Ecological Modelling 320 (2016) 258–272

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

The importance of local versus external nutrient loads for Chl *a* and primary production in the Western Baltic Sea

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ARTICLE INFO

Article history:
Received 26 June 2015
Received in revised form
14 September 2015
Accepted 18 September 2015
Available online 11 November 2015

Keywords:
Eutrophication
Primary production
Biogeochemical modelling
Nutrient loads
Baltic Sea

ABSTRACT

The Western Baltic Sea is affected by eutrophication and receives nutrients from local land-based sources, atmospheric deposition and by advection from the neighbouring North Sea and Baltic Sea. In the present study, we evaluated the importance of local (Danish) versus external (Baltic Sea–North Sea) nutrient loads for surface Chl *a*-concentrations, total areal primary production and the vertical distributions of primary production in the W. Baltic Sea using the 3D coupled HBM-ERGOM model. This was assessed by improving descriptions of nutrient loads and primary production in the model and by conducting scenarios of different nutrient loads according to (i) the eutrophication level in 1990, (ii) the new Danish Water Plan (DWP) and iii) DWP+ the Baltic Sea Action Plan (BSAP2). The model results showed that local nutrient reductions have a profound effect on Chl *a* concentrations and primary production in the coastal areas of the Western Kattegat and the Belt Sea with the highest impact <10–25 km from the coast. However, on average for the study area, Danish reductions have a limited effect. The DWP complemented the BSAP2 reductions spatially, since they had the highest impact in different areas and both were important for improving the ecological status of the ecosystem. The model suggested a significant change in the vertical distribution of primary production with less deep primary production in response to increased nutrient load. We recommend using this redistribution as an ecological indicator of eutrophication in seasonally stratified seas. The new description of primary production takes into account that carbon fixation continue, even when phytoplankton is severely nutrient limited. This model improvement increases primary production by a factor of 2.6 and brings the model estimates in agreement with measurements and the physiology of phytoplankton. We recommend that other dynamic ecosystem models using Liebig's law for primary production consider a similar approach.

1. Introduction

Eutrophication of coastal marine waters is a worldwide problem resulting from over-enrichment with nutrients due to human activities. The effects of eutrophication emerge as high primary productivity, (harmful) algae blooms, frequent events of hypoxia and anoxia, reduction in water clarity, decrease in the depth distribution of submerged vegetation, a shift from benthic to pelagic primary production, decrease in biodiversity and, occasionally, mass mortality of benthos (Nixon, 1995; Cloern, 2001; HELCOM, 2009; Krause-Jensen et al., 2012; Riemann et al., 2015). Marine ecological indicators used to track changes in the environmental status of coastal waters often focus on state variables (e.g. winter nutrients and Chl *a*-concentrations), whereas rate measurements (e.g. primary production, grazing, remineralisation) are less often considered. Pelagic primary production is directly linked to nutrient loads in coastal marine ecosystems (Nixon et al., 1996; Cloern, 1999) and is one of the few biogeochemical rates that is measured regularly. Rate measurements are important, since top-down processes (e.g. grazing pressure) may cause losses that level out changes in the phytoplankton biomass that otherwise would have been caused by an altered primary productivity (Duarte et al., 2009). Similarly, nutrient uptake by phytoplankton is often able to keep inorganic nutrient concentrations at very low levels during the growth season despite a high nutrient input. Recently, it was documented that reductions in land-based nitrogen loads also alter

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http://dx.doi.org/10.1016/j.ecolmodel.2015.09.023
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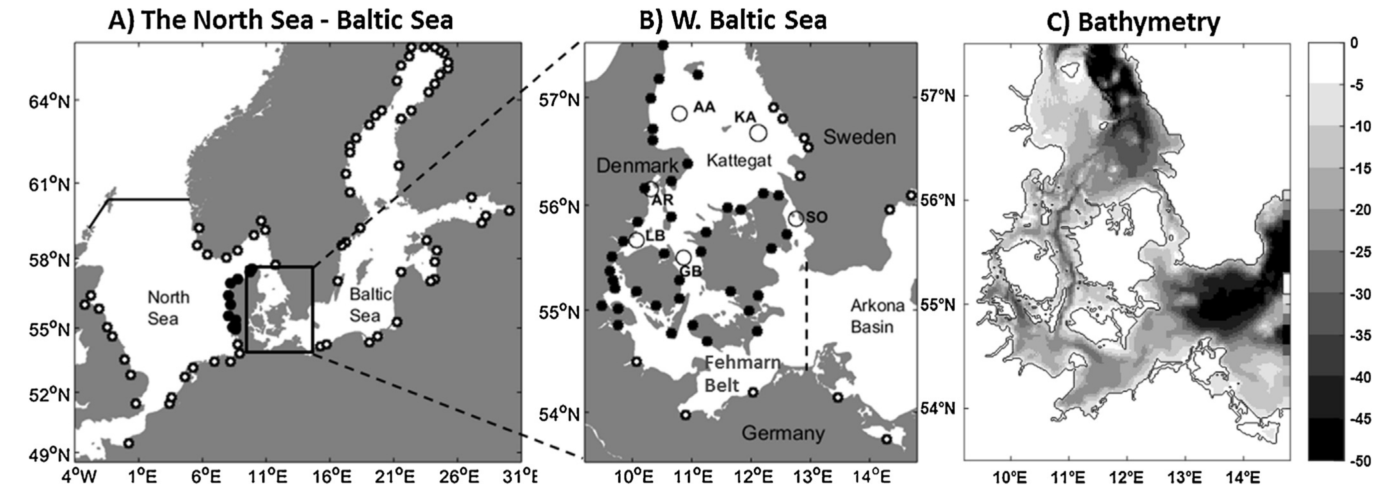

