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Long-term coastal monitoring data show nutrient-driven reduction in chlorophyll



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ABSTRACT

In this study we have compiled a long-term monitoring dataset from the inner Oslofjorden and supplemented it with short-term research data from the same station. Using generalized additive models analysing the data from this time series, we have examined how chlorophyll-*a*, hydrography, and various nutrient concentrations have changed during 1973–2017 and how they correlate. We describe the seasonality in chlorophyll-*a*, nitrogen, phosphorus, Secchi-depth, temperature and salinity and how the levels of each variable have changed the last forty years. The results show specifically how levels of chlorophyll-*a* have decreased significantly and how this correlates with decrease in nitrogen and phosphorus levels. Our results show a significantly positive correlation between chlorophyll-*a* and phosphorus during spring bloom and between chlorophyll-*a* and nitrogen during autumn bloom. However, phosphorus levels have increased again during the last 20 years, but chlorophyll-*a* levels are still low, indicating that the chlorophyll-*a* level currently may be controlled by the continuous decreasing trend in nitrogen. If nitrogen increase again, the chlorophyll-*a* level may also begin to increase. The impact of increasing temperature and possible change in starting point for the growing season should be studied further.

1. Introduction

Eutrophication is a major threat to coastal marine ecosystems worldwide, and has been known as such for more than 50 years (Ryther and Dunstan, 1971). Increased supply of nutrients to the ecosystem causes increased phytoplankton production and can lead to reduced surface water quality (Nixon, 1995; Paasche and Erga, 1987). Sinking plankton biomass can further contribute to oxygen consumption and thereby lower oxygen levels in the deeper basins (Cloern, 2001; Staalström, 2015). Eutrophication may also lead to an increased occurrence of toxic algal blooms (Heisler et al., 2008).

Phytoplankton seasonality is primarily controlled by light, nutrient availability, and stratification. In temperate marine environments, phytoplankton phenology is dominated by two bloom events (Longhurst, 1995). During winter, when growth is limited by light and water masses are unstable, the density of phytoplankton is low. Spring bloom starts when increased daily irradiance and increased stratification cause phytoplankton to grow rapidly in the upper mixed layer on nutrients supplied by prior turbulence and convective mixing of the

upper water column (Erga and Heimdal, 1984; Kristiansen et al., 2001; Sverdrup, 1953). The spring bloom ends by combined effects of nutrient depletion, grazing, and sometimes viral control (Erga, 1989; Kristiansen et al., 2001; Larsen et al., 2004). In the inner Oslofjorden, as in other Norwegian fjords, it is also common to have a second bloom in May or June when snow is melting in the highlands and nutrient-rich melting water is reaching the coast (Paasche and Erga, 1988). The autumn bloom occurs when and if seasonally increasing vertical mixing (convective cooling and winds) renews the nutrient supply in the euphotic zone before light availability becomes limiting (Findlay et al., 2006; Paasche and Ostergren, 1980).

The water quality of the inner Oslofjorden is believed to have improved significantly from the 1960s until today and the fjord, which was found polluted and unattractive by the general public until the 1990s can be considered a summer paradise today with appealing beaches and swimming facilities close to the city centre (Baalsrud and Magnusson, 2002). The fjord is used both for transportation and recreation for a growing population, and it is the main recipient of wastewater for the city of Oslo, the capital of Norway. Records from as

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early as the 1900s describe increased phytoplankton abundance attributed to the supply of nutrients in the near city and the harbour areas (Braarud, 1969). The release of wastewater sewage into the fjord increased dramatically after the introduction of water closets around 1900, and the first sewage plant (Skarpsno) was built in 1911. This sewage plant provided only physical cleaning, but later Skarpsno was the first sewage treatment plant with chemical removal of nutrients (phosphorus), which was introduced in 1975 (Baalsrud and Magnusson, 2002). From this time and onwards, more sewage plants were built, and gradually more of the wastewater was collected and treated. Nitrogen removal by biological treatment was established in the first plant (VEAS) in 1997, and the last one (Bekkelaget) in 2000 (Baalsrud and Magnusson, 2002).

Eutrophication impact on the phytoplankton community in the Oslofjorden has been documented through surveys from the early 1900s (see Braarud, 1969). An extensive survey was carried out by the University of Oslo in 1933–34, which showed that the seasonal patterns of phytoplankton were very different in the inner and outer parts of the fjord and that this was caused by the nutrient loads (Braarud, 1945). An extensive study conducted in 1962–64 documented that the upper water column was heavily eutrofied, and nutrient supply from land-based activities was one of the main sources causing this problem (Munthe-Kaas, 1968). Therefore a monitoring program of the water quality in inner Oslofjorden started in 1973 and is still ongoing (Lundsør et al., 2018; Magnusson and Källkvist, 1974a).

Maintaining a good environmental status is one of the major prerequisites for the ecosystem to be able to provide the necessary habitat for marine organisms (Dickey-Collas et al., 2017). Knowledge about the dynamics of the phytoplankton community and phenology is a prerequisite for the understanding of processes and drivers of changes in the marine ecosystem (Johannessen, 2014). Chlorophyll-*a* is commonly used as a proxy for phytoplankton biomass and as an indicator of environmental status. Chlorophyll-*a* levels above a specified threshold (area-specific) are an indication of reduced water quality. The EU Water Framework Directive (WFD, 2000/60/EC) has set a requirement that water should be of “good” to “very good quality,” as measured by various ecological parameters (Borja et al., 2010). Norway adopted the WFD in 2000, and the Norwegian Environment Agency published the first national guidelines in 2013. The evaluation of the ecological status of pelagic waters of the inner Oslofjorden in 2018 (Lundsør et al., 2018) states that chlorophyll-*a* levels qualify for “good to moderate” ecological conditions by the WFD (Direktoratgruppen vanddirektivet, 2018).

Increased knowledge about the causes of observed changes in chlorophyll-*a* is fundamental for the management of the Oslofjorden and other coastal waters under pressure. To determine if such changes are caused by anthropogenic pressures or by natural variability is, however, difficult in habitats with high variability in salinity, temperature, and light (Elliott and Quintino, 2007), and require long-term observations of chlorophyll-*a* as well as potential drivers of the changes. Therefore we have used data from the monitoring program and previous research projects where chlorophyll-*a*, nutrients and hydrography data have been collected for 45 years. This time series provides a unique opportunity for studying and better understanding the effects of climate and eutrophication on changes in chlorophyll-*a*.

This study aimed to understand how chlorophyll-*a* levels have changed over time and investigate the causes of these changes. In particular, we wanted to determine how nutrient levels, together with temperature and salinity, control chlorophyll levels through the year (seasonality) and over the years. To accomplish these goals, we used generalized additive models (GAM) and determined how the key environmental variables temperature, salinity, Secchi depth, and various nutrient concentrations have changed with the season and over the years. This knowledge is necessary to understand how anthropogenic impact contributes to eutrophication and changes in phytoplankton biomass, which is fundamental for knowledge-based long-term

management of temperate fjord systems.

2. Material and methods

2.1. The study area

The inner Oslofjorden is a sill fjord of 190 km² size (Baalsrud and Magnusson, 2002). The connection to the more open outer Oslofjorden and Skagerrak is through the narrow sound of Drøbaksundet, where the sill is as shallow as 19.5 m. North of the Drøbak sill more sills divide the fjord into several basins, such as Vestfjorden, Bærumsbassenget, Bekkelagsbassenget, and Bunnefjorden. This bathymetry is a constraint to efficient deep-water renewal (Magnusson and Berge, 2015; Staalstrøm, 2015) that takes place in the inner Bunnefjorden basin only on average every 3–5 years (Baalsrud and Magnusson, 2002). In Vestfjorden, the deep-water exchange takes place every year.

Rivers and streams are the major sources of new bioavailable phosphate in the fjord, but the contribution from sewage treatment plants and overflow runoff is also significant (Vogelsang 2011). The limited deep-water exchange makes the fjord especially vulnerable to pollution, especially of nutrients and organic matter that may lead to high levels of oxygen consumption in the deep-water (Staalstrøm, 2015).

The Oslofjorden is a relatively sheltered area with calm weather. The prevailing winds are southerly or south-westerly in the summer and northerly during winter (Baalsrud and Magnusson, 2002). Long periods of northerly winds are favourable for water exchange since such winds pull the surface mixed layer southwards, thereby producing a water deficiency that facilitates the influx of oxygen-enriched, saline, and heavy Atlantic water northwards along the bottom and pass the sills. Climate changes seem to lead to weaker or shorter periods of these northerly winds that impact the frequency of deep-water exchange (Thaulow and Faafeng, 2014).

2.2. Compilation of historical water quality data from the inner Oslofjorden

The monitoring program of the inner Oslofjorden presently covers 22 stations. The sampling station Dk1 is one of the two major stations that are visited on all surveys and with the longest time series of data collected. It is situated in Vestfjorden at N 59.8149 E 10.5694 (west of the islands “Steilene”) and is 100 m deep (Fig. 1). The compilation of historical data was conducted in collaboration between Norconsult, University of Oslo and Norwegian Institute for Water Research (NIVA). The data used in this study are the variables temperature, salinity, nutrients, Secchi depth, and chlorophyll-*a* from monthly surveys. Water sampling methods have been either by a hand-held water sampler, Niskin water bottles attached to a CTD-rosette lowered to the sampling depths or a 2 m plastic Ramberg sampler for an integrated 0–2 m sample (Lundsør et al., 2018; Magnusson and Källkvist, 1974a).

Over time there have been different sampling regimes, and chlorophyll-*a* has been sampled at different standard depths, ranging from 0, 0–2, 4, and 5 m. We here used data from 0 m, which is the most common sampling depth in our material.

2.3. Hydrography, nutrients, and chlorophyll-*a*

Water samples have been collected from station Dk1 in the inner Oslofjorden by NIVA for “Fagrådet for vann- og avløpsteknisk samarbeid i Indre Oslofjorden” (Fagrådet) for most years since 1973 and by Norconsult for the years 2015–2018 (see Fig. 2 for data overview). Most data used were already digitalized, but the remaining were compiled from written reports in this study. For the years 1980–1981, Svein Kristiansen provided data from a study by Paasche and Kristiansen (1982).

Chlorophyll-*a* samples were analysed by a standard spectrophotometric method (Dahl and Sørensen, 1981) from early 1980s using

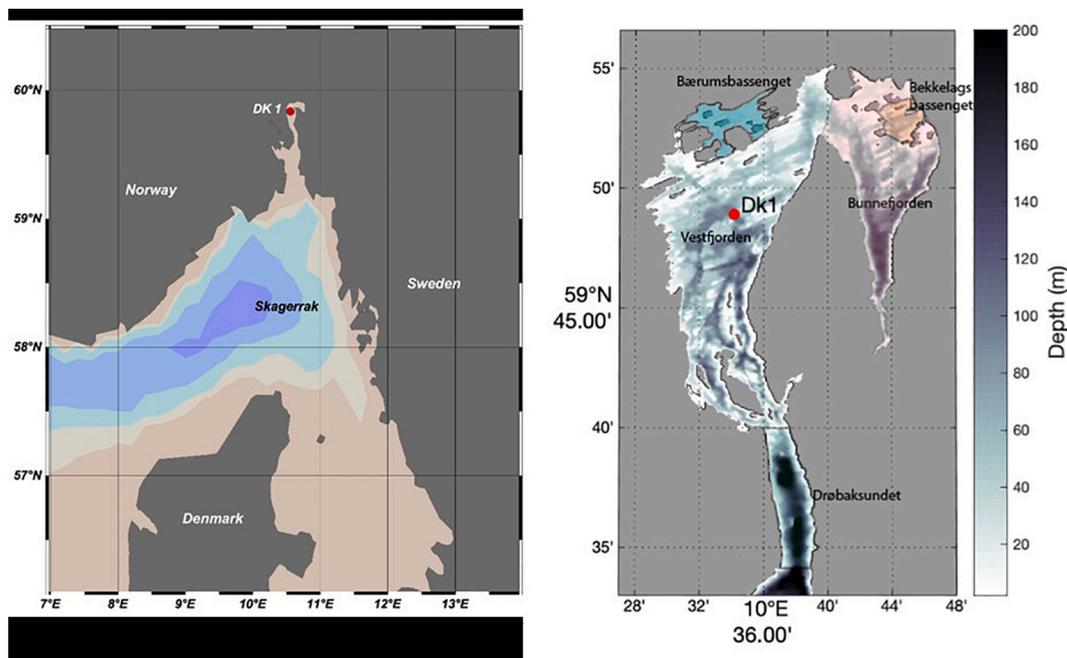


Fig. 1. Sampling station Dk1 (Steilene) in the inner Oslofjorden, Norway, a fjord of the Skagerrak.

a 90%-acetone extraction with homogenisation of the extract. This became later the Norwegian Standard NS 4766 (NS4766, 1983). Before 1980s NIVA used mainly in vitro fluorometric methods, either a FM3 or a Turner filterfluorometer, which were calibrated with the 90%-acetone spectrophotometric method using algal cultures. From 1989 the NS4766 method was replaced with the spectrophotometric 100% methanol extraction method following the Norwegian Standard NS4767 (NS4767, 1983) (Kai Sørensen, pers.com.). We here analysed the data on ln-scale ($\log\text{Chl} = \ln[\mu\text{g/L chlorophyll-}a]$) to homogenize the variance.

Water for analyses of nutrient and chlorophyll-*a* concentrations was collected together and mostly from the same sampling bottles, which means that time and place are the same. The water samples were analysed in the laboratory by NIVA (1973–2014) and ALS Scandinavia in Oslo (2015–2018). The methodology for the analysis of dissolved, inorganic, and organic concentrations of total nitrogen (N) and total phosphorus (P) used from 1973 to 1984 (P) and to 1993 (N) was photo-oxidation with ultraviolet radiation (Henriksen, 1970). The Norwegian standard spectrophotometric methods for determination were implemented in 1984 for phosphorus and 1993 for nitrogen (NS 4725 and NS 4743). We here analysed data on ln-scale ($\log\text{N} = \ln[\mu\text{M total N}]$, $\log\text{P} = \ln[\mu\text{M total P}]$), as we expected the response variable in the analysis, $\log\text{Chl}$, to be linearly related to $\log\text{N}$ and $\log\text{P}$.

Sea surface temperature (SST, °C) was measured with a reversing thermometer until CTD measurements were used from 1985. Sea Surface Salinity (S, practical salinity units, PSU) was measured from water samples with a laboratory salinometer (Magnusson and Källkvist, 1974b) until 1985 when salinity was estimated from conductivity measured by CTD. We here analysed data on ln-scale ($\log\text{S} = \ln[\text{S}]$) to avoid undue large influence from a few low values. Secchi depth (Secchi, m) is measured by lowering a disk into the water and measuring what depth the plate becomes invisible, lowering further and hauling it up until it is visible again. The average depth of the two observations is measured by a standard white disk of approx. 30 cm in diameter. Measuring Secchi depth is a useful tool for checking vertical visibility in the water, and is used as a supplement to other variables in order to describe the water quality (Aas et al., 2014; Direktoratgruppen vann-direktivet, 2018). We here analysed data on ln-scale ($\log\text{Secchi} = \ln[\text{m}]$) as we expected a linear relationship between $\log\text{Secchi}$ and $\log\text{Chl}$.

2.4. Statistical analyses

2.4.1. Quantification of trends

To quantify and describe the seasonal and interannual trends in chlorophyll-*a*, nutrient levels and hydrographical factors, a non-parametric regression analysis was performed. Generalized additive models (GAMs) were used as implemented in the mgcv-package version 1.8–26 (Wood, 2017) in the statistical programming environment R version 3.5.1 (R Core Team, 2017).

Three models with different levels of complexity were considered for each response variable. The alternative response variables were $\log\text{Chl}_t$, $\log\text{Secchi}_t$, $\log\text{N}_t$, $\log\text{P}_t$, $\log\text{S}_t$ and SST_t (in Eqs. (1)–(3) referred to by the generic notation X_t). The subscript *t* refers to time.

The predictor variables were day of the year (*D*) and year (*Y*). Model M1 (Eq. (1)) shows average seasonal patterns with the assumption of no trends between years:

$$X_t = a + f(D_t) + \varepsilon_t \quad (1)$$

Here, *a* is an intercept, *f* is a smooth function of *D* (a cyclic cubic spline, whose ends match to wrap the last day of the year to the first one in a seasonal cycle), and ε is an independent and normal distributed error term. Model M2 (Eq. (2)) includes trends between years but has the assumption of no changes in seasonal patterns over the years:

$$X_t = a + f(D_t) + g(Y_t) + \varepsilon_t \quad (2)$$

Here, *a*, *f* and ε have the same interpretation as in Eq. (1) but are estimated separately from that model, and *g* is a smooth function of *Y* (a thin plate regression spline, i.e., the default spline function in the mgcv package). Model M3 (Eq. (3)) includes seasonal and interannual trends and allows for possible changes in seasonal patterns over the years:

$$X_t = a + h(D_t, Y_t) + \varepsilon_t \quad (3)$$

Here, *h* is a two-dimensional tensor product smooth function of *D* and *Y* (a tensor product of two basis functions: a cyclic cubic spline function of *D* and a thin plate regression spline function of *Y*).

2.4.2. The relationship between chlorophyll-*a* and environmental variables

In the second part of the analysis, we investigated how variation in nutrients and hydrographical variables could explain the variation in

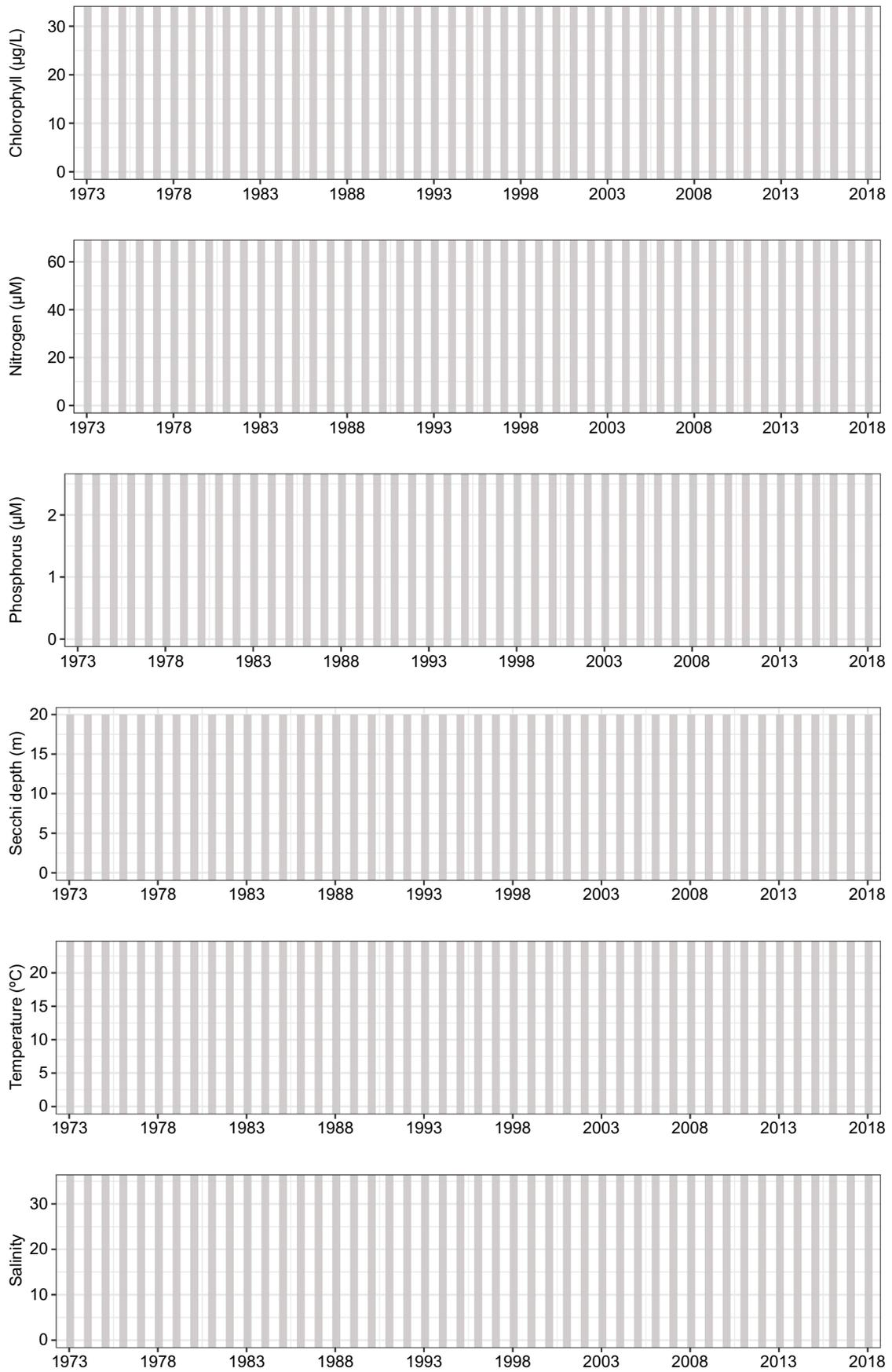


Fig. 2. Hydrographical surface data from station Dk1, inner Oslofjorden, Norway, used in this study. Dark areas indicate winter season from October to March.

chlorophyll-*a* levels. Model M4 (Eq. (4)) shows the seasonal correlation between levels of chlorophyll-*a* ($\log Chl$), phosphorous ($\log P$) and nitrogen ($\log N$):

$$\log Chl_t = b + k(D_t) + m(D_t) \cdot \log Pc_t + n(D_t) \cdot \log Nc_t + \varepsilon_t \quad (4)$$

Here, b is the intercept, k , m and n are smooth (cyclic cubic spline) functions of D , $\log Pc$ is $\log P$ centred by subtracting the mean, and $\log Nc$ is $\log N$ centred by subtracting the mean. The function $k(D_t)$ gives the seasonal trend predicted for $\log Pc = 0$ and $\log Nc = 0$, that is, for mean values of $\log P$ and $\log N$. The functions $m(D_t)$ and $n(D_t)$ give the season-dependent coefficients for, respectively, the effects of $\log Pc$ and $\log Nc$ on $\log Chl$. These two functions thereby show how the interannual correlations between $\log Chl$ and $\log P$ and between $\log Chl$ and $\log N$ change through the season.

Model M5 (Eq. (5)) shows associations between chlorophyll-*a* and nutrients as well as temperature and salinity:

$$\log Chl_t = c + o(\log N_t, \log P_t) + p(T_t, \log S_t) + \varepsilon_t \quad (5)$$

Here, c is the intercept, and o and p are two-dimensional smooth functions (tensor products of thin plate regression spline basis functions). This analysis was restricted to the part of the year when nutrients could be limiting the growth (day 100–300, April to October), as indicated by positive correlations between nutrient levels and $\log Chl$ according to the results of model M4. In addition to the full model (Eq. (5)), we considered reduced models with either of the two-dimensional smooth functions omitted or replaced by one-dimensional thin plate regression spline smooth functions, $r(\log N_t)$, $s(\log P_t)$, $u(T_t)$ or $v(\log S_t)$.

2.4.3. Model comparison and diagnostics

Alternative model formulations were compared based on the Akaike's Information Criterion (AIC) (Akaike, 1974), the generalized cross-validation score (GCV, Wood 2006), and the percentage of deviance explained (R^2). The AIC measures the trade-off between goodness-of-fit and model parsimony and the GCV is a measure of leave-one-sample-out prediction error. Models with low AIC and low GCV were preferred over models with higher AIC and GCV. Only differences in AIC of more than 2 were considered statistically significant. To assess if residuals were approximately normally distributed and homoscedastic, we inspected quantile-quantile normal plots of the residuals and plots of residuals versus each covariate; to assess for temporal dependency, we plotted the autocorrelation function of the residuals. To assess if multicollinearity among predictor variables led to serious variance inflation in models M4 and M5, we calculated the variance inflation factor (VIF). The VIF estimates how much higher the uncertainty of the parameter estimates is because of collinearity; high VIF (e.g., $VIF > 5$) indicates that predictor effects cannot be separated based on the data used (Sheather, 2009). For M4, we calculated the VIF for each month separately, based on month-specific linear models that jointly are equivalent to M4:

$$\log Chl_{t,i} = b0_i + b1_i \cdot \log Pc_{t,i} + b2_i \cdot \log Nc_{t,i} + \varepsilon_{t,i} \quad (6)$$

Here, $\log Chl_{t,i}$, $\log Pc_{t,i}$ and $\log Nc_{t,i}$ refer, respectively to mean values of $\log Chl$, $\log Pc$ and $\log Nc$ in year t and month i , $b0_i$, $b1_i$ and $b2_i$ are regression coefficients (corresponding to the smooth functions k , i and n in Eq. (4)), and $\varepsilon_{t,i}$ is an error term. For M5 we calculated the VIF for a simplified model compared to Eq. (5) with linear and additive effects of $\log N$, $\log P$, T and $\log S$.

3. Results

3.1. Overview of time series data

The sampling frequency and number of variables studied have varied slightly over time, depending on the aim of the surveys. Type of variables and sampling frequency at DK1, inner Oslofjorden are given in Fig. 2. The number of sampling events has varied from 5 to 22 per

year.

3.2. Seasonality and long-term trends

To determine seasonal and yearly changes in chlorophyll-*a* levels and the environmental variables, i.e., temperature, salinity, Secchi disk depth, and nutrient concentrations, we first analysed the data with day of year (D) and year as explanatory variables.

Three alternative models were tested and compared (Table 1). The comparison shows that season alone (model M1) explains 16.5% of the variation in chlorophyll-*a*, 94% in SST (sea surface temperature), and between 24 and 58% of the variation in the other variables. When also including changes over the years (model M2), R^2 increases for all variables and especially for chlorophyll-*a*, phosphorus, and nitrogen. At the same time, the GCV score is reduced, and AIC reduced with more than 2, which implies that there are significant changes between the years. However, for all variables except phosphorus, the model that also allows changes in seasonal patterns between years (model M3) is best fit to explain the variations. In comparison with the previous two, this model reduces GCV score and AIC with more than a factor 2. R^2 increases to between 33.5 and 95.4%. This shows that there are both changes between years and in seasonal patterns over the years.

3.3. Chlorophyll-*a* long-term trends

The seasonal and interannual trends in chlorophyll-*a* estimated from model M2 are shown on a logarithmic scale in Fig. 3a and b. The seasonal trends represent the average seasonality from all years monitored from 1973 to 2017. The model indicated a seasonal cycle with a spring bloom in March/April, an early summer bloom in June and autumn bloom in September (Fig. 3a). Fig. 3b shows that chlorophyll levels increased in the 1970s to a peak around 1980, decreased during the 1980s, and remained low from the 1990s to today. In the 1970s, the chlorophyll level was commonly around 20 $\mu\text{g/L}$ during the spring bloom and often above 10 $\mu\text{g/L}$ during summer months. Blooming levels in the last years were mostly below 6 $\mu\text{g/L}$ (Fig. 2a). The change over time was statistically significant, as evidenced by a reduction in AIC of more than 2 when comparing model M2 to model M1 (Table 1), as well as by the confidence bands of the year trend (Fig. 3b).

The best model in terms of AIC and GCV was the one assuming that not only has the overall chlorophyll-*a* level varied over the years but also that the seasonal pattern varied (i.e., M3, Table 1). This model shows that the relative magnitudes of the spring bloom, summer low and autumn bloom have varied over time, and also suggests a tendency of later spring blooms in later years (Fig. 3c, with estimated seasonal patterns in selected years shown in the supplementary Fig. S1).

3.4. Nutrients

The nitrogen model indicated a seasonal cycle with a constant decrease in the amount of total nitrogen from January until the last days of August (Fig. 4a), which coincided with the autumn bloom (Fig. 3). Fig. 4b shows that there has been a declining trend in the nitrogen level since 1982, and that the levels have continued to decrease throughout the investigated period. The change over time was statistically significant (Table 1, Fig. 4).

Similar to chlorophyll-*a* and Secchi depth, the best model in terms of AIC and GCV was the one considering that not only has the overall amount of total nitrogen varied over the years but also that the seasonal patterns have varied (i.e., M3, Table 1). Specifically, it appeared that summer levels of total nitrogen started to decrease already in the 1970s while the winter levels first started to decrease in the 1990s (Fig. 4c, Fig. S2).

The seasonal model for phosphorus (M1) indicated a seasonal cycle similar to nitrogen, with decreasing concentrations from the beginning of the year until September (Fig. 5a). However, for phosphorus, we see

Table 1

Generalized Additive Model (GAM) results of the three different seasonal models tested for each response variable (Eqs. (1)–(3)). Model M1 (Eq. (1)) shows average seasonal patterns with the assumption of no changes between years. Model M2 (Eq. (2)) includes changes through years but has the assumption of no changes in seasonal patterns over the years (i.e., effects of season and year are additive at the scale of the predictor-variable). Model M3 (Eq. (3)) shows both seasonal and yearly variations, allowing for changes in seasonal patterns over the years. Model performance was measured by the Generalized cross-validation (GCV) score, Akaike's Information Criterion (AIC), and percentage of deviance explained (R^2). All models are significant, with $p < .01$. The model with the lowest AIC and GCV is marked bold.

Response	Model M1			Model M2			Model M3		
	AIC	GCV	R^2	AIC	GCV	R^2	AIC	GCV	R^2
Chlorophyll-a	1310	0.827	16.5%	1251.8	0.735	27.7%	1227.8	0.706	36.5%
Secchi depth	802.1	0.168	24.2%	748.5	0.154	30.8%	740.1	0.152	33.5%
Phosphorus	496.5	0.212	43.1%	412.8	0.170	55.8%	422.9	0.176	58.0%
Nitrogen	190.8	0.099	32.1%	65.5	0.070	53.6%	61.5	0.069	55.7%
Salinity	-514.0	0.015	37.8%	-533.0	0.014	43%	-541	0.014	46.6%
SST	2260.5	2.623	94.1%	2230.4	2.494	94.5%	2166.9	2.247	95.4%

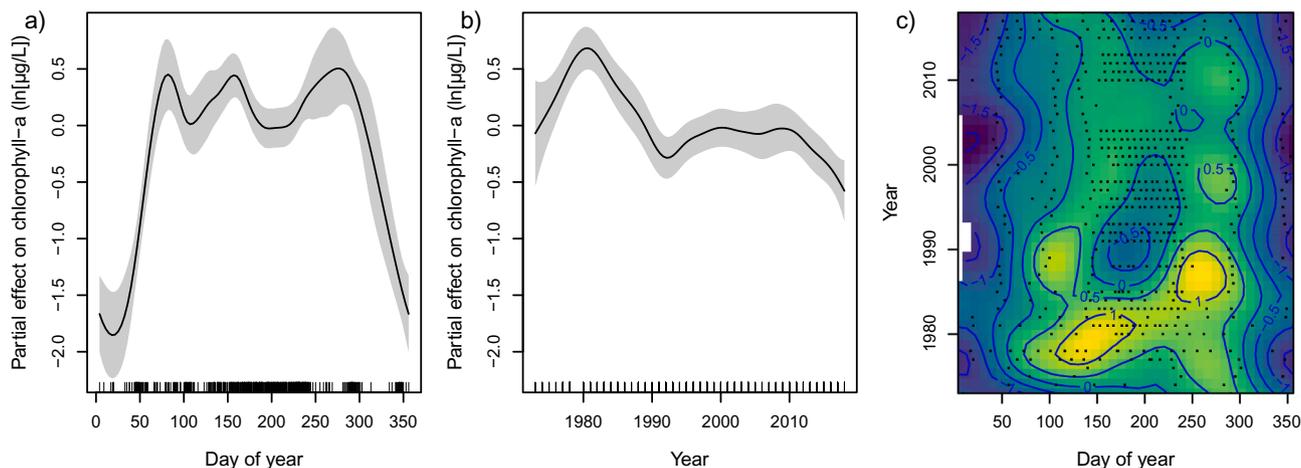


Fig. 3. Seasonal and yearly changes in chlorophyll-a level from 1973 to 2017 at station DK1 in the inner Oslofjorden estimated by model M2 (a and b) and M3 (c). Seasonal (a) and interannual (b) patterns are shown with 95% confidence intervals in grey. Combined seasonal and interannual patterns (c) are shown with lighter colours for higher levels of chlorophyll-a. The tick marks on the x-axes in panels a and b and the dots in panel c show the locations of the data. White areas in panel c are due to lack of data.

that the steepest decrease was from winter to April (Day 100), which coincided with the spring bloom (Fig. 3). Fig. 5b shows that there was a decline in the phosphorus level from 1973 to 1998 but that it has increased again after 2000. The change over time is statistically

significant (Table 1, Fig. 5).

As model M2 was the best in terms of AIC and GCV (Table 1), the results indicated that the seasonality of phosphorus levels has not changed to the same degree as for other variables presented here.

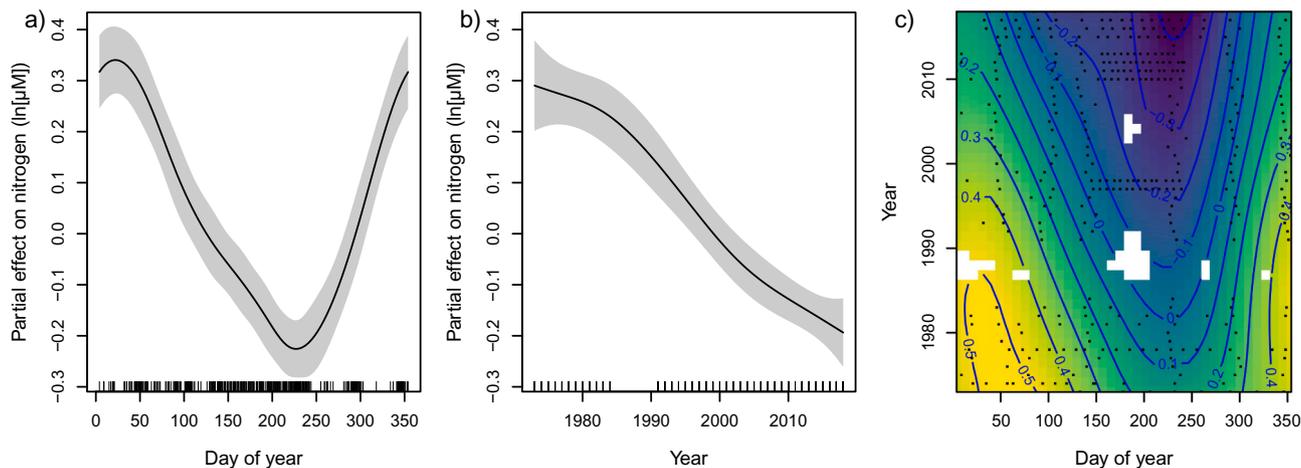


Fig. 4. Seasonal and yearly changes in nitrogen from 1973 to 2017 at DK1 (Steilene) in the inner Oslofjorden estimated by model M2 (a and b) and M3 (c). Seasonal (a) and interannual (b) patterns are shown with 95% confidence intervals in grey. Combined seasonal and interannual patterns (c) are shown with lighter colours for higher levels of total nitrogen. The tick marks on the x-axes in panels a and b and the dots in panel c show the locations of the data. White areas in panel c are due to lack of data.

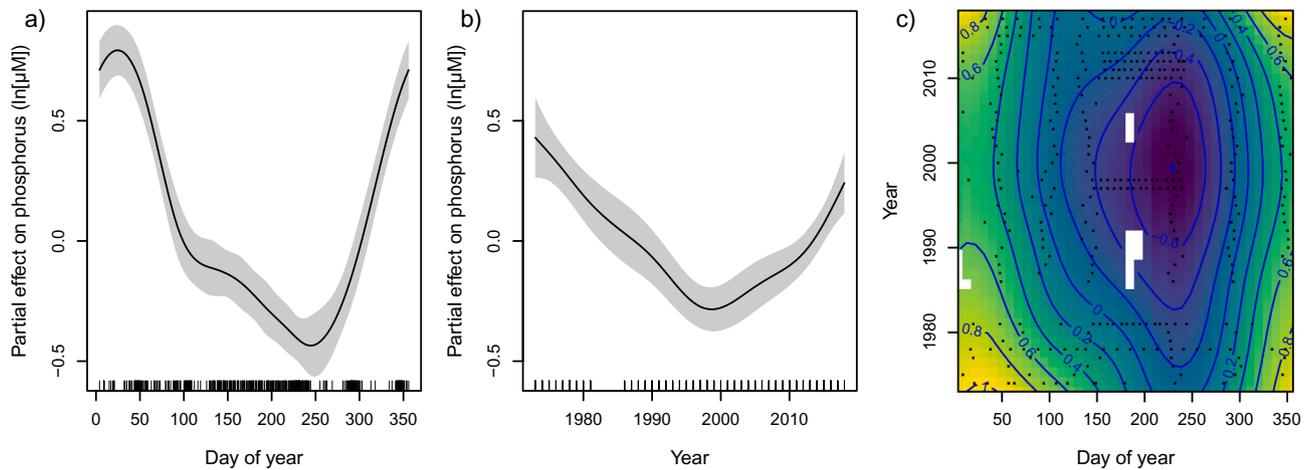


Fig. 5. Seasonal and yearly changes in phosphorus from 1973 to 2017 at DK1 (Steilene) in the inner Oslofjorden estimated by model M2 (a and b) and M3 (c). Seasonal (a) and interannual (b) patterns are shown with 95% confidence intervals in grey. Combined seasonal and interannual patterns (c) are shown with lighter colours for higher levels of total phosphorus. The tick marks on the x-axes in panels a and b and the dots in panel c show the locations of the data. White areas in panel c are due to a lack of data.

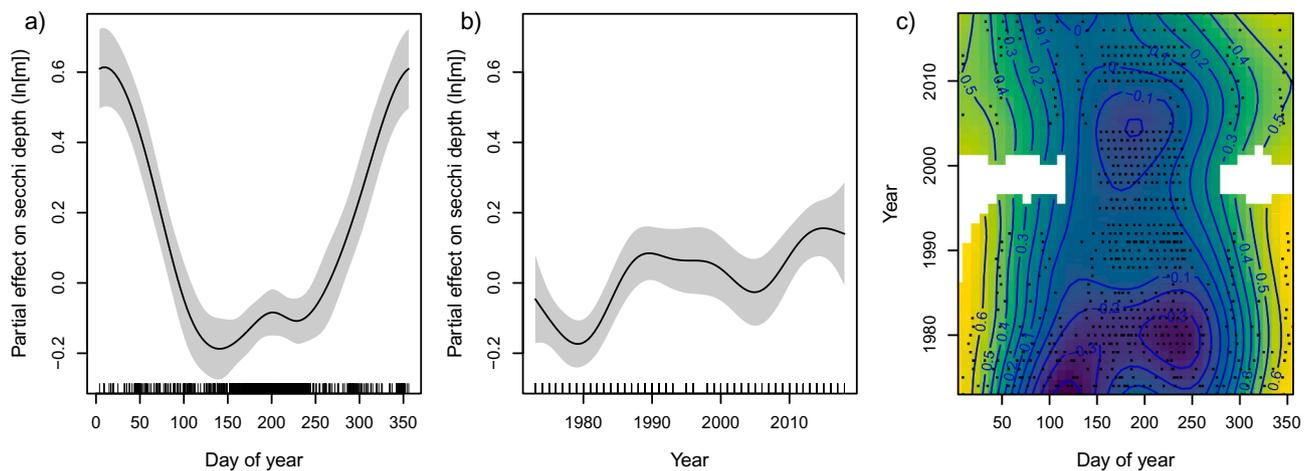


Fig. 6. Seasonal and yearly changes in Secchi depth from 1973 to 2017 at DK1 (Steilene) in the inner Oslofjorden estimated by model M2 (a and b) and M3 (c). Seasonal (a) and interannual (b) patterns are shown with 95% confidence intervals in grey. Combined seasonal and interannual patterns (c) are shown with lighter colours for higher levels of Secchi depth. The tick marks on the x-axes in panels a and b and the dots in panel c show the locations of the data. White areas in panel c are due to lack of data.

Consistent with this finding, we found that the phosphorus levels decreased in all seasons until 1998, when the levels started to increase again. Note that while the proportional changes were similar in all seasons, the changes in terms of μM phosphorus were largest in winter (Fig. 5c, Fig. S3).

3.5. Secchi depth

The analysis of Secchi depth data showed a seasonal cycle with decreasing Secchi depth from winter until the beginning of May, when the Secchi depth tended to be at the shallowest (Fig. 6a). The shallow Secchi depth was found to continue throughout the growing season with a slight increase during summer and a small decrease again during autumn bloom. Fig. 6b shows that there has been a trend towards deeper Secchi depth, starting in 1980. The best model in terms of AIC and GCV was the one considering that not only has the overall Secchi depth level varied over the years but also that the seasonal pattern varied (i.e., M3, Table 1). This model showed that the period with low Secchi depth in summer generally became shorter during the 1980s and 1990s, and also suggested a tendency of earlier increase in turbidity during the last ten years (Fig. 6c, Fig. S6. Comparison between yearly

pattern of Secchi depth (Fig. 3b) and chlorophyll-*a* (Fig. 3b) showed that there was an inverse relationship between these two variables, with low values for Secchi depth and high chlorophyll-*a* levels during the 1970s and 1980s, but in later years, generally but not always, coinciding with high chlorophyll-*a* levels.

3.6. Temperature and salinity

Sea surface temperature and salinity showed opposite seasonality, with SST increasing and salinity decreasing from winter to summer (Figs. 7a and 8a). Fig. 7b shows that there has been an increase in SST from 1973 to 2017. This change over time was statistically significant (Table 1, Fig. 7b). For salinity, the change over the years was statistically significant (Table 1) but with no clear long-term trend (Fig. 8b).

As for most of the other variables, the best models for SST and salinity were the ones considering changes over the years in seasonal patterns (i.e., M3, Table 1). These models suggested a tendency of more pronounced increase in winter than summer sea surface temperatures (Fig. 7c, Fig. S5), and variability between years in the timing of spring reduction and autumn increase in sea surface salinity (Fig. 8, Fig. S6).

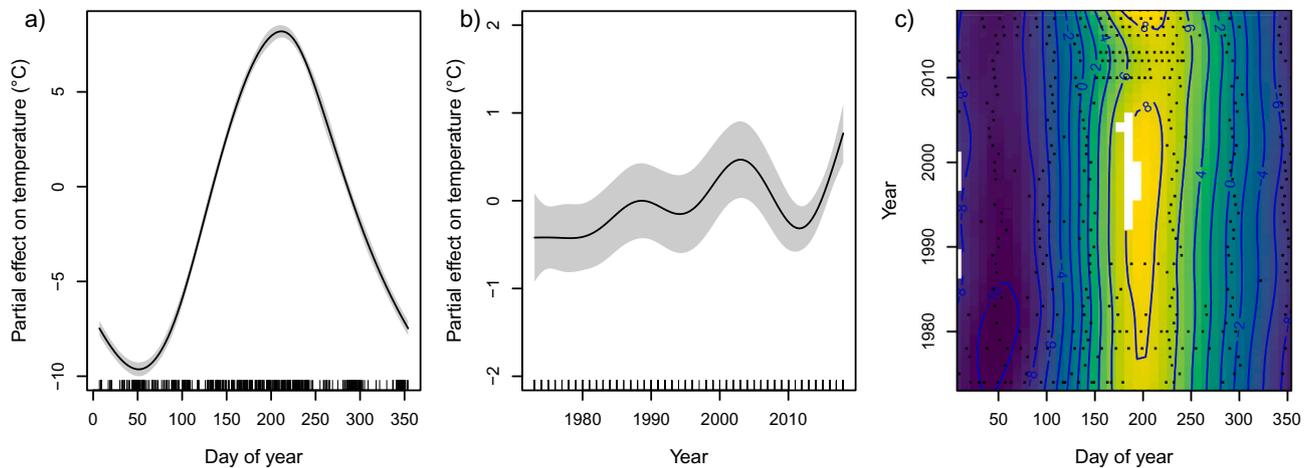


Fig. 7. Seasonal and yearly changes in sea surface temperature (SST) from 1973 to 2017 at DK1 (Steilene) in the inner Oslofjorden estimated by model M2 (a and b) and M3 (c). Seasonal (a) and interannual (b) patterns are shown with 95% confidence intervals in grey. Note the different y-axis scales. Combined seasonal and interannual patterns (c) are shown with lighter colours for higher temperature levels. The tick marks on the x-axes in panels a and b and the dots in panel c show the locations of the data. White areas in panel c are due to lack of data.

3.7. Correlation between chlorophyll-*a* and nutrient levels

The interannual correlation between the levels of chlorophyll-*a* and total phosphorus dependent on the day of year is shown in Fig. 9b. During the winter (October to February), there was a negative correlation that was changing to a strong positive correlation in April–May, which was the time just after the spring bloom. A significantly positive correlation in May was also shown by a linear model using only data from this month (Table S1). From June through November the correlation was close to zero. The total nitrogen levels showed a positive correlation with chlorophyll-*a* throughout the growth season (March–October) (Fig. 9c) and decreased slowly after that until the end of the growth period in October/November. The correlation between chlorophyll-*a* and total phosphorus was only significantly positive during the first blooming (spring bloom), while the positive correlation between chlorophyll-*a* and nitrogen was significantly different from zero from June to October. The magnitude of collinearity between the nutrient variables was checked by calculating the variance inflation factor (VIF). VIF was 2.15 for February and below 1.6 for all other months (Table S1), which is well below the cut-off value of 5 often used (Sheather, 2009).

3.8. Which environmental variables best explain the changes in chlorophyll-*a*?

The aim of the analysis using model M5 was to explore which environmental drivers were associated with the changes in chlorophyll-*a* over the years. The results showed that the full model, including total nitrogen, phosphorus, temperature as well as salinity as predictors of chlorophyll-*a*, was best in terms of GCV, AIC, and R^2 (Table 2). The interaction effect of total nitrogen and phosphorus showed that both these nutrients contributed to explain variations in chlorophyll-*a* and suggested that low levels of either nutrient could lead to reduced chlorophyll-*a* (Fig. 10a). The highest chlorophyll-*a* levels (bloom) were observed when both nutrients were at high levels. The interaction effect of SST and salinity showed that chlorophyll-*a* levels were low in typical winter situations when temperatures were low, and salinity was high. The highest chlorophyll-*a* levels were observed at temperatures around 10 °C and high salinities, which is typical for the spring situation when water is mixed and just starting to get stratified (Fig. 10b). The data available for this model are scarce, and it may be less robust than the previous models. VIF was below 2.6 for all variables (Table S2) which is below the cut-off of 5 and considered acceptable.

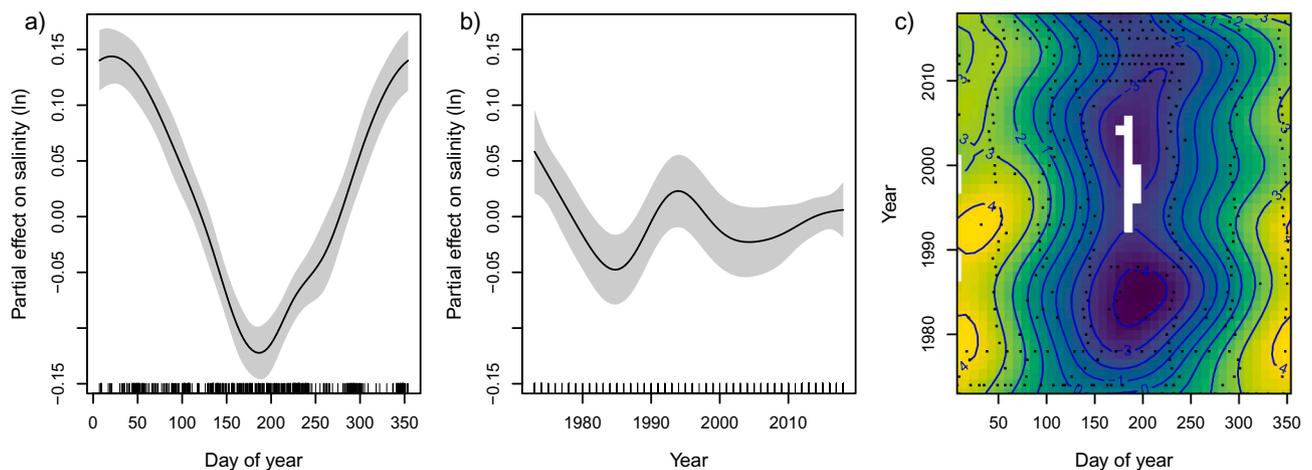


Fig. 8. Seasonal and yearly changes in sea surface salinity from 1973 to 2017 at DK1 (Steilene) in the inner Oslofjorden estimated by model M2 (a and b) and M3 (c). Seasonal (a) and interannual (b) patterns are shown with 95% confidence intervals in grey. Combined seasonal and interannual patterns (c) are shown with lighter colours for higher salinity levels. The tick marks on the x-axes in panels a and b and the dots in panel c show the locations of the data. White areas in panel c are due to lack of data.

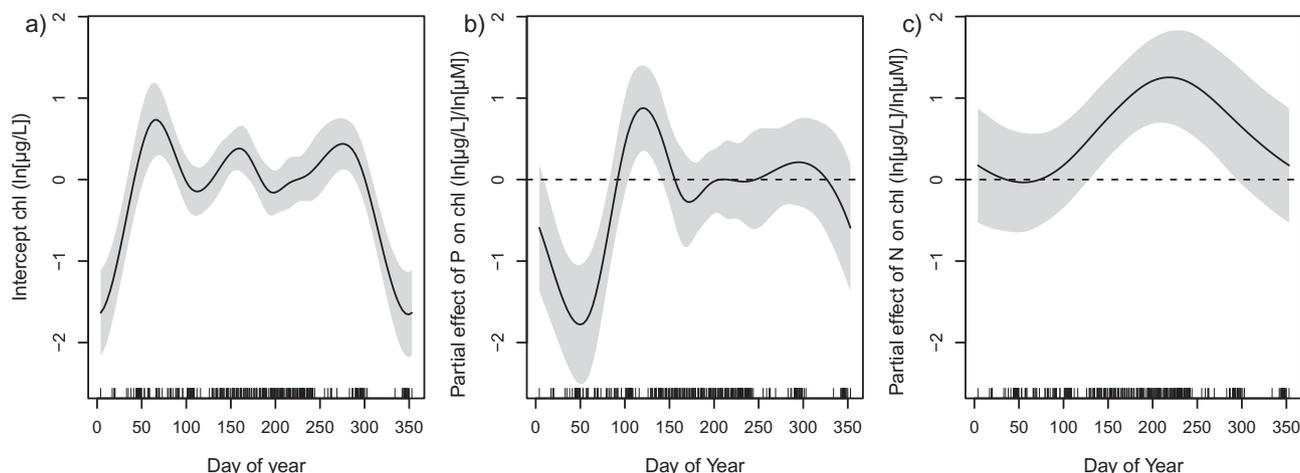


Fig. 9. Seasonally varying coefficient model showing the seasonal specific correlation between chlorophyll-a and total phosphorus (panel b) and nitrogen (panel c) estimated by model M4. Panel a) is the intercept. Panels b and c show the estimated ln-scale change in chlorophyll-a for one-ln-unit increases in, respectively, phosphorus (P) and nitrogen (N) compared to the long-term averages of ln(P) and ln(N) for a given time of year. The stippled lines show the location of zero, corresponding to no correlation between chlorophyll-a and P or N.

Table 2

Generalized Additive Model (GAM) results for effects of nitrogen (logN), phosphorus (logP), temperature (T) and salinity (S) on chlorophyll-a (logChl). The table shows Generalized cross-validation (GCV) score, percentage of variance explained (R^2 , %), and Akaike's Information Criterion (AIC) for the full as well as for reduced models (Eq. (5)). Only models with all terms statistically significant ($p < .05$) are shown. The best model is marked bold.

Predictor functions	GCV	R^2	AIC
$o(\log N_t, \log P_t) + p(T_t, S_t)$	0.499	37.4%	300.9
$o(\log N_t, \log P_t) + u(T_t)$	0.510	32.0%	304.5
$o(\log N_t, \log P_t)$	0.556	23.6%	316.8
$p(T_t, S_t)$	0.644	14.5%	337.3
$r(\log N_t) + p(T_t, S_t)$	0.513	32.6%	305.2
$s(\log P_t) + p(T_t, S_t)$	0.571	26.5%	320.1

3.9. Variability of predicted chlorophyll-a during five decades

To further explore the relative roles of nutrients (N and P) and physical factors (temperature and salinity) in explaining the changes in chlorophyll-a, we compared the observed trends in chlorophyll-a with three sets of predictions from model M5: from the full model, from a reduced model formulation with only nutrients as predictors, and from a reduced model formulation with only physical factors as predictors

(Fig. 11). We found that only model formulations that included nutrient variables (shown by red and green lines in Fig. 11) were able to explain the high chlorophyll-a levels in the 1970s and 1980s, and that physical factors alone could not explain this phenomenon. In contrast, a model with only temperature and salinity (blue lines in Fig. 11) showed similar chlorophyll-a levels in the 1970s and 1980s as in later decades. The physical factors mainly contributed to explain the seasonal pattern in chlorophyll-a levels, for example the increase from April to May, which was not explainable through nutrients alone (i.e., the nutrients-only model, shown by green lines in Fig. 11, predicted constant chlorophyll-a during these months).

4. Discussion

Changing from a fjord that was found dirty and unattractive by the general public, the marine pelagic environment of the inner Oslofjorden is believed to have improved significantly during the last thirty years. Data from the monitoring program compiled as far back as 1973 made it possible to study the changes in chlorophyll during this transition period and the possible drivers for these changes. Our analyses revealed that chlorophyll-a levels have been significantly reduced during the period 1980 to 1990 and that this reduction is most likely due to a major reduction in the supply of total nitrogen and phosphorus.

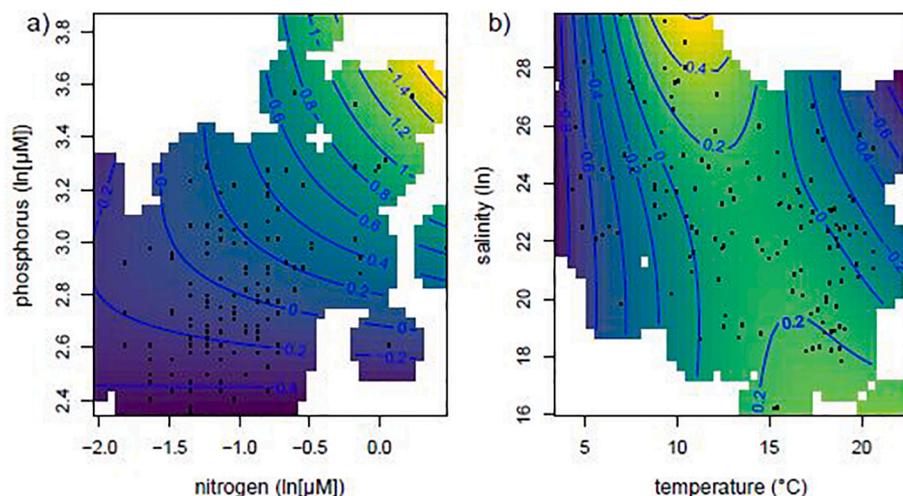


Fig. 10. Combined effects of nutrients (a) and temperature and salinity (b) for the levels of chlorophyll-a at DK1 (Steilene) in the inner Oslofjorden estimated by model M5. The plots are from the model with the best AIC and GCV scores, with 37% of variance explained. Chlorophyll-a levels are shown with lighter colours for higher levels. White area is due to a lack of data.

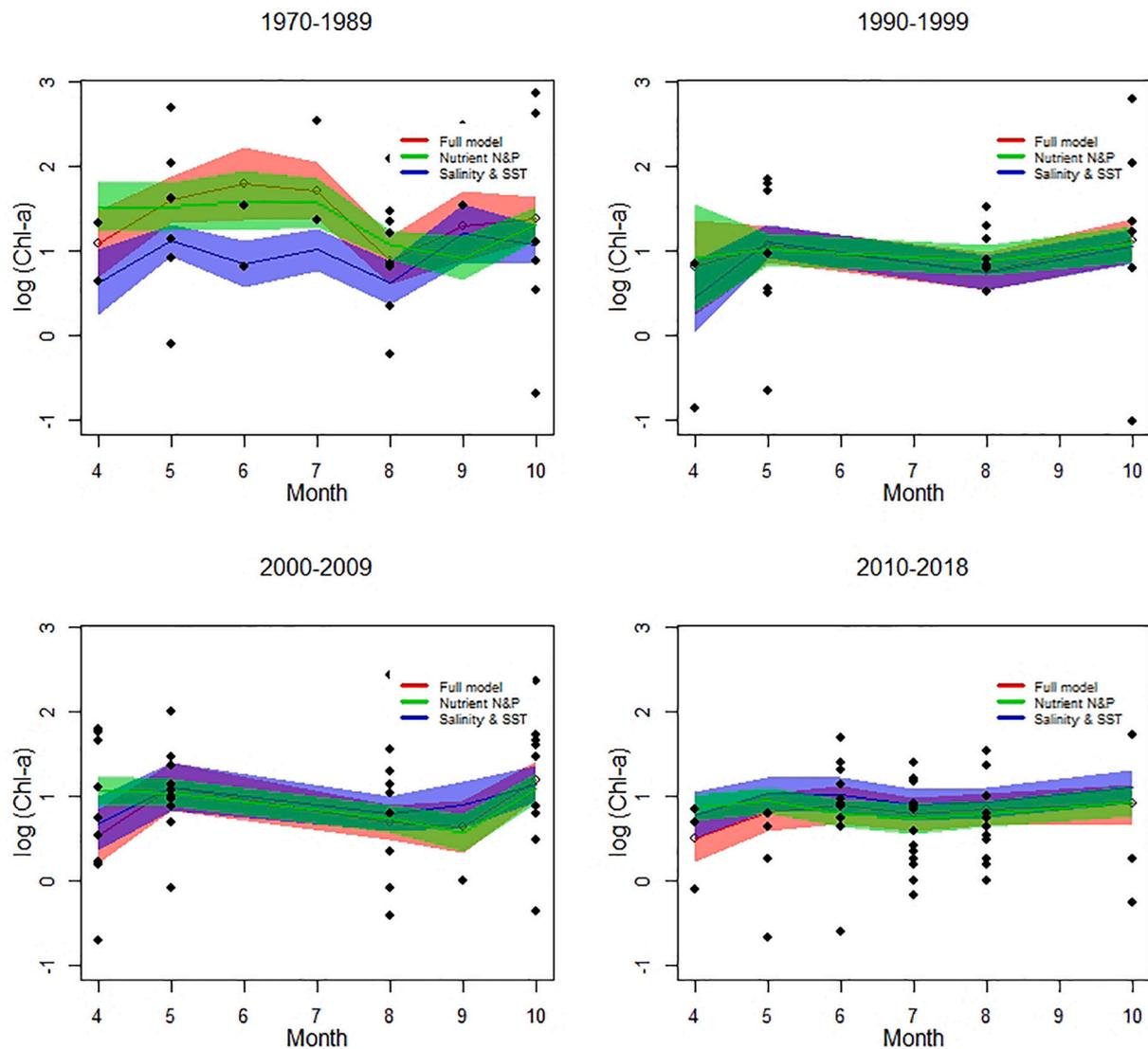


Fig. 11. Predictions of chlorophyll-a obtained from model M5 for the five decades covered by the time series. Red colour shows model predictions from the full model, green colour from a model formulation with only nutrients as predictors, and blue colour from a model formulation with only physical factors as predictors. Black points represent observed data from the relevant decade. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.1. Seasonality

The analyses of seasonal trends showed a strong seasonality in all parameters, as expected at high latitudes (Cloern and Jassby, 2010; Longhurst, 1995). There is a distinct spring bloom in March/April, when light conditions become sufficient, and often an early summer bloom in June and an autumn bloom in September, which is a common pattern in this and nearby areas, like the outer Oslofjorden (Aure et al., 2014; Paasche and Ostergren, 1980) and the Swedish Westcoast (Skjevik et al., 2011). The timing of the two latter blooms are however more variable than the first one. The main changes through the study period were found in the level of the blooms; while before 1990 the chlorophyll-*a* levels could reach 20 $\mu\text{g/L}$, it has only rarely exceeded 10 $\mu\text{g/L}$ thereafter. Our analyses also indicated that there has been a change towards a later onset of the growth season. This shift is possibly related to increased surface water temperatures (Fig. 7), however, increased temperatures are expected to lead to an earlier onset of the spring bloom (Desmit et al., 2019), while we have seen a possible delay. A prerequisite for the onset of the spring bloom is stratification of the upper water column and our analyses shows a slight seasonal change in

salinity, e.g. with the spring decline in salinity occurring later in the year after the 1980s (Fig. 8, Fig. S6). Salinity generally contributes more than temperature to the stratification in Oslofjorden (Staalstrøm et al., 2012). A delay of the spring bloom could also be related to darkening of coastal waters because of increased amounts of organic matters in the freshwater discharge into the fjords (Opdal et al., 2019). It could also be caused by top-down control by zooplankton (Behrenfeld and Boss, 2014) that hypothetically survive in higher numbers during warm winters.

Our analyses showed a stronger positive correlation of chlorophyll-*a* with phosphorus than with nitrogen in April–May when the chlorophyll-*a* levels are decreasing after the spring bloom and nutrient levels are declining. This finding indicates that year to year trends in chlorophyll-*a* levels at this time of year were best explained by the trends in phosphorus. The concentrations of nutrients (total nitrogen and total phosphorus) decrease through spring and summer to a minimum at the end of August. Our analysis further show a stronger positive correlation of chlorophyll-*a* with nitrogen than phosphorus in June to October, which suggests that year to year trends of the chlorophyll-*a* level at this time of year was best explained by the trends in nitrogen (Fig. 9). One

interpretation of these findings is that phosphorus limits phytoplankton growth during spring bloom while nitrogen is limiting late in summer. This was also found in the western Dutch Wadden Sea (Ly et al., 2014). However, a study from Oslofjorden in 1986 indicated that the summer period was especially phosphorus limited (Paasche and Erga, 1988). Phytoplankton respond to a shortage of phosphate by producing the enzyme alkaline phosphatase, which hydrolyses organic phosphorus into phosphate used for phytoplankton growth. This ability to store organic phosphorus may make the phytoplankton more adaptive to low levels of phosphorus than nitrogen (Lin et al., 2016).

Our analyses are based on total amounts of nitrogen and phosphorus due to limited data of dissolved inorganic nutrients in the long-term dataset. Total N and total P may have limitations in predicting nutrient limitation in autotrophic phytoplankton as they also include biologically unavailable fractions of the nutrients. However, it has been found to perform moderately well with the main shortcoming being high threshold levels (Ptacnik et al., 2010). We therefore conclude that the nutrient-chlorophyll associations found may be underestimated, but significant.

4.2. Long term trends

The chlorophyll-*a* levels in inner Oslofjorden decreased by around 70% in the period 1980–1990 (i.e. -1 on the ln scale in Fig. 2), and fluctuated after that, but remained at low levels representing good ecological status. The effects of eutrophication on the phytoplankton community have been documