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External nutrient loading from land, sea and atmosphere to all 656 Swedish coastal water bodies

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ABSTRACT

Identifying the main sources of nutrient loading is a key factor for efficient mitigation of eutrophication. This study has investigated the pathways of external nutrient loading to 656 coastal water bodies along the entire Swedish coastline. The studied water bodies have been delineated to meet requirements in the European Union's Water Framework Directive, and recent status assessments have shown that 57% of them fail to attain good or high ecological status with respect to nutrients. The analysis in the study was performed on data from mass-balance based nutrient budgets computed using the modelling framework Vattenwebb. The external nutrient contribution from the sea to the water bodies was highly variable, ranging from about 1% to nearly 100%, but the median contribution was >99% of the total external loading regarding both nitrogen and phosphorus. External loading from the atmosphere and local catchment area played a minor role in general. However, 45 coastal water bodies received >25% of the external nitrogen and phosphorus from their catchments. Loading from land typically peaked in April following ice-break and snow melting and was comparatively low during summer. The results indicate that for many eutrophicated Swedish coastal water bodies, nutrient abatement is likely to be optimally effective when potential measures in all of the catchment area of the concerned sea basin are considered. Local-scale mitigation in single water bodies will likely be locally effective only in the small proportion of areas where water and thereby also nutrient input from the catchment is high compared to the influx from the sea. Future studies should include nutrient reduction scenarios in order to refine these conclusions and to identify relevant spatial scales for coastal eutrophication mitigation measures from a water body perspective.

1. Introduction

Anthropogenic nutrient loading (phosphorus and/or nitrogen) to coastal waters is a global concern and commonly leads to eutrophication. Large external nutrient inputs can yield excessive production of phytoplankton and fast growing filamentous algae which cause decreased water clarity, increased oxygen consumption and hypoxia (Bonsdorff et al., 1997; Conley et al., 2009; Gustafsson et al., 2012; Cerco and Noel, 2013; Stigebrandt et al., 2014; Matthews and Odermatt, 2015; Schernewski et al., 2015; Pavlidou et al., 2016). For Swedish waters, the Baltic Sea Action Plan (HELCOM, 2007) as well as the European Water Framework Directive (WFD; Anon, 2000) and the Marine Strategy Framework Directive (Anon, 2008) require that anthropogenic nutrient inputs to the sea are at levels which enable a sustainable ecological or environmental status of coastal and marine ecosystems (Schernewski et al., 2015).

The extent to which nutrient concentrations in coastal waters are affected by nutrient loading from adjacent areas can be assessed by quantitatively comparing local, land-based nutrient loading from the catchment to other external nutrient sources, such as input from the atmosphere and from the surrounding sea (Rosenberg et al., 1990; Engqvist, 1996; Wulff et al., 1996; Humborg et al., 2003; Karlsson et al., 2014; Schernewski et al., 2015). By such a comparison, it is possible to determine where nutrient abatement would be the most effective; i.e., abatement in the catchment, by targeting atmospheric emission and deposition onto the water body, or instead with a focus on loading to the outside sea or sea basin (Engqvist, 1996; Wulff et al., 1996; Dimberg and Bryhn, 2014a; Karlsson et al., 2014; Schernewski et al., 2015). A possibility for a quantitative comparison of fluxes in and out of Swedish coastal water bodies has been provided by an extensive modelling framework with output published by SMHI (2016). This modelling output contains mass-balance based nutrient budgets for all 656 water bodies distributed along the entire Swedish coastline. The division into 656 water bodies was made in order to meet the assessment requirements of the WFD (Sahlberg, 2009; VISS, 2016) which is legally

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binding regarding coastal waters in Sweden and the rest of the European Union (Anon, 2000; Schernewski et al., 2015). However, an explicit quantitative comparison among coastal water bodies with respect to the relative distributions of external nutrient inputs has not been made before for the whole coastline of Sweden or any other country.

This study aims at comparing different pathways of nutrient input, concerning fluxes of nitrogen (N) and phosphorus (P) to the Swedish coastal water bodies, by assessing the relative distribution of different types of nutrient loading. Areas which are the most influenced by nutrient loading from the local catchment and from the atmosphere are identified, and their specific features are evaluated in order to potentially identify common patterns. Furthermore, the seasonal variation in catchment-based enrichment is studied with the aim to assess its pattern and magnitude.

2. Background and methods

Sweden has one of the longest coastlines among countries in Europe, with 11,600 km of coast along the mainland and 33,100 km around islands (Statistics Sweden, 2013). The Swedish coastal zone as defined by the WFD covers 35,830 km^2 (55–66°N, 10–25°E; Fig. 1; SMHI, 2003). This zone has been divided further into coastal water bodies with relatively homogeneous physical characteristics and which constitute the smallest assessment and management units of the WFD (Sahlberg, 2009; VISS, 2016). A total of 656 of these coastal water bodies border to island or mainland shores and have a direct water discharge and nutrient input from land (SMHI, 2016). One additional coastal water body lacked land connection and was removed from the dataset. Among the 656 water bodies bordering to land, 71 (11%) extended out to the coastal baseline and were hence not delineated in an optimal way for modelling; e.g., according to the topographical bottleneck principle used by Gyllenhammar and Håkanson (2005), Lindgren (2011) and Dimberg and Bryhn (2014a). However, as these water bodies are delineated with respect to the WFD and are encompassed by WFD management requirements, we found it motivated to include them in the analyses.

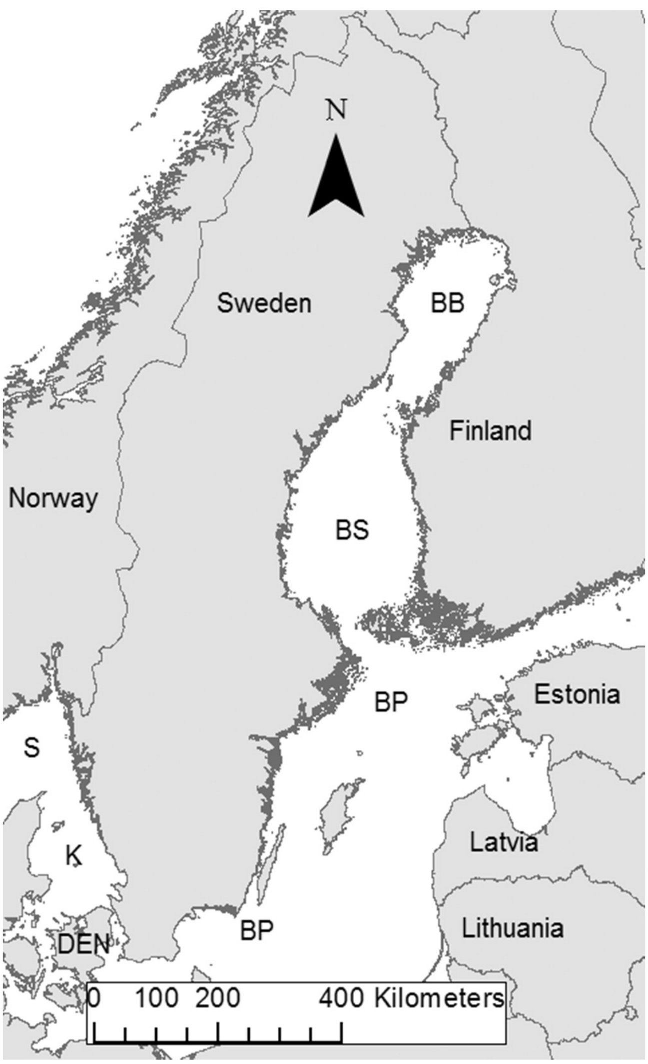

Fig. 1. The Swedish coastline and the main sea basins bordering Sweden. Location in northern Europe. BB: Bothnian Bay, BS: Bothnian Sea, BP: Baltic Proper, K: Kattegat, S: Skagerrak. DEN: Denmark.

The size of the 656 water bodies range from 0.41 km^2 to 2334 km^2 (mean: 57 km^2, standard deviation: 114 km^2), and their mean depths range from 0.4 to 77 m (mean: 12 m, standard deviation: 11 m). Maximum depths are between 1 and 241 m (mean: 29 m, standard deviation: 35 m). The catchment areas of the water bodies cover between 0.03 and 50,150 km^2 (mean: 874 km^2, standard deviation: 4599 km^2; SMHI, 2003). Salinities are close to zero near river mouths and can reach up to about 35 (psu) in deep waters along the Swedish west coast (SMHI, 2016).

Thresholds for assessing the nutrient concentration status differ between water bodies and depend on e.g. differences in natural background concentrations (Anon, 2000). Satisfactory nutrient concentration status according to the WFD occurs when a water body is classified as "good" or "high", while "moderate", "poor" and "bad" status imply that conditions must be improved. In the southern and more densely populated part of the country (south of the Bothnian Sea; Fig. 1), many coastal water bodies have an unsatisfactory status due to eutrophication, according to WFD criteria. Conversely, coastal water bodies in the northern part of the country have typically been classified as having good or high nutrient concentration status, although exceptions occur. In total, 57% of Swedish coastal water bodies have been assessed to have unsatisfactory nutrient concentration status (VISS, 2016).

2.1. Nutrient cycles in coastal waters

Nutrient inflow from land into coastal waters can come from point sources, e.g., industries or sewage treatment plants, but also from diffusive sources, e.g., involving leakage from agricultural or forest soil to groundwater. A part of the land-based nutrient inflow consists of a site-specific proportion of natural background nutrients, which can emanate from bedrock weathering and natural soil maceration, whereas the remainder comes from anthropogenic sources, such as soil fertilisation, sewage or exhausts (Håkanson and Bryhn, 2008; HELCOM, 2015).

Atmospheric exchange of P is only an input, consisting of wet and dry deposition from the atmosphere to the water surface, whereas it for N occurs in both directions. Input of N consists of wet and dry deposition from the atmosphere as well as supply of nitrogen gas (N_2) which can be fixed in biomass and added to the food web by cyanobacteria (Håkanson and Bryhn, 2008; Gustafsson et al., 2012). The atmospheric outflow of N consists of ammonia evaporation as well as denitrification and anammox (anaerobic ammonium oxidation). The two latter processes both generate dissolved N_2 that can evaporate into the atmosphere (Vymazal, 2007; Chlot, 2013).

The water exchange between the coastal water body and the sea also brings nutrients along (Engqvist, 1996; Dimberg and Bryhn, 2014b; Karlsson et al., 2014). Water generally flows in and out to a massive extent and the average water retention time in coastal water bodies along the Swedish east coast where there is a negligible tidal influence is < 10 days (Dimberg and Bryhn, 2014b). Thereby, water and nutrients can be transported from afar, or follow a coastal current carrying nutrients along the coast from more adjacent catchment areas (Rydberg et al., 1996; Håkanson and Bryhn, 2008; Jędrasik et al., 2008; Omstedt