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Nutrient budgets for European seas: A measure of the effectiveness of nutrient reduction policies

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ABSTRACT

Socio-economic development in Europe has exerted increasing pressure on the marine environment. Eutrophication, caused by nutrient enrichment, is evident in regions of all European seas. Its severity varies but has, in places, adversely impacted socio-economic activities. This paper aims to evaluate the effectiveness of recently adopted policies to reduce anthropogenic nutrient inputs to European seas. Nitrogen and phosphorus budgets were constructed for three different periods (prior to severe eutrophication, during severe eutrophication and contemporary) to capture changes in the relative importance of different nutrient sources in four European seas suffering from eutrophication (Baltic Proper, coastal North Sea, Northern Adriatic and North-Western Black Sea Shelf). Policy success is evident for point sources, notably for P in the Baltic and North Seas, but reduction of diffuse sources has been more problematic.

1. Introduction

European marine ecosystems are being degraded as a consequence of continuously increasing pressure from anthropogenic activities. Several EU reports (EEA, 2001b, 2003a,b, 2006) have highlighted the state of the marine environment, its increasing vulnerability and the need for further and stricter regulation of nutrient release. Eutrophication, a product of anthropogenic nutrient enrichment of water bodies, is an important current state change affecting the integrity of European seas (EEA, 2001a, 2003a). The EU has already adopted several directives and policies intended, directly or indirectly, to combat eutrophication (e.g. Nitrates Directive, Urban Waste Water Treatment Directive, Water Framework Directive, Common Agricultural Policy). The EU's Water Framework Directive will coordinate much of this action within national and international catchment-scale ("River Basin District") boundaries. Special measures and interventions (policy and legal reforms, investments in nutrient reduction technology at source) have been planned and partially implemented through coordinated international and national actions by the regional seas conventions and their secretariats (HELCOM in the Baltic, OSPAR in the North Sea, the Barcelona Convention in the Mediterranean and the Bucharest Convention in the Black Sea), together with associated projects and programmes. A new European Marine Strategy Directive is under review and will provide environmental quality targets (Good Environmental Status) that cannot be achieved without tackling eutrophication.

The intensity and spatial extent of eutrophication in European seas varies widely (Fig. 1), from small hot spots in enclosed bays (e.g. Kastela Bay in the Adriatic Sea, or Izmir Bay in the Aegean Sea), to sub-regional areas (e.g. the Wadden and Adriatic Seas) to almost entire seas (e.g. the Baltic Sea). To compare the effectiveness of nutrient regulation in four European regional seas, one case study of an area affected by eutrophication was selected for each sea, viz.: the Northern Adriatic for the Mediterranean Sea (Justic et al., 1987; Vollenweider et al., 1992), the coastal North Sea for the North-East Atlantic (Brockmann et al., 1988; Pätsch and Radach, 1997), the Baltic Proper (Wulff and Stigebrandt, 1989; Wulff and Stigebrandt, 1990) and the North-Western (NW) Black Sea shelf (Lancelot et al., 2002). The large spatial scale addressed in this study responds directly to the needs of policy-makers to guide the integrated management of Europe's regional seas.

We applied a comparative aggregated mass balance approach on each sub-regional basin for three time periods. Our aim is to assess and to compare changes over past decades in the nutrient

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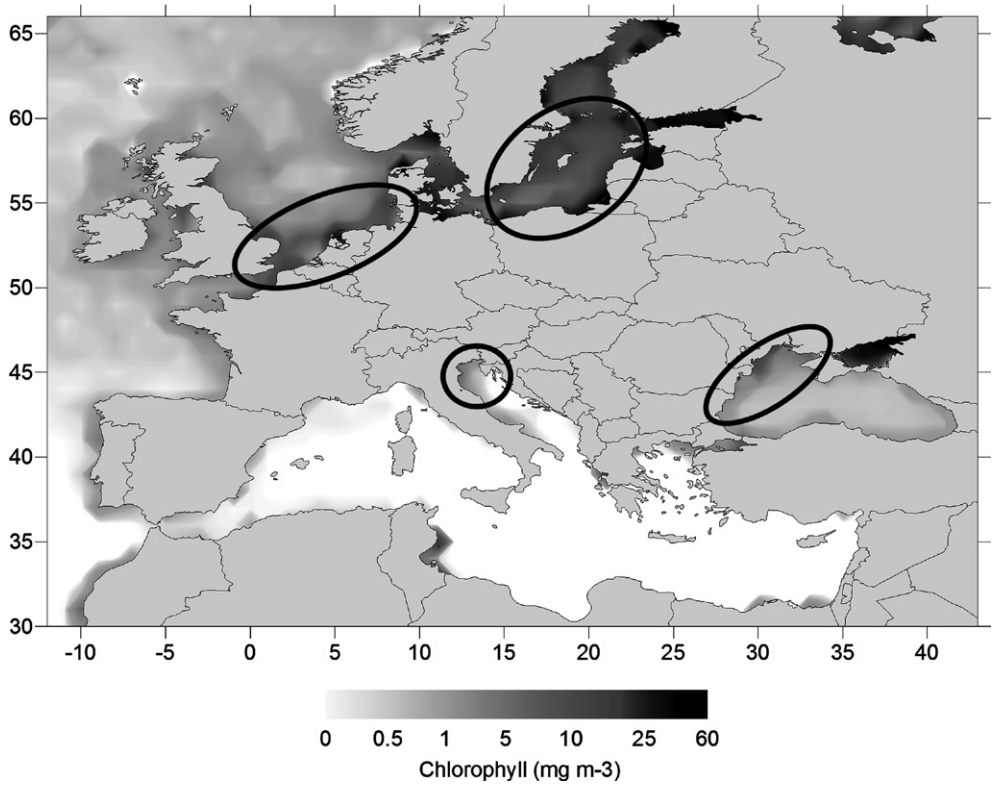

