. The inorganic nitrogen concentrations responded less to the applied perturbations than the concentrations of inorganic phosphorus, especially in the nitrogen-limited basins south of the Gulf of Bothnia. In these basins, the nitrogen pool appeared to be self-regulated by denitrification that acts as a negative feedback, counteracting the chain of positive feedbacks: nitrogen input → primary production → sedimentation → sediment nitrogen pool. In Bothnian Bay, nitrogen uptake is strongly limited by phosphorus availability, and changes of nitrogen concentrations simply follow the changes in nitrogen supply. The larger response of DIP resulted in corresponding changes of DIN : DIP ratios and rates of nitrogen fixation that increased or decreased according to changes in the nutrient inputs.

The effects of slightly changed water transports in the wf-experiment were generally insignificant everywhere except in the Bothnian Bay and in the deep layer of the Baltic Proper. In the Bothnian Bay, the increased water exchange resulted in higher nitrogen export due to a large DIN gradient toward the Bothnian Sea (cf. Fig. 2). In the Baltic Proper deep box, the decreased oxygen transport inflicted expansion of the hypoxic area up to 48 471 km^2 with corresponding augmentation of both denitrification and phosphate release from the sediments.

The omission of about 14% of external phosphorus input in the pfs-experiment predictably resulted in what may be considered as overall oligotrophication, i.e., reduction of both the phosphorus pools and intensity of biogeochemical fluxes, including nitrogen fixation.

The largest systematic decreases and increases of the Secchi depth emerged in +sd and −sd experiments, respectively, and are consistently explained by altered inputs of both bioavailable nutrients and refractory fractions of organic nutrients, although the responses were still within natural variations (Fig. 3)

In contrast to other basins, the most peculiar responses in the sensitivity experiments were produced in the Gulf of Riga, where we also had some difficulties during tuning, mostly related to the phosphorus cycle. Closer examination of the data on nutrient inputs obtained from HELCOM revealed that the DIP : TP ratio in river load to the Gulf of Riga of 0.58 was clearly higher than the ratios in any of the other basins: from 0.24 in the Gulf of Finland to 0.48 in the Danish Straits. The most likely reason for this peculiarity is that the loads of total phosphorus, officially reported to HELCOM for rivers draining into the Gulf of Riga, were based on filtered samples. If this is the case, the total phosphorus load to the Gulf of Riga used in all the experiments just presented was underestimated. The unknown suspended fraction of total phosphorus concentration can be rather variable both seasonally and interannually. Therefore, we decided to use the official HELCOM data instead of guessing on correction factors.

Because all analyzed responses of SANBALTS solution to the imposed perturbations are also in a good agreement with the existing general knowledge on the coupling between nitrogen and phosphorus cycles in the Baltic Sea, these results may be considered as a verification of internal consistency of the model.

A common feature of all the described responses, important also from the ecosystem management perspective, is that because of the high buffer capacity of the Baltic Sea indicated by the nutrient budgets (Fig. 4), the changes in ecological indicators of 10%–20% (Fig. 5) were generally smaller than the imposed changes in land loads of about 20%–30% (Table 1). In fact, these changes are quite comparable to natural variations (Figs. 2 and 3) and, perhaps, would not be easily detected in routine monitoring programs. It is also important to stress that simulated steady state concentrations and budgets reflect average conditions at equilibrium, while observations, even scaled up to the annual and basinwide levels characterize some snapshots of a system being permanently in a transient state. Therefore, another important question to explore is how long it would take for the system to transit from one state to another.

Age and Response Times of Nutrients

The temporal response of the coupled nitrogen and phosphorus cycles in the Baltic Sea is demonstrated by the results from two numerical experiments with extremely different initial and boundary conditions (Fig. 6). In one of them, the Baltic Sea, including its sediments was assumed initially free of nutrients and then was filled up with nitrogen and phosphorus to the present state by the same contemporary inputs that were used in St. Run (Table 1). In a second, flushing out experiment the simulation started from the contemporary state (Figs. 2–4), and the Baltic Sea was emptied of nutrients by omitting all the external nutrient inputs. Quantitatively, the exact temporal dynamics are slightly different in different basins, with the Kattegat being faster in response because of the Skagerrak influence than the dead ends of Bothnian Bay and the Gulf of Finland. Qualitatively, the dynamics are quite similar because the same mechanisms operate everywhere, and are shown here only for the Baltic Proper.