Fig. 1. Maps showing (A) the North Sea-Baltic Sea area covered by the coarse model grid, (B) the Western Baltic Sea (here defined as the area west of the vertical dashed line) and (C) model bathymetry within the fine model grid. Freshwater sources delivering nutrient inputs are indicated as filled circles for Danish sources and open circles for other than Danish sources. The monitoring stations for primary production are shown as larger open circles in the transitions area, where AA = Aalborg Bight, AR = Aarhus Bight, LB = Little Belt, KA = Kattegat, GB = Great Belt, and SO = The Sound. The solid line in (A) indicates the open boundary of the model domain to the North Atlantic. The other open boundary is located in the English Channel (SW North Sea).

the vertical distribution of pelagic primary production by favouring production below the pycnocline (Lyngsgaard et al., 2014a). Primary production below the pycnocline significantly improves bottom water oxygen conditions and increases sedimentation to the bottom, thereby supporting a benthic food web (Lehrter et al., 2009; Lindegren et al., 2012; Lyngsgaard et al., 2014b). This suggests that marine ecological indicators, such as Chl *a*-concentrations, should be combined with estimates of total and deep primary production to give a correct picture of the status of the marine environment.

The Western Baltic Sea (here defined as the Kattegat, the Belt Sea, the Sound and the Fehmarn Belt, Fig. 1B) is affected by eutrophication (Carstensen et al., 2006; Andersen et al., 2011). Phytoplankton primary production in the area is mainly limited by nitrogen (Graneli et al., 1990; Richardson and Christoffersen, 1991), and a close positive relationship has been found between nitrogen load and total production in the water column (Markager and Storm, 2003; Rydberg et al., 2006; Lyngsgaard et al., 2014a). In the Belt Sea, phosphorous can also become limiting during the spring (Jørgensen et al., 2014). During the summer, a significant fraction of the phytoplankton primary production can occur within or below the pycnocline layer if there is enough light to support growth (Klausmeier and Litchman, 2001). The deep primary production (DPP) can constitute up to 30% of the annual primary production (Richardson and Christoffersen, 1991; Lyngsgaard et al., 2014a). DPP was shown to increase from 1998 and onwards simultaneously with decreasing nutrient loads in the Kattegat-Belt Sea area due to higher water transparency (Lyngsgaard et al., 2014a).

The area receives nutrient inputs from local freshwater sources from Denmark, Sweden and Northern Germany (Windolf et al.,

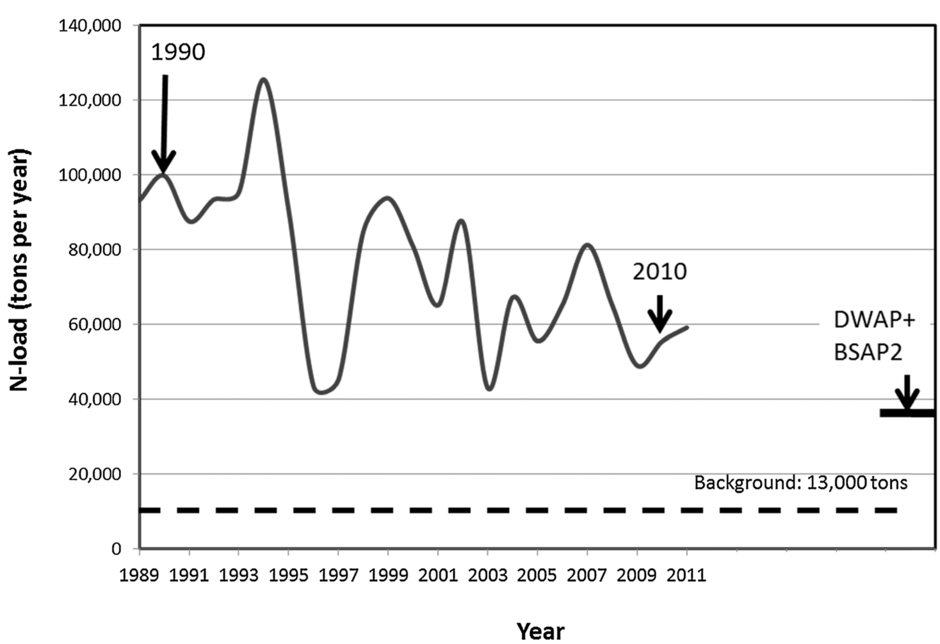

Fig. 2. Land-based loadings of total nitrogen from Denmark from 1989 to 2011. The nutrient loads used as baseline (2010) and the hind-cast scenario (1990) are indicated with arrows together with the DWP and BSAP2 scenarios to the right (arbitrarily set to 2020). The estimated background loading at the year 1900 is indicated by the dashed line.