Fig. 1. Seawifs composite image of chlorophyll-a for the year 2007. Satellite images have not been corrected for yellow substances, hence chlorophyll-a concentration may be overestimated in some region (particularly in the Baltic Sea). The four case studies are evidenced. From upper left proceeding clokwise: coastal North Sea, Baltic Proper, North-western Black Sea shelf, Northern Adriatic.

budgets (for nitrogen – N and phosphorus – P) of four sub-regional basins of four European seas. These changes reflect the nutrient loading of coastal waters, and changes in loading due to policy that is largely coordinated at the European scale. Finally we draw implications for the further development of nutrient reduction policy.

2. Materials and methods

2.1. Case study areas

The main hydromorphologic characteristics of the four selected areas are summarized in Table 1.

The Northern Adriatic is a shallow enclosed basin (average depth 35 m) located between Italy and the Balkans and delimited by the 100 m isobath. The seabed is gently sloping and mostly sandy or muddy. It receives large fresh water discharges (about 80 km^3/yr), particularly from Italian rivers (e.g. Po, Adige, Isonzo, Tagliamento) that drain intensely developed catchments where about 50% of Italy's national production of agriculture and livestock, and 40% of its population, are concentrated. The Northern Adriatic is one of the most productive areas in the Mediterranean, and in the '80 s suffered severe eutrophication as evidenced by hypoxia and fish kills (Degobbis et al., 2000; Vollenweider et al., 1992).

Table 1
Hydromorphological characteristics of the selected case study areas

	Area 10^3 km^2	Volume 10^3 km^3	Residence time months
Northern Adriatic	44.0	1.5	3.3[a]
Baltic Proper	211.0	13.0	54.0[b]
Coastal North Sea	154.0	3.5	0.9[c]
NW shelf Black Sea	50.0	4.7	12.0[d]

[a] Calculated from Zavatarelli and Pinardi (2003).
[b] Calculated from Savchuk (2005).
[c] Calculated from Lenhart et al. (1995).
[d] Calculated from Gregoire and Lacroix (2003).

The Baltic Sea is better considered as a large estuary where marine North Sea water and freshwaters from land drainage mix, forming horizontal and vertical salinity gradients. Salinity ranges from 3 PSU in the northernmost Bothnian Bay to 20 PSU in the Danish straits and Kattegat. A sharp, vertical density gradient (pycnocline) separates a less saline upper layer and a highly saline, deeper layer (e.g. Conley et al., 2002a,b). Due to high nutrient input from rivers (particularly southern and eastern catchments where population and agriculture are most concentrated) and to the long residence time, the Baltic Sea has become a highly eutrophied basin. In this paper we focus on the Baltic Proper (Savchuk, 2005). This basin is deep (240 m in the Gotland Deep) and permanently stratified. It receives freshwater from the largest rivers in the Baltic catchment (e.g. Vistula, Neva, Oder) and discharges from large cities (e.g. Stockholm, Gdansk). It suffers from intense algal blooms and periods of stagnation with expanding hypoxia in bottom waters.

The North Sea is among the most intensively exploited shelf seas of the world (OSPAR, 2000). It covers approximately 515,000 km^2 and has a mean depth of 78 m. Human exploitation includes fisheries, fossil fuel extraction, sediment excavation, transportation and waste disposal. Bathymetry, hydrodynamics, remote sensing imagery of suspended matter and chlorophyll concentrations as well as models (Eleveld et al., 2004; Lenhart et al., 1995; McQuatters-Gollop et al., 2007) suggest a distinction between the shallow coastal zone (mean depth 22 m) and a deeper, open zone (mean depth 102 m) that stratifies during summer and is well-flushed with Atlantic water. Eutrophication symptoms such as hypoxia and enhanced algal blooms have been reported for coastal stations in sheltered areas such as the Wadden Sea and the German Bight (e.g. Brockmann et al., 1988; Druon et al., 2004; Hickel, 1998; van