The flushing out experiment presented in the right halves of graphs in Fig. 6 gives estimates of the nutrient response time scales similar to those estimated earlier for salinity in the Baltic Sea (48, 49). Initially, nitrogen is flushed out from the Baltic Sea much faster than phosphorus—it took only 20 years for the integrated nitrogen pool to decrease by a half, while for phosphorus the corresponding time is over 50 years (Fig. 6A). This delay decreased with time and 5% of the initial pools of both nitrogen and phosphorus were reached in about 200 years. Using the e-folding time concept ($e^{-3} = 0.05$), the response time scale can then be estimated on the order of 60–70 years. The reason for the initial fast decrease of total nitrogen is a literally passive flushing out of the dissolved refractory organic compounds by advection (Fig. 6B). To the contrary, the response of dissolved inorganic nitrogen is hampered and even displays a convex shape due to a growing difference between decreasing sink and a continuing nitrogen fixation, which for a rather long time compensates for the cutting-off of external inputs. Actually, the nitrogen fixation had even increased over the first few dozen years because of an increased relative "Redfield surplus" of phosphate in the nitrogen-limited basins. By "Redfield surplus" we mean the amount of one nutrient (N or P) that would be left underutilized after another nutrient (P or N) has been totally consumed according to the Redfield molar ratio N:P = 16.

The role of both misbalances in nutrient inputs relative to the Redfield ratio and a tight coupling between nitrogen and phosphorus cycles is even more evident in the filling up experiment presented in the left halves of the graphs in Fig. 6. Initially, because of a large "Redfield surplus" of nitrogen in inputs, the nutrient uptake was strongly limited by phosphorus availability and the underutilized inorganic nitrogen is rapidly accumulating in the system during the first two decades (Fig. 6B). However, the parallel accumulation in the sediment nitrogen pool resulted in a fast acceleration of the dinitrogen production, and by the years 60–70 from the start of the experiment, the Baltic Proper system had switched into a nitrogen-limited state. Continuing accumulation of underutilized phosphate resulted in a corresponding increase in nitrogen fixation, albeit this additional input of nitrogen did not show up in the nitrogen pool because of efficient dinitrogen formation both in the sediments and in the water column.

The exact lengths of time characterizing reactions of nutrient variables on the imposed perturbations differ slightly between the basins and could somewhat change with a more precise tuning of the model. However, the estimated response time of several decades is probably one of the fundamental features of the Baltic Sea biogeochemistry that should always be considered in the large scale ecosystem management of this semienclosed multibasin sea.

CONCLUSIONS

A parsimonious model of coupled nitrogen and phosphorus cycles has been built with an interplay of large scale sources and sink terms determined by external inputs, water transports, and major biogeochemical fluxes. The model was tuned to fit measured concentrations and validated by comparison with independently estimated biogeochemical fluxes. Internal consistency of the model is demonstrated by its coherent behavior in the sensitivity experiments. Thus, we believe that the model can be used as a reliable tool in the decision support system Nest.

The responses of the Baltic Sea trophic states simulated under contemporary and altered nutrient loads demonstrate several biogeochemical properties of the Baltic Sea important for ecosystem management.

Detailed nitrogen and phosphorus budgets clearly show that contemporary nutrient cycles are driven by internal biogeochemical processes in which annual rates are one to two orders of magnitude larger than external inputs and advective transports. Consequently, the trophic status of the entire sea and its subbasins would react slowly to any external perturbations caused either by humans or by climatic changes.

Because of the high interconnectivity of the Baltic Sea basins, the nutrient loads into individual basins from their watersheds are comparable with imports from other basins. Consequently, the impacts of local water protection measures would always be modified by long-range transports of nutrients entering the sea via other basins. This property has its positive and negative consequences for eutrophication of the Baltic Sea basins and should be used as a base for cost-effective measures.

Taken together with the so-called vicious circle of positive and negative feedbacks (33), this high buffer capacity and strong interconnectivity of the basins determine the slow and relatively weak responses of the Baltic Sea trophic state to possible reductions of the nutrient loads. The responses to insignificant reductions would be so small that they could hardly be detected from field data acquired in the routine monitoring.

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