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# Phosphorus input by upwelling in the eastern Gotland Basin (Baltic Sea) in summer and its effects on filamentous cyanobacteria

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## ABSTRACT

In July 2007, phosphorus input by an upwelling event along the east coast of Gotland Island and the response of filamentous cyanobacteria were studied to determine whether introduced phosphorus can intensify cyanobacterial bloom formation in the eastern Gotland Basin. Surface temperature, nutrient concentrations, phytoplankton biomass and its stoichiometry, as well as phosphate uptake rates were determined in two transects between the coasts of Gotland and Latvia and in a short grid offshore of Gotland. In the upwelling area, surface temperatures of 11–12 °C and average dissolved inorganic phosphorus (DIP) concentrations of 0.26 μM were measured. Outside the upwelling, surface temperatures were higher (15.5–16.6 °C) and DIP supplies in the upper 10 m layer were exhausted. Nitrite and nitrate concentrations (0.01–0.22 μM) were very low within and outside the upwelling region. Abundances of filamentous cyanobacteria were highly reduced in the upwelling area, accounting for only 1.4–6.0% of the total phytoplankton biomass, in contrast to 18–20% outside the upwelling. The C:P ratio of filamentous cyanobacteria varied between 32.8 and 310 in the upwelling region, most likely due to the introduction of phosphorus-depleted organisms into the upwelling water. These organisms accumulate DIP in upwelling water and have lower C:P ratios as long as they remain in DIP-rich water. Thus, diazotrophic cyanobacteria benefit from phosphorus input directly in the upwelling region. Outside the upwelling region, the C:P ratios of filamentous cyanobacteria varied widely, between 240 and 463, whereas those of particulate material in the water ranged only between 96 and 224. To reduce their C:P ratio from 300 to 35, cyanobacteria in the upwelling region had to take up 0.05 mmol $m^{-3}$ DIP, which is about 20% of the available DIP. Thus, a larger biomass of filamentous cyanobacteria may be able to benefit from a given DIP input. As determined from the DIP uptake rates measured in upwelling cells, the time needed to reduce the C:P ratio from 300 to 35 was too long to explain the huge bloom formations that typically occur in summer. However, phosphorus uptake rates increased significantly with increasing C:P ratios, allowing phosphorus accumulation within 4–5 days, a span of time suitable for bloom formation in July and August.

## 1. Introduction

In the Baltic Sea, frequent wind driven upwelling events can occur due to its topographic and geographic characteristics. The topography of the sea bottom, marked by sills, islands, and semi-enclosed basins, favours the induction of upwelling in response to nearly all wind directions. Due to the predominant southwest winds, upwelling occurs most frequently at the Swedish coast in the Baltic Proper and in the Bothnian Bay (Gidhagen, 1987). Upwelling is also reported at the northern and southern coasts of the Gulf of Finland (Haapala, 1994; Suursaar and Aps, 2007), the Polish coasts (Kowalewski and Ostrowski, 2005), and the German islands (Lass et al., 1996). The frequency of upwelling events varies from region to region (Kowalewski and Ostrowski, 2005), depending on the alignment of the coastline with respect to the prevailing wind direction.

With changing wind direction, an upwelling area can be converted to a downwelling one and vice versa (Kowalewski and Ostrowski, 2005). At the Swedish coast, upwelling areas up to 100 km long and spreading 5–20 km into the sea have been

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described by Gidhagen (1987). In the summer of 2006, Suursaar and Aps (2007) observed an upwelling event at the Estonian coast that extended over a length of 360 km. According to Myrberg and Andrejev (2003), the wind has to blow from a favorable wind direction for at least 50–60 h before an upwelling is created.

Temperature is a useful indicator of the presence of upwelling regions. Upwellings can be identified clearly only in summer, when warm surface water with temperature of 16–21 °C (Siegel et al., 2008), is separated by a thermocline from the underlying intermediate winter water of 4–6 °C. In the center of an upwelling, the surface temperature can drop by 5 °C when deep and surface water are mixed (Gidhagen, 1987).

Upwelling water originates from depths of 20–40 m (Gidhagen, 1987) and is depleted of inorganic nitrogen compounds but contains significant phosphate concentrations of up to 0.50 μM (Nausch et al., 2007) which are in the range of the winter surface concentrations. These nutrient conditions have been described in upwelling regions in the northern Gulf of Finland (Vahtera et al., 2005) and the Hel Peninsula at the Polish coast as well (Kowalewski, 2005). Due to the low molar N/P ratio of the surface water in winter (Nausch et al., 2008a), the phytoplankton spring bloom is nitrogen-limited. The amount of phosphate remaining after the spring bloom is used to calculate biomass development and nitrogen fixation by diazotrophic cyanobacteria (Janssen et al., 2004; Kahru et al., 2007). However, the surplus phosphate remaining after the spring bloom and the changes in internal phosphorus pools do not always explain the enormous biomass development and huge bloom formation in each year (Lilover and Laanemets, 2006; Nausch et al., 2008b). The model simulations of Laanemets et al. (2006) showed the best fit of *Nodularia spumigena* blooms when both turbulent mixing and upwelling were taken into account. Using a hydrodynamic model, Ennet et al. (2000) demonstrated for the Gulf of Riga that the spring bloom as well as the cyanobacteria summer bloom can be intensified by upwelling. According to Vahtera et al. (2005), nutrient input by upwelling does not directly effect the development of filamentous cyanobacteria; rather, the relaxation of older, warmer water and its mixing with upwelled cold phosphorus-rich water favour cyanobacteria development after a lag time of 2–3 weeks.

