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Responses of biological and chemical components in North East Atlantic coastal water to experimental nitrogen and phosphorus addition – A full scale ecosystem study and its relevance for management ☆

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HIGHLIGHTS

- A full-scale 5 year experimental study of ecosystem responses to increased nutrients.
- Concentrations of DIN and DIP did not respond positively to increased nutrient input.
- Concentrations of PON and POP and phytoplankton biomass responded positively.
- PON is suggested as credible indicator for chemical and ecological state.
- A general scientific concept for managing nutrient input to coastal waters is presented.

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ABSTRACT

The objective of this study was to quantify chemical and biological responses to an experimentally increased nutrient input to an open coastal planktonic ecosystem and to contribute to a scientific concept and credible indicators for managing nutrient supply to coastal waters. Data were derived in a 5 year fertilisation experiment of a tidal driven coastal lagoon at the outer coast off Central Norway (*63°36′ N, 9°33′ E*), with a surface area of 275.000 m^2, volume of 5.5 mill m^3, mean depth of 22 m and a water exchange rate of 0.19 day^{-1}. The lagoon was fertilised in the summer season 1998 and 1999, while summer seasons 1996-97 and 2000 and inflowing water were used as unfertilised references. Most measured chemical and biological variables showed linear responses with an increasing loading rate of inorganic N and P (L_N and L_P, respectively). PON, POP and POC (< 200 μm) responded significantly ($P < 0.05$) as did chlorophyll *a* and phytoplankton C. DIN and DIP remained, however, constant and independent of L_N and L_P, respectively ($P > 0.05$) as did heterotrophic biomass ($P > 0.05$). We evaluate the response variables assuming a stepwise incorporation process of nutrients in the planktonic ecosystem and how that will interact with biological response times and water dilution rates. We suggest that PON is a credible indicator of both chemical and ecological states of the planktonic ecosystem and that natural background and upper critical concentrations are 46 and 88 mg PON m^{-3}, respectively. The study was supported by data from mesocosms. We discuss the scientific relevance of our suggestions, how results can be extrapolated to a broader geographical scale, and we propose a science-based concept for the management of nutrient emission to open coastal waters.

1. Introduction

Coastal eutrophication caused by human activities, or anthropogenic eutrophication, is primarily a problem in densely populated coastal regions. Reports describing causes and consequences of enhanced anthropogenic nutrient emission to the coastal zone are numerous (e.g., Schiewer, 1998; Capriulo et al., 2002; Colijn et al., 2002; Grizzetti et al., 2012). It has been well documented that enhanced nutrient inputs increase the primary production and phytoplankton biomass, but there is also evidence for an order-of-magnitude difference in biomass yield

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per unit of nutrient input among systems (e.g., Nixon and Pilson, 1983; Borum, 1996; Cloern, 2001; Carstensen et al., 2011). This pronounced variability in the quantitative responses of increased nutrient input suggests that factors other than nutrient loading rate and nutrient concentration affect autotrophic biomass. The confusions and uncertainties associated with the lack of more uniform chemical and ecological responses (e.g., Capriulo et al., 2002) are among the reasons why there is still no general concept established for managing nutrient emission to coastal waters (Cloern, 2001).

The underlying reasons for system variability are probably complex, but the variable rate of water dilution driven by physical forcing and direct or indirect effects by zooplankton predation will obviously affect the structure and function of the planktonic food web and therefore also the autotrophic yields (Sommer and Stibor, 2002; Stibor et al., 2004a; Vadstein et al., 2004). Another factor is that phytoplankton biomass yields per unit of nutrients incorporated vary systematically by a factor >2 with the specific growth rate, or their nutritional state (Droop, 1983).

One practical way to reduce variability is to secure a standardised and representative data input for a geographic area instead of using more fragmented data for single days and sampling spots. European legislation requires that environmental management must be ecosystem-based, and the unit area of management – the ecosystem - must therefore have a certain geographical extension. It is also logical that the data for management must cover relevant time periods (Ferreira et al., 2011). For coastal eutrophication in moderately affected or pristine North-East (NE) Atlantic water, negative ecological effects of eutrophication in pelagic euphotic ecosystems will only become expressed in the summer season (Cloern, 2001), which is defined as the period from after the decline of the spring bloom until the onset of autumn turnover of water masses, i.e. June until the end of September in Norwegian temperate coastal waters. The use of input data that are temporarily and spatially representative will probably reduce variability in both data inputs and the outputs.

It is also important for management of coastal seas to establish science-based, credible and readily measurable indicators and procedures that can predict the ecological state of open coastal waters (e.g., Caruso et al., 2010; Andersen et al., 2011; Ferreira et al., 2011). We agree that there is no general concept established for a knowledge-based management of open coastal waters today (Cloern, 2001; Kitsiou and Karydis, 2011), in contrast to the simple principles used to freshwater eutrophication (Vollenweider, 1976). European environmental legislation has recently defined environmental objectives for a science-based management of surface waters in general (Tett, 2008; WFD-Water Framework Directive, 2000/60/EC; MSFD-Marine Strategy Framework Directive, 2008/56/EC), which would benefit from the establishment of a unified concept for assessing and managing coastal eutrophication. The WFD states that the concentrations of naturally occurring substances like nutrients should not be increased much above the natural background, whereas the structure and function of the ecosystem should be maintained in a Very Good or Good state category (Tett, 2008; Andersen et al., 2011). The principles of the WFD are attractive, but implementation is still a challenge because most present indicators (Caruso et al., 2010) are only determined empirically, showing a high variability among coastal regions (e.g., Nixon and Pilson, 1983; Borum, 1996; Cloern, 2001; Carstensen et al., 2011). The need to determine natural background values for the indicators is a particular challenge emphasised in the WFD (Tett, 2008), and comprehensive knowledge on background values are vital for their use as unified indicators.

The ultimate objective of the present study was to quantify chemical and biological responses of enhanced nutrient input to an open coastal planktonic ecosystem, and to contribute to the development of a scientific-based concept and credible indicators for managing anthropogenic nutrient supply to coastal waters. To address these questions, we carried out a full scale 5 year fertilisation experiment of a dynamic and tidal driven coastal lagoon situated at the outer coast off Central Norway in 1996-2000. The euphotic zone of the lagoon received a daily addition of inorganic nitrogen, phosphorus and silica (DIN and DIP, in Redfield proportions with half ration of Si) in the summer period in 1998 (low dose) and 1999 (high dose). The years 1996, 1997 and 2000 represented control years where no nutrients were added. In addition, regular sampling of the inflowing non-affected water also served as an internal control throughout the experiment. Sampling was performed weekly in the summer period, and involved many common physical, chemical and biological variables.

Our current interpretation of the results of the full scale fertilisation experiment is supported by a number of mesocosm experiments carried out in the course of and after the fertilisation experiment (e.g., Gismervik et al., 2002; Stibor et al., 2004a,b, 2006; Vadstein et al., 2004, 2012; Børsheim et al., 2005; Sommer et al., 2004, 2005; Olsen et al., 2006, 2007, 2011; Sundt-Hansen et al., 2006). The general knowledge gathered in these experiments is instrumental for the conclusions made in the present study.

2. Materials and methods

2.1. Description of the study area

The effects of experimental nutrient supply to coastal waters were studied in a tidal driven coastal lagoon named Hopavaagen (*63°36' N, 9°33' E*), situated in a sparsely populated area with a low human influence at the outer coast of Central Norway (Table 1). The coastal lagoon has a surface area of 275,000 m^2 and a total volume and a volume of euphotic waters (0–10 m) of 5.5 and 3.2×10^6 m^3, respectively. The depth of the main basin is 22-32 m, and the bottom is relatively flat with an average depth of 20 m. The mean water exchange rate of the mixed euphotic water layer is 0.19 day^{-1}, corresponding to a water renewal time of the mixed euphotic water layer of 5.2 ± 1.9 days. The inflowing water is drained from and considered representative of the Norwegian Coastal Current.

Due to the narrow inlet, the tidal range in Hopavaagen is smaller compared to that outside. The daily water exchange is variable and dependent primarily on the tidal cycle, but air pressure and wind speed and direction are also of importance. For prediction of the exchange rate of water, we used coastal astronomical tidal level changes for the area and meteorological data measured at Ørlandet airport close by.

Table 1
Characteristics of the tidal driven coastal lagoon Hopavaagen situated in Central Norway.

Characteristics of the coastal lagoon Hopavågen (SE)			Unit
Coordinates	N 63° 35.636' E 9° 32.809'		WGS 84
Surface area	275,000		m^2
Total volume	5.5		10^6 m^3
Mixed volume	3.2		10^6 m^3
Mean depth	20 (range 0-32)		m
Tidal range outside	1-2		m
Tidal range inside	0.3 – 1.0		m
Volume exchanges by tides	0.61 ± 0.22		10^6 m^3 day^{-1}
Replacement time of mixed volume	5.2 ± 1.9		day
Exchange rate of mixed volume	0.19 ± 0.07		day^{-1}
Exchange rate of total volume	0.11 ± 0.04		day^{-1}
Catchment area	1.9		km^2
Salinity and temperature in lagoon (0.5 - 10 m)	Temperature ± SD	Salinity ± SD	°C and ppt
1996	11.6 ± 1.6	32.6 ± 0.6	
1997	12.8 ± 2.3	30.2 ± 2.4	
1998	11.6 ± 1.8	31.3 ± 1.6	
1999	12.5 ± 1.5	31.4 ± 1.3	
2000	11.3 ± 1.0	31.1 ± 1.6	