A new project:

Kerteminde Fjord/Kertinge Nor: impact of nutrients from former sewage outlet *versus* present runoff from farmland

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Abstract:
The aim of this project is to evaluate the environmental impact of freshwater input of nutrients (N, P) versus release from sediment in Kerteminde Fjord and Kertinge Nor (Fig. 1). The design of the project is based on knowledge on the dynamic interplay between hydrography and key filter-feeding organisms, which is crucial for understanding the impact of suggested shutting down of surrounding farmland to reduce especially input of nitrogen to the fjord-system.

Aim of project

Sewage outlet from Munkebo and Kerteminde to Kerteminde Fjord and Kertinge Nor was stopped in late 1989, which reduced the annual land-based discharges of nitrogen (N) by 43%. In 1990 to 2003 the mean load was 110 t N/year, indicating that the annual load was 256 t N before stoppage of the sewage input. In 2024, the N load had further reduced to 50 t N, indicating a mean yearly reduction of (110/21 =) 4.8 t N, which indicates that the N-reductions has mainly been due to washout and denitrification of N stored in the sediment before 1990. Since, 1990, the external N load may solely or mainly have been due to runoff from surrounding farmlands, i.e. nitrate in streams from the catchment areas during winter (Riisgård et al. 2008). Due to the Green Tripartite Agreement (GTA, 18 November 2024), which is an arrangement between stakeholders to manage Denmark's agri-food transition, the load of N from farmlands to Danish fjords and coastal waters must be strongly reduced. In the case of Kerteminde Fjord and Kertinge Nor, the N-load should be reduced by 30 %, i.e. from present 42.3 t N/year to 12.7 t N/year by 2027 (Miljøministeriet/Vandområdeplanerne 2021-2027).

In the present project, we want to quantify the yearly input of mainly N (but also P) to the fjord-system from the freshwater catchment area to check if a 38% reduction obtained by taking farmland out of culture may result in the required reduction of 19 t N/year. Thus, by regular measuring the concentration of N (nitrate, ammonium) in the streams that run into the fjord-system (Fig. 2) and multiply the N-concentrations with the volume flow of each stream (current speed × cross sectional area of water stream), we get an estimate of the total input of

N to the fjord-system. If this is less than 19 t N/year the required goal cannot be fulfilled, and then the question is if the natural yearly reduction of 4.8 t N may over the years fulfil the environmental goal of 31 t N/year.

An important environmental parameter used by the environmental authorities to evaluate the water quality in marine areas is the concentration of chlorophyll *a*. In the case of Kerteminde Fjord and Kertinge Nor, the future goal/demand is 3.8 µg chl *a* l^{-1} by 2027. The mean conecntration in the years 2015-2019 was 5.0 ± 3.6 µg chl *a* l^{-1} (Fig. 6). The big variations during the year is caused by the interplay between hydrography and filter-feeding benthic ascidians that graze the phytoplankton (Fig. 5) and pelagic jellyfish that remove the grazing holoplanktonic copepods and other zooplankton (Fig. 4).

In the present project, we want to study if the high chlorophyl *a* concentrations may primarily be explained by release of N (ammonium) from the sediment during summer rather than by N (nitrate) washed out from the surrounding farmland during the winter. This load may then be compared to the demanded reduction of 19 t N/year. If the present N-load is significantly lower the environmental goal can not be obtained by taking out the surrounding farmland.

Execution of project

The project is based on two types of sampling cruises in the fjord-system, namely routine- and special cruises.

Routine cruises: water samples are taken every second week in the 3 freshwater streams with runoff water from the catchment area. The water is analysed for N to obtain concentrations of nitrate and ammonium. Further, the volume flow is estimated from measured current speed × cross-sectional of stream. This allows an estimate of total load of N with freshwater to the fjord-system at collection time, and by integration to give an estimate of total N input to the fjord-system in tons per year. Another, very conservative estimate may also be made from the know maximum freshwater input of 0.05 $m^3 s^{-1}$ multiplied by the highest measured N concentration in the streams.

Special cruises: when a great difference in salinity is measured on a routine cruise in the inlet to Kerteminde Fjord compared to measured salinity in Kertinge Nor, this triggers a special cruise where the hydrographical situation is mapped in order to measure chlorophyll *a* and take water samples for N and P analyses in both "new" and "old" seawater (cf. Figs. 4 & 5). This will make possible an evaluation of sources of N and P, and of the impact of key filter-feeders (ascidians and jellyfish) on the distribution and concentrations of chlorophyll *a*. An important aspect is knowledge about factors controlling the chlorophyl *a* biomass; is it nutrients from freshwater run-off or nutrients released from the sediment, or grazing impact by benthic filter-feeding ascidians?

Background, history and earlier studies

The fjord-system, catchments areas and water exchange

The fjord-system consisting of Kerteminde Fjord and Kertinge Nor covers an area of 8.5 km^2 and has a mean water depth of approximately 2 m and a maximum depth of 8 m (Fig. 1). The fjord has a sill at its mouth to the open sea (Great Belt). The discharge over the sill is forced by a diurnal tide with an average amplitude of approximately 20 cm. The tide gives rise to maximum discharges at the fjord entrance of 100 to 200 m^3 s^{-1}. The catchments areas to Kerteminde Fjord and Kertinge Nor are limited (1 % of the island of Fyn), 18.6 and 17.4 km^2, respectively, most of which is agricultural land and forests (Fig. 2). The freshwater input of <0.05 m^3 s^{-1} is negligible with respect to the water exchange of the fjord-system. The salinity in the central part of the system varies typically between 15 and 21 ‰ over the year.

Water exchange of the fjord-system is governed by density-driven circulation. The salinity in the Great Belt outside the fjord varies because of changing flow situations (Jürgensen 1995, Møller 1996). Outflow of water from the Baltic Sea gives salinities down to less than 10 PSU whereas inflow to the Baltic Sea gives salinities up to 27 PSU in the upper layer of the Great Belt. Because saline water is more dense than fresh water the salinity variations cause longitudinal density variations from the inner part of the fjord-system to the mouth, and density driven vertical circulation occurs. When dense water by tidal forcing is flushed over the sill it will flow down below the fjord water and give rise to a density driven circulation system within the entire fjord-system. When, on the other hand, light water is forced into the fjord the circulation is in the opposite direction. On an annual time scale the two circulation directions have equal probability. Because of the dynamics of the exchange processes the term 'residence time' is somewhat dubious in this fjord-system. An approximate time scale for the residence time for the water in the central areas of the system lies between one week and a few months, with an average of approximately 1.5 month (Jürgensen 1995).

Stoppage of sewage outfall and decrease of N and P

The stoppage of the sewage outfall to the Kertinge Nor/Kerteminde Fjord fjord-system during the last part of the 1980s meant that land-based nutrient loads markedly fell. Thus, annual land-based discharges of nitrogen and phosphorus were reduced by 43 and 92 %, respectively, when comparing the 1976-89 and 1990-2003 means. Since 1990, the nutrient loads have almost solely been due to diffuse sources, which imply that they covary with the freshwater run-off. The significant load-reductions down to 110 tons N and 1.2 tons P (mean 1990-2003) made the fjord-system suitable for studying effects of nutrient reduction on its recovery from eutrophication, as the obtained reduction nearly fulfilled the objectives of the first Danish Action Plan of the Aquatic Environment, the so-called APAE 1 from 1987 (Fyn County 2001), of 49 % reduction of N and 80 % reduction of P.

The dramatic decrease in the P-load is clearly reflected in the annual means of phosphate in Kertinge Nor (Fig. 3). The decrease discern able for the N-load is less pronounced, and the actual annual load varies with more than 100 %, dependent on the freshwater run off. The annual means of nitrogen in Kertinge Nor show large fluctuations and no temporal trend, but to some extent seem to follow the annual fluctuations in N-load. This may reflect that both the relative importance and the temporal changes in load are secondary. Thus, the inter-annual variations in N-load are still noticeable and the mean reduction of lesser magnitude compared to the P-reduction.

The mean seasonal variation in inorganic nutrients in Kertinge Nor is shown in Fig. 3. Thus, the seasonal variation of inorganic nitrogen is typical with high concentrations during winter, up to about 600 µg N l^{-1}, and a progressive depletion of the pool with low concentrations, often potentially limiting for the phytoplankton, during summer. The inorganic phosphate concentrations peak during summer at about 25 µg P l^{-1} where the release from the sediment is high due to a depletion of the oxidized iron pool to which the phosphate is bound.

There are generally two biomass peaks of phytoplankton in Kertinge Nor, as reflected in the seasonal chlorophyll-*a* cycle (Fig. 3), one in spring and one in late summer/autumn. The seasonal primary production pattern is typically more distinct with a clear peak in mid-summer (Fig. 5). This peak is displaced in relation to the later biomass peak which presumably reflects the grazing patterns (see below).

Key organisms in Kertinge Nor

Jellyfish. In Kertinge Nor the maximum diameter of the umbrella of *Aurelia aurita* is usually only a few centimetres, although high abundances of such small jellyfish (up to several hundred per m^3 of water) control the zooplankton biomass (Olesen et al. 1994, Riisgård et al. 1995, Frandsen and Riisgård 1997). The implications of density-driven currents for the interaction between *Aurelia aurita* and zooplankton, and thus the phytoplankton were studied in the Kertinge Nor by Nielsen et al. (1997). It was found that the local population of jellyfish is highly influenced by the density-driven circulation created by the frequent salinity changes in the adjacent Great Belt. When new water of either higher or lower salinity enters the fjord, changes in the jellyfish distribution are apparent. The time it takes for the jellyfish to enter a new water mass of higher or lower salinity has been found to be dependent on the degree of changes in salinity. The disappearance of incoming holoplanktonic copepods from the Great Belt occurred simultaneously with the conquest of the new water mass by the jellyfish (Fig. 4). The filtering activity of the *A. aurita* population was able to keep the zooplankton biomass low (mean residence time of a zooplankton organism varied between 10 and 20 h) and a negligible zooplankton grazing explain why the chlorophyll *a* concentration may increase markedly during a few days of rapid growth when the benthic filter feeding *Ciona intestinalis* are uncoupled due to stratification (cf. Riisgård et al. 1996b, 1998). The occurrence of *A. aurita* in different hydrographical situations showed that the density of jellyfish was always highest in the "old" fjord water (Nielsen et al. 1997, Goldstein and Riisgård 2016, Lüskow and Riisgård 2016).

Benthic filter feeders. The realisation of the benthic filter feeders grazing potential is highly dependent on currents and mixing of the overlying water. Grazing impact is enhanced by the turbulent mixing of the water mass due to wind-, wave- and current action, coupling the benthic filter feeders to the pelagic biomasses. However, the grazing ascidians, *Ciona intestinalis*, in Kertinge Nor may be restricted by stratification of the water body caused by salinity differences as frequently seen in the Great Belt. The stratification reduces or even prevents the supply of algae across the interface, decoupling the benthic filter feeders from the pelagic biomass. Thus, a key to the understanding of spatial and time dependent variations in pelagic biomasses (chlorophyll-*a*) is knowledge of the circumstances under which coupling/decoupling of benthic filter feeding take place. The hydrodynamic conditions in Kertinge Nor have been studied in detail by Riisgård et al. (1996b, 1998). The focus of these studies was on the importance of density-driven currents in determining the grazing impact of *C. intestinalis*. Thus, it has been observed that the grazing behaviour of *C. intestinalis* may at times be restricted to a boundary-layer flow created by these currents which are, in turn controlled by the varying hydrographic situation in the surrounding open sea (Fig. 5).

Nutrient fluxes

Rysgaard et al. (1995) studied seasonal variations in oxygen and nutrient fluxes, and denitrification in the shallow (0.5 m) southernmost part of Kertinge Nor with sandy sediment colonized by benthic microalgae and burrowing zoobenthos. Oxygen dynamics in the upper sediment layers were controlled by the microalgae and there was a net flux of O_2 out of the sediment during spring and autumn and a reduced efflux of NH_4^+ and PO_4^{3-} from the sediment to the water during daytime. Denitrification based on NO_3^- from the water column (D_w) only occurred in winter and spring, when NO_3^- was present in the water column, and activity was proportional to the water column NO_3^- concentration. Coupled nitrification-denitrification (D_n) in the sediment was stimulated by the O_2 production during winter and spring, at which times NO_3^- and NH_4^+ were present in the water column in high concentrations. In contrast, during summer, when the concentration of NO_3^- and NH_4^+ in the water column was low, benthic microalgae inhibited D_n by competing with nitrifying bacteria for NH_4^+. D_w accounted for 80 % of the total denitrification during winter, while on an annual basis, D_w and D_n each accounted for 50 % of the total denitrification activity. For further explanation and discussion, se Appendix 1.

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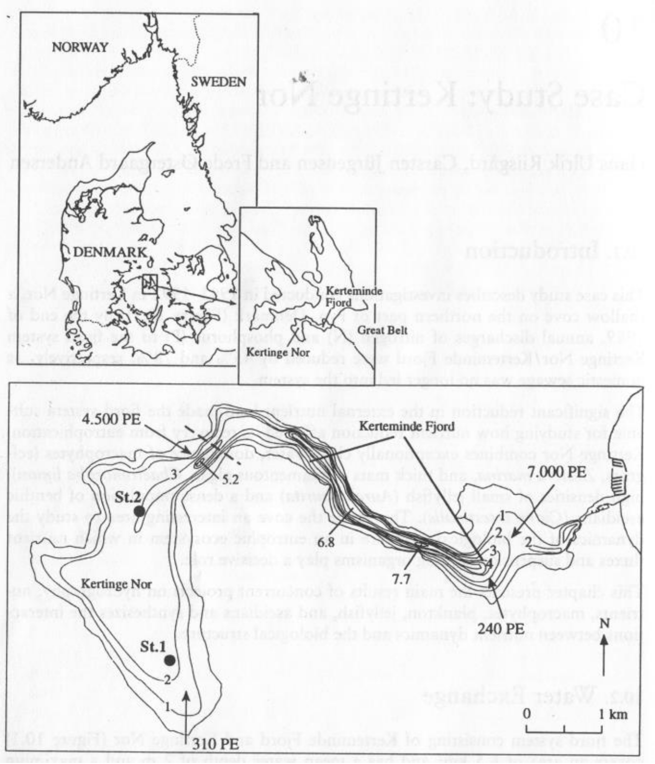

Fig. 1. Map of Kerteminde Fjord and Kertinge Nor. Water depths (m) are shown, PE = person equivalents to the fjord-system in 1989, before sewage reduction. From Christensen et al. (1992).

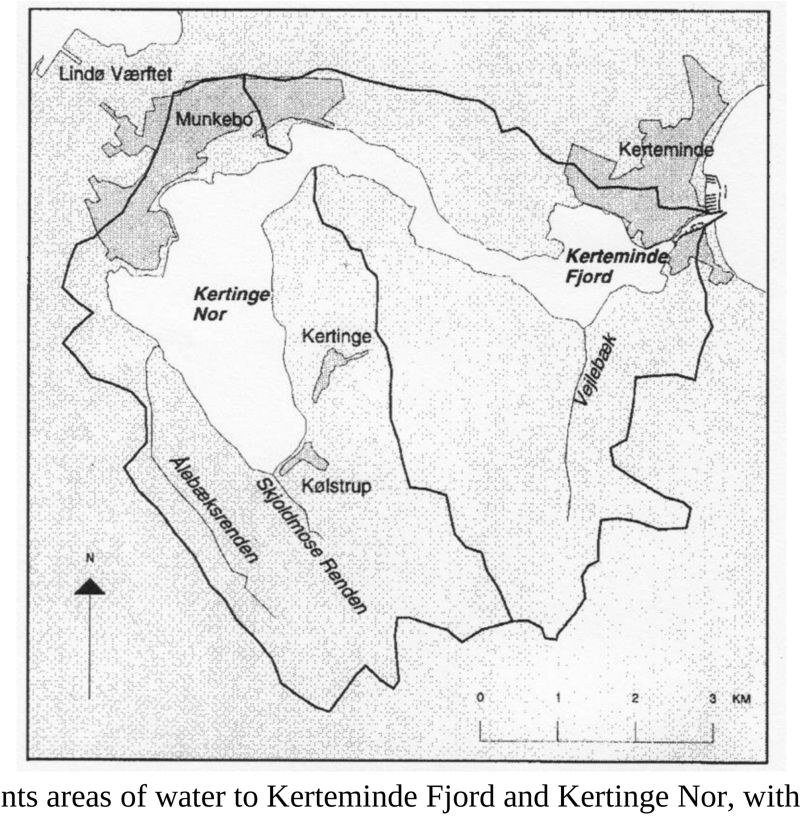

Fig. 2. Catchments areas of water to Kerteminde Fjord and Kertinge Nor, with 18.6 and 17.4 km^2, respectively. Freshwater input to Kertinge Nor comes from two streams, Skjoldmose Renden and Ålebæksrenden. From Christensen et al. (1992).

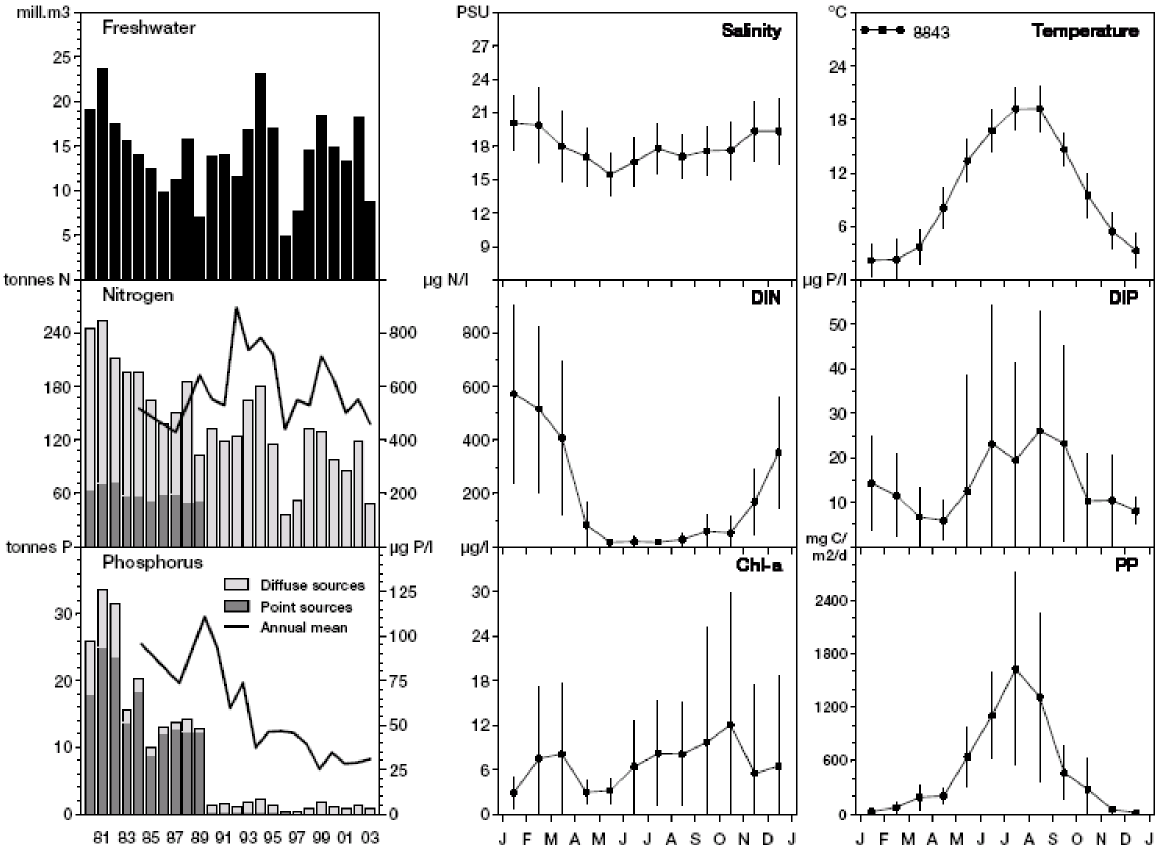

Fig. 3. (Left column) Freshwater, nitrogen and phosphorus run-off to Kertinge Nor and Kerteminde Fjord, annual means of total nitrogen (TN), and phosphorous (TP) at 2.7 m water depth in the central part of Kertinge Nor, 1980-2003. The nitrogen and phosphorus run-off are source-apportioned into point sources (mainly industrial and municipal wastewater) and diffuse sources (mainly run-off from agricultural land). (Right columns) Temperature, salinity (PSU), dissolved inorganic nitrogen (DIN) and phosphate (DIP), chlorophyll-*a* and depth-integrated primary production (PP) at 2.7 m in Kertinge Nor; data are monthly means ± SD (1989-2003) in surface water, except primary production (1998-2003). From Riisgård et a. (2008).

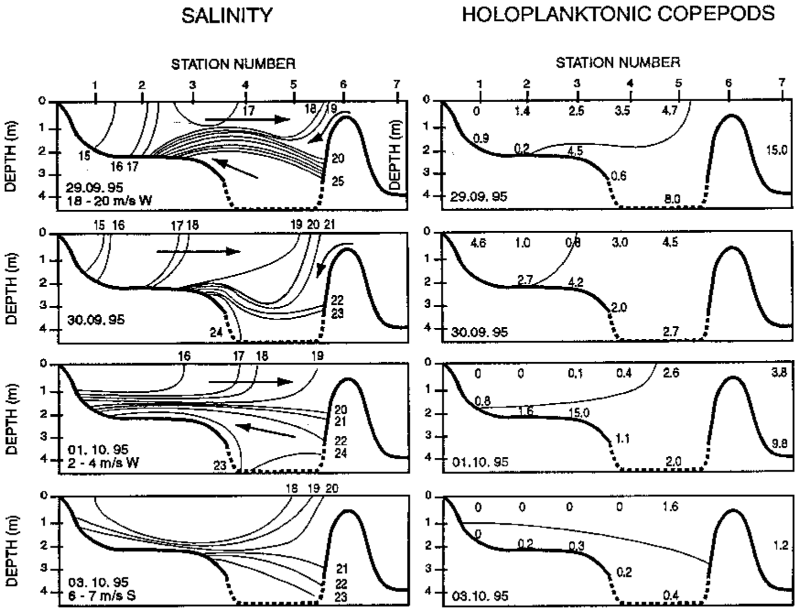

Fig. 4. Hydrographical situations (sketches on left side) and the biomasses (µg C l^{-1}) of holoplanktonic copepods (right side) on 4 days between 29 September 1995 and 3 October 1995. Wind speed and direction is indicated, and arrows show the direction of density-driven water circulation in the fjord. From Nielsen et al. (1997).

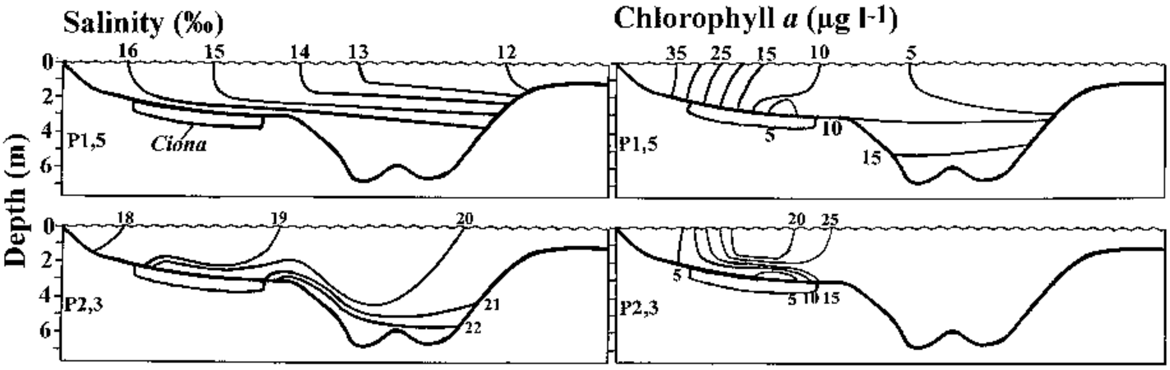

Fig. 5. Iso-lines for salinity and chlorophyll *a* in Kerteminde Fjord/Kertinge Nor on two days (P1,5 and P2,3) in late summer 1994. The area populated with *Ciona intestinalis* in Kertinge Nor is indicated. On the first day, salinity observations (upper left) suggest that a 0.5 m thick near-bottom density-driven current was flowing northwards along the bottom. The upstream chlorophyll-*a* concentration, measured to be 36 µg l^{-1}, was reduced to a downstream concentration of 5 µg l^{-1} by passing over the *C. intestinalis* bed. On the second day (lower), no density-driven current was detected. The stratification, which uncoupled the benthic filter feeders, caused low chlorophyll-*a* concentrations in the near-bottom water. However, above the halocline, a phytoplankton bloom was developing. From Riisgård et al. (1996b).

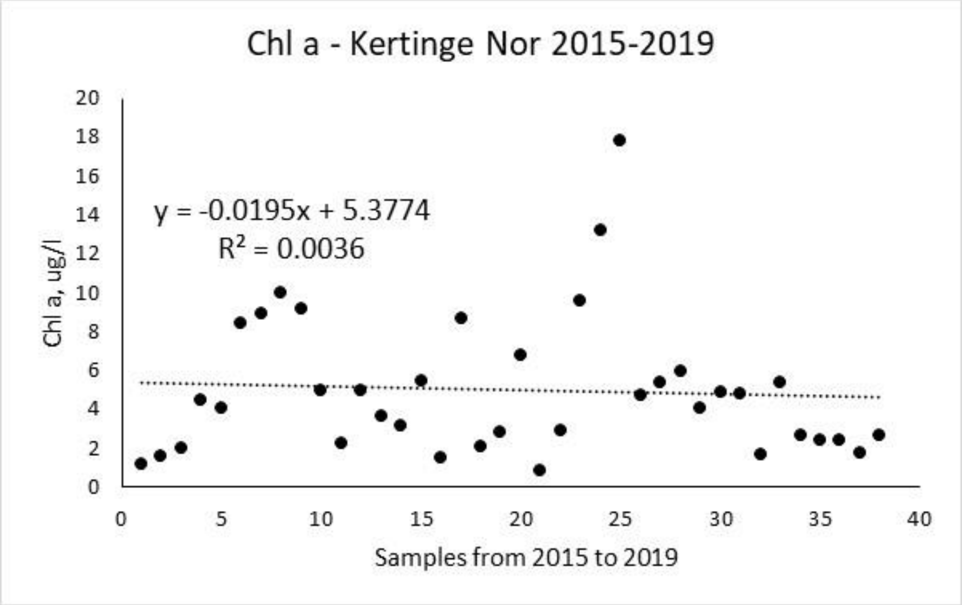

Fig. 6. Concentration of chl a measured about two times per months in May to September during 2015 to 2019. The mean conecntration was 5.0 ± 3.6 µg chl *a* l^{-1}, which is higher than the new environmental demand of 3.8 µg chl *a* l^{-1}. Data from the Danish national monitoring programme.

Appendix 1:

About nitrogen in nature, based on Riisgård (2017).

When plants die and decompose or are eaten by animals the proteins are transported through the food chains and the amino groups ($-NH_2$) of the amino acids are split off and released to the surroundings as ammonia (NH_3) or excreted in the urine as urea. This process is called *deamination*. Ammonia and ammonium (NH_4^+) are a corresponding acid-base pair. At pH 7, the concentration of ammonium is about 200 × higher than the concentration of ammonia. Ammonium does not leach out very easy because the positive charge allows it to bind to the negatively charged particles of clay and humus in the soil. Nevertheless, the nitrogen compounds leach because the ammonium ions can be oxidized to nitrite (NO_2^-) of chemoautotrophic bacteria (*Nitrosomonas*). Nitrite can be further converted to nitrate (NO_3^-) by other bacteria (*Nitrobacter*). The conversion of ammonia to nitrite and further to nitrate is called *nitrification.* Under anaerobic conditions, nitrate is reduced to free nitrogen (N_2) by a process known as *denitrification*, which is performed by the bacterium *Pseudomonas denitrificans*: glucose + $NO_3^- \rightarrow CO_2 + N_2$ + 2387 kJ.

Thus, when organic material breaks down in farmland, ammonium (NH_4^+) is released and bound to negatively charged soil particles. But due to nitrification ammonium is converted to nitrate (NO_3^-) which is mobile in the soil and can therefore leach out into the sea where it may accumulate during winter and subsequently cause a boom of phytoplankton in the spring, which lasts until all the nitrate has been used up. Later, when the phytoplankton settle and die on the bottom this may cause oxygen depletion and subsequent release of ammonium from de decaying organic matter in the sediment. In this way, however, it is possible to discriminate between “new” N (nitrate) and “regenerated” N (ammonium) in the sea. In Kertinge Nor “regenerated” N may primarily come from breakdown of old organic material produced before the sewage outlet from Munkebo was stopped in 1989.