During a cruise with the R/V "Poseidon" in July 2007, we studied phosphorus input during upwelling events taking place at the eastern coast of Gotland and subsequent phosphorus transformations in the surface layer along transects extending as far as the coast of Latvia. Focusing on filamentous cyanobacteria, we sought to answer the following questions:

- Is cyanobacterial growth promoted by phosphorus input from upwelling?
- Can cyanobacteria immediately use the phosphate supplied by the upwelling region, or is there a delay between phosphate input and cyanobacterial uptake?
- Is phosphorus introduced only as phosphate or as dissolved organic phosphorus as well?
- How do cyanobacterial biomass, intracellular phosphorus content, and C:N:P ratios change with distance from the upwelling region?

Answering these questions would resolve the broader question: Does phosphorus supplied by the upwelling induce or intensify cyanobacterial blooms in the Gotland Basin?

## 2. Material and methods

### 2.1. Investigation area and sampling

Investigations were conducted in 2007, between July 10th and 23rd, in the eastern Gotland Basin. During this period, winds came predominantly from southwest to northwest directions (200–300°), with wind speeds ranging between 4 and 18 m s$^{-1}$ (Lass et al., submitted for publication). On 3 days only (July 17, 21, 22), the wind speed was lower, for few hours, and the wind direction changed to east. Air temperature ranged between 13.5 and 17.4 °C. Global radiation reached maximum values of 850–1000 W m$^{-2}$. This was one of the typical summer weather patterns in the Baltic Sea region characterized by westerly circulation with embedded cyclones. Under these meteorological conditions, an upwelling was induced at the southeast coast of the Gotland Island, as indicated by sea surface temperature of about 10 °C as determined from a satellite image (Fig. 1). Water samples were taken on two transects between the coasts of Gotland and Latvia (Fig. 1). The distance between sampling stations was 10 n.m.. A filament of upwelled water was tracked in a third short grid (Fig. 1).

A rosette sampler (Hydrobios) consisting of thirteen 5 l free-flow bottles was used to obtain the water samples. The rosette was equipped with a Seabird SBE 911, consisting of sensors for depth, conductivity, temperature, and chlorophyll fluorescence, as well as a light sensor to measure photosynthetically available radiation (PAR).

Filamentous cyanobacteria were sampled from the thermocline up to the surface using a WP2 plankton net with a mesh size of 100 μm. To eliminate zooplankton, the samples were resuspended in GF/F-filtered seawater in a 2 l bottle and two-thirds covered with black wrapping for 2 h, causing the zooplankton to move to the still-lighted bottom such that pure filamentous cyanobacteria could be collected from the upper portion.

### 2.2. Analytical methods

#### 2.2.1. Inorganic nutrient analysis

Nutrient concentrations (dissolved inorganic phosphorus (DIP), nitrate, nitrite, ammonium, silicate) were determined by standard photometric methods, as described by Rohde and Nehring (1979) and Grasshoff et al. (1983). Water samples were filtered through pre-combusted (450 °C, 4 h) Whatman-GF/F filters. Nitrite, nitrate, phosphate and silicate concentrations were determined simultaneously using an autoanalyzer (Evolution III, Alliance). Ammonium was determined manually in unfiltered samples.

#### 2.2.2. Dissolved and particulate organic phosphorus

For the determination of total and dissolved phosphorus, 40 ml subsamples were stored at −20 °C before and after filtration

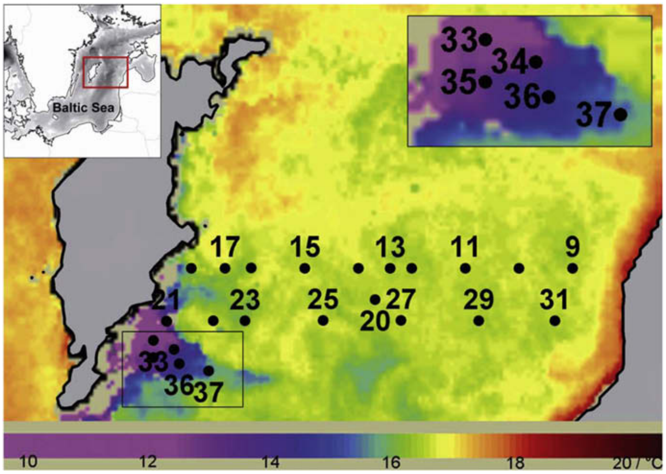

**Fig. 1.** Satellite image of the upwelling event at the east coast of the Gotland Island in July 2007 and sampling stations.