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Eutrophication and sediment denitrification in coastal marine waters, the example of Kiel Bight

P. Kähler

Institut für Meereskunde an der Universität Kiel
Düsternbrooker Weg 20, D-2300 Kiel, Germany

Abstract

Denitrification rates were measured by the acetylene blockage method in the various sediment types occurring in Kiel Bight, namely sand, muddy sand, and mud, during the course of almost two years. Nitrate concentration in the sediments was found to be the major factor controlling denitrification. The source of the nitrate is nitrification in the sediments themselves. Nitrification there is mainly controlled by oxygen supply. In this way, the anaerobic process of denitrification indirectly requires oxygen. Anoxic muds have hence the lowest, oxic sands the highest denitrification rates. Effects of eutrophication like increased supply of nitrogen and organic matter to the sediments and the increased incidence of anoxia in the bottom water tend to reduce denitrification in such a situation.

Introduction

The issue of eutrophication in coastal waters in which combined nitrogen is most often limiting to plant growth has prompted research into denitrification since by this process plant-available combined nitrogen (nitrate) is transformed into the largely inert nitrogen gas; thus denitrification counteracts eutrophication. Performed by aerobic bacteria which use nitrate to oxidize organic matter only in the absence of the otherwise preferred oxygen, denitrification has three basic requirements: the availability of nitrate and organic matter and the absence or scarcity of oxygen (PAYNE 1981). This combination of factors exists in surface sediments and therefore the study of denitrification in coastal waters concentrates on their sediments.

The intensity of the three factors mentioned is closely related to the extent of eutrophication: where the sea is fertilized with nitrate an increase in the production and sedimentation of organic matter is likely to increase the oxygen consumption of the sediments, and to promote the formation of anoxic zones there and in bottom waters. Such a rise in nitrate and organic matter coupled with a decline of oxygen would meet the demands of - and should enhance - denitrification. This general picture of a negative feedback loop - eutrophication limiting itself by promoting denitrification - has been advocated by a number of authors, and it was said to be working in the Baltic Sea as a whole (RÖNNER

1985). In a study of denitrification in Kiel Bight sediments the system was found to operate in a different way. The results of the study are presented in detail elsewhere (KÄHLER 1990, KÄHLER and BALZER, ms. in preparation); in this paper some of them are discussed in their relation to eutrophication.

The study area: Kiel Bight is situated at the south of the Belt Sea, Western Baltic. Its sediments are made up of glacial till which is eroded at cliffs and in its shallowest waters leaving lag sediments there, the eroded material is deposited in deeper sediments. Sands dominate water depths down to 14 m; as the water becomes deeper the sediments become more finely graded reflecting the decreasing impact of waves with depth. Muddy sands are abundant in intermediate depths (14-24 m), sandy muds follow, and the greatest depths down to 30 m are the domain of muds (BABENERD and GERLACH 1987). The organic matter content (dry weight) increases from ca. 0.5 % in the sands to 5 % in the muds (BALZER et al. 1987).

Seasonality in the hydrographic regime with thermo-haline stratification of the water column prevailing from March to October and mixed waters during winter, with its consequences on nutrient dynamics, gives rise to phytoplankton blooms during spring and autumn. It is from these blooms that the sediments receive the bulk of their organic matter inputs (SMETACEK et al. 1987). During summer stagnation oxygen concentrations decline in the water over the sediments, most severely in the deepest parts where anoxia over the muds frequently occurs in late summer. An increase in the incidence of late-summer anoxia in the deep waters of Kiel Bight during the past decade has been discussed as a likely effect of eutrophication (GERLACH 1990).

Results and discussion

The denitrification rates measured in Kiel Bight (by the acetylene blockage method, Fig. 1) shows a marked seasonality linked to the events in the water column. There are pronounced maxima of denitrification in late spring, just after the buildup of water stratification, which coincide with the sedimentation of the

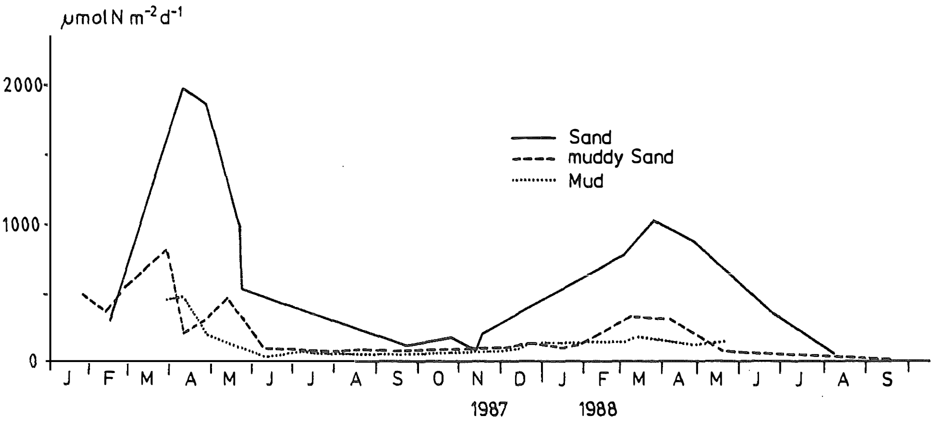

Fig. 1. Denitrification rates of sediments in Kiel Bight. Lines represent averages for sites of the respective sediment type.

spring phytoplankton bloom (trap measurements by SOMMER 1990). The rates are greatest in sands and smallest in muds. During the stagnation period they drop to near zero, most quickly in the sediments below the thermo/halocline (at ca. 17 m).

In the overall picture, the response of denitrification is contrary to two of its direct requirements mentioned above, namely organic matter and oxygen: The richer the sediments in organic matter, the lower their denitrification, and, concerning oxygen, denitrification almost ceases during periods of oxygen deficiency and peak denitrification occurs during times of oxygenated bottom water.

Nitrate concentration in the pore waters at the sediment surface correlated directly and closely with denitrification. Since nitrate was always more concentrated in the top sediment layer than in the bottom water, no transport of nitrate into the sediment from the overlying water by diffusive processes is assumed. The source of nitrate is in the sediments themselves; it is produced there by the nitrification of ammonium from the mineralization of organic matter. Nitrification, an autotrophic process, is independent of organic carbon and requires oxygen. With the supply of nitrate, i.e. the nitrification rate, determining the rate of denitrification, its inverse response to the factors organic matter and oxygen can be understood.

In the sequence of N-transformations leading to denitrification when coupled to nitrification (N_{org} --> NH_4 --> NO_3 --> N_2) organic matter is not only the source of carbon to the heterotrophic denitrifyers, but also the ultimate source of the produced nitrogen. There is evidence that in Kiel Bight nitrification is the limiting step in the sequence, and that this process itself is limited by oxygen availability: In the deeper sediments the supply and decay of organic matter is sufficient to meet the demands of nitrification as regards ammonium. In these sediments, oxygen consumption was found to be directly dependent on the oxygen content of the bottom water, and since nitrification is more sensitive to low oxygen concentrations than heterotrophic processes (HENRIKSEN and KEMP 1988) it can also be assumed to be controlled by the oxygen supply to the sediments only. In the sands, at first there is a stimulation of denitrification with organic material sedimenting in late spring, but soon this is reversed, and controls similar to those in the deeper-lying sediments operate. This is shown in Fig. 2 for the various sands studied in late spring. The relationship between oxygen consumption, i.e. the intensity of organic matter breakdown, and denitrification is negative; so is the relationship between ammonium content in the porewater and denitrification.

These findings are interpreted in the following way to yield a comprehensive conception of the control of denitrification in coastal sediments. Starting from sediments poor in organic matter an increasing supply of C_{org} increases denitrification as long as nitrification in the sediment is ammonium-limited. As nitrification becomes oxygen limited due to increasing oxygen consumption by heterotrophs, a further increase of organic matter supply suppresses nitrification for lack of oxygen and, with it, denitrification for lack of nitrate.

Two ways in which denitrification's limitation can be relieved are: 1. supply of nitrate to the sediments from the water column, and 2. high water turbulence ensuring a better oxygen supply. Note that where a stimulation of denitrification by increasing organic matter addition or nitrogen fertilization has been described, conditions were of either of these types (e.g. 1.: JÖRGENSEN and SÖRENSEN 1988, JENSEN et al. 1988, 1990; 2. BILLEN 1982, SEITZINGER and NIXON 1985).

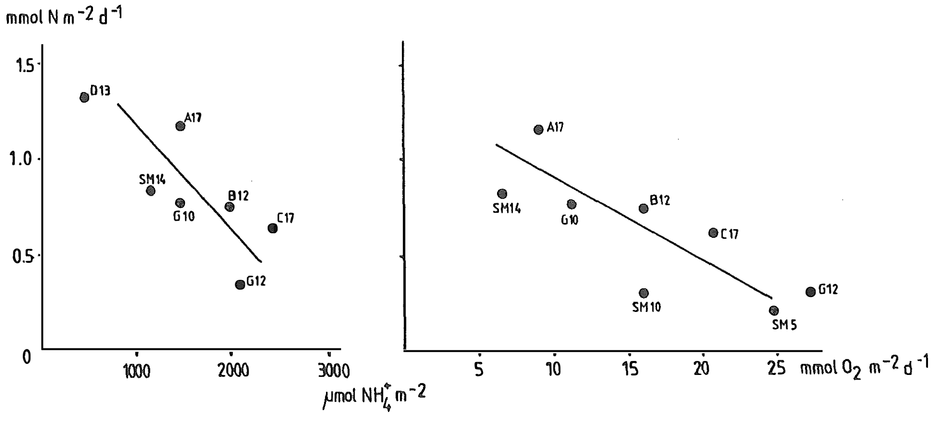

Fig. 2. Relationships between denitrification rates in sands during late spring and ammonium content (left) and oxygen consumption (right) in the denitrifying layer. Letters denote different localities in Kiel Bight, figures are water depth in meters.

In turbulent or nitrate-rich waters the organic-matter level at which an enhancement of sediment denitrification turns into a suppression would be high. In stagnant, nitrate-poor waters such as those of Kiel Bight this occurs at organic-matter levels considerably lower. It is concluded that an increase of the nitrogen load to Kiel Bight (increased eutrophication) will not be compensated for (not even partly) by an increased denitrification rate as has been observed in other coastal waters and has been postulated for the Baltic Sea as a whole. Likely effects of eutrophication such as the increase of biomass production with increased sedimentation of organic matter, and the increasing incidence of oxygen deficiency near the bottom, do in fact satisfy the direct demands of denitrifying organisms. But since these effects tend to counteract nitrification, they will also counteract the combined action of nitrifyers and denitrifyers which is at work in Kiel Bight sediments.

This conclusion is confirmed by the difference in the denitrification rates of spring 1987 and spring 1988 (Fig. 1). There is evidence that in spring 1988 organic matter production was greater than in the year before (ANONYMOUS 1989); oxygen levels in the water dropped much more quickly (own measurements), and denitrification was lower in all sediments.

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