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Factors controlling phosphorus release from sediments in coastal archipelago areas

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A B S T R A C T

In coastal archipelago areas of the northern Baltic Sea, significantly higher phosphate concentrations (6.0 ± 4.5 μmol/l, mean ± SD) were measured in water samples close to the sediment surface compared with those from 1 m above the seafloor (1.6 ± 2.0 μmol/l). The results indicated notable phosphate release from sediments under the bottom water oxygen concentrations of up to 250 μmol/l, especially in areas that had experienced recent temporal fluctuation between oxic and hypoxic/anoxic conditions. No single factor alone was found to control the elevated PO_4-P concentrations in the near-bottom water. In addition to the oxygen in the water, the contents of potentially mobile phosphorus fractions, grain-size, the organic content at the sediment surface, and the water depth were all important factors controlling the internal loading of phosphorus. The complexity of this process needs to be accounted for in assessments of the internal loading of phosphorus and in potential mitigation plans.

1. Introduction

Coastal waters throughout the world are strongly influenced by human activities, and nutrients from terrestrial runoff often cause major problems (Smith, 2003; Diaz and Rosenberg, 2008). In many areas, nutrient enrichment has led to increased biological production (Kennish and Townsend, 2007; Diaz and Rosenberg, 2008) and, as a consequence, to increased accumulation of organic matter in the sediments (Emeis et al., 2000). In addition to the effects of external nutrient sources, recycling of phosphorus (P) through sediments, referred to as internal loading, has considerable impacts on coastal eutrophication (Conley et al., 2002; Rydin et al., 2011; Puttonen et al., 2014). Augmented degradation of organic matter enhances oxygen consumption causing hypoxia in stratified coastal waters (Diaz and Rosenberg, 2008). Oxygen depletion induces dissolution of iron-(oxy)hydroxides resulting in the release of iron-bound P (Mortimer, 1941; Boström et al., 1988; Ingall and Jahnke, 1994). This additional supply of P supports enhanced growth of particularly nitrogen-fixing cyanobacteria (Tyrrell, 1999; Vahtera et al., 2007; Conley et al., 2009; Funkey et al., 2014). Nitrogen fixation results in more nitrogen being introduced into the system, thus also sustaining eutrophication (Westman et al., 2003; Conley et al., 2009).

Phosphorus release from sediments driven by anoxia is widely described in deep, permanently anoxic basins, where hydrodynamic conditions are steady, and sediment accumulation is continuous (e.g. Conley et al., 2002; Funkey et al., 2014). There are few studies of P cycling processes in shallow coastal and archipelago sediments, even though the environmental conditions differ from those in deep marine basins. Internal P cycling in shallow coastal areas is also assumed to play a notable role in eutrophication (Rydin et al., 2011), but the controlling factors may be different from those in deep areas. In shallow temperate waters, although the halocline can be lacking, a thermal stratification is created during the summer months by the rising temperatures warming up the surface water. Organic matter originated from high primary production, and subsequent degradation of it increases oxygen consumption in the bottom. Oxygen supply from the surface layer and adjacent areas is hindered due to restricted vertical and horizontal water exchange. In coastal stratified waters of high productivity, seasonal hypoxia developed by biochemical processes is a typical phenomenon (Rowe, 2001; Connolly et al., 2010). In contrast to deep anoxic basins, where hydrodynamic conditions are stable, waves and bioturbation make sedimentary conditions fluctuate in coastal areas, and sediment accumulation rates are widely variable (Mattila et al., 2006). Excessive anthropogenic nutrient loading leads to high contents of P in the sediments (Emeis et al., 2000; Rabalais et al., 2007). Further field studies in shallow marine areas are needed to understand the role of various environmental factors and their interactions concerning P cycling between sediments and water.

In the Baltic Sea eutrophication is one of the major environmental concerns, and the current, primary remediation method is reduction in anthropogenic nutrient input (Carstensen et al., 2006; Heisler et al., 2008; HELCOM, 2014). Although external inputs of both nitrogen and P to the Baltic Sea have been considerably reduced during the last two decades, nutrient levels in the water have not markedly decreased, and the Baltic Sea is still highly affected by eutrophication (HELCOM,

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2014). The delayed response to the reductions in external nutrient loading can be attributed partly to P remobilization from the sediments, as the release of P from the sediments creates a self-supporting cycle maintaining a high trophic level even decades after reductions in the anthropogenic nutrient input (Eilola et al., 2009).

The aim of this field study was to estimate the intensity and causes of P release during summer months from soft, organic-rich sediments into the water column in a shallow eutrophied coastal area, in the Archipelago Sea region of the northern Baltic Sea. The study assesses the following: the role of oxygen and temperature in the near-bottom water, the total P and potentially mobile P forms, the grain-size distribution and organic content at the sediment surface, and the water depth and exposure to wave action in relation to P concentrations in the near-bottom water.

2. Materials and methods

2.1. Study area

Our study area, the Archipelago Sea, is located in the south-western part of Finland, in the northern Baltic Sea (Fig. 1). It is a shallow brackish-water sub-basin with an average depth of 23 m and salinity between 5 and 7 in the study area. The Archipelago Sea is characterized by a mosaic of thousands of islands and skerries. In the shelter of the numerous islands, accumulation of fine-grained sediments can take place in fairly shallow waters, while deeper areas may experience erosion due to strong bottom currents (Virtasalo et al., 2005).

The water in the Archipelago Sea is thermally stratified during the summer months, and seasonal hypoxia, with declining oxygen concentrations towards late summer, is a common phenomenon (Virtasalo et al., 2005). The area and intensity of hypoxia are increasing because of anthropogenic pressure (Conley et al., 2011). The ecological conditions in the southern and south-western coastal waters of Finland have deteriorated due to human activities (Putkuri et al., 2013). Despite the shallow water depth, an almost continuous accumulation of fine-grained and organic-rich sediment occurs in numerous small basins within the shelter of the islands (Virtasalo et al., 2005). The accumulation rate in the inner archipelago varies from 0.7–2.3 cm year^{-1} inferred from ^{137}Cs dating and sediment lamina couplet counting (Nordmyr, 2002; Jokinen et al., 2015). Water mixing is restricted both horizontally and vertically due to the abundance of islands and temporal water stratification. Consequently, much of the nutrients transported from the land and by currents from the Baltic Proper and the Gulf of Finland are used in biological production or trapped in the sediments in the Archipelago Sea, rather than carried further by the currents. For this reason, the Archipelago Sea has been said to act as a filter for nutrients (Mälkki et al., 1979; Jumppanen and Mattila, 1994). The content of P in the sediments is high, and a major part of this can be transformed into a bioavailable form (Virtasalo et al., 2005; Puttonen et al., 2014). Thus, the sediments compose an extensive source of potential P release in the area.

2.2. Sampling of the sediment and water

Sediment and water samples were retrieved at 39 sampling stations in the Archipelago Sea in Finland (Fig. 1) during June–September 2010,

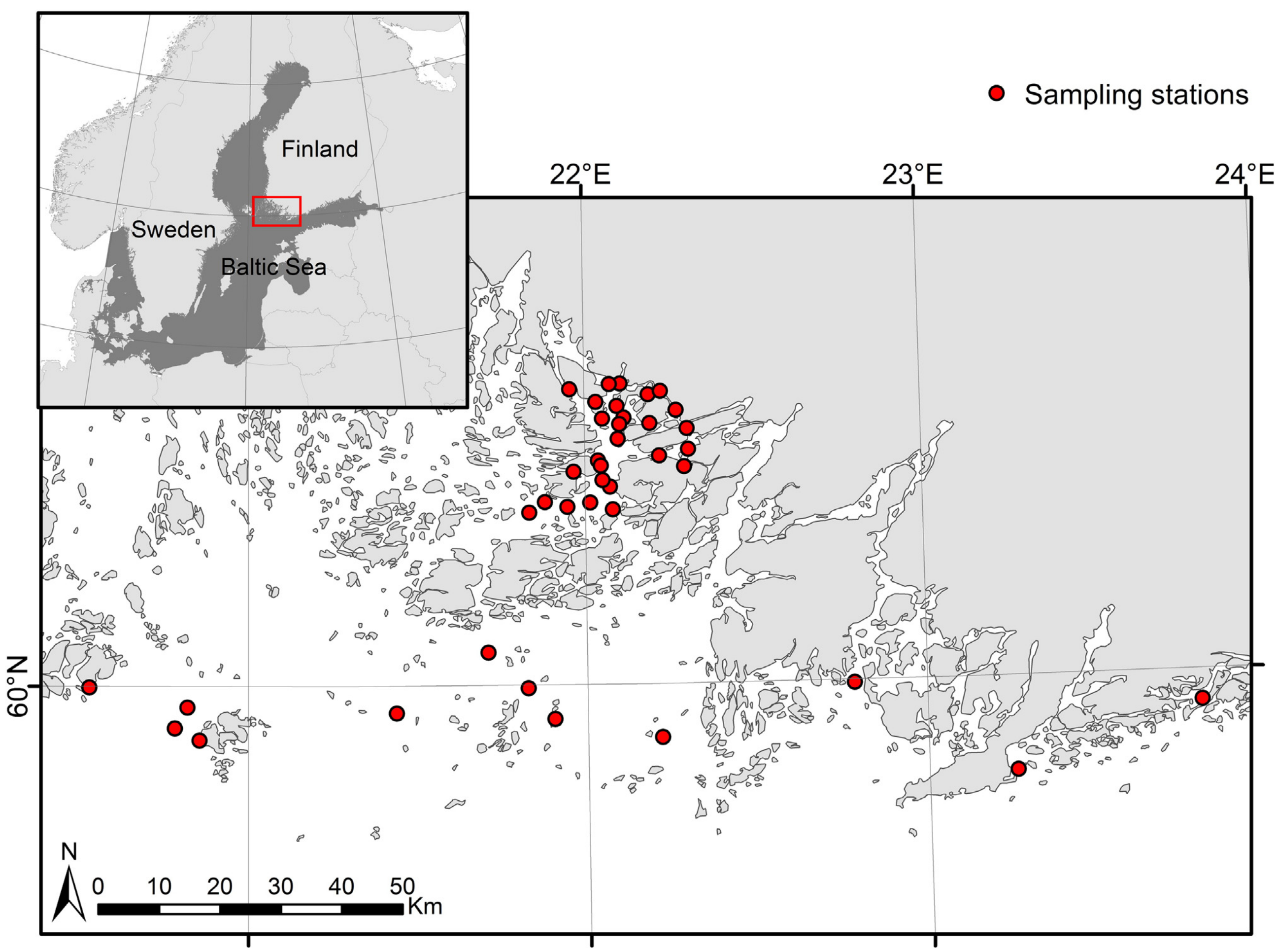

Fig. 1. The study area and the sampling stations are located in the Finnish Archipelago Sea, which is part of the Baltic Sea. Sediment and water samples were collected at 39 stations during 2010–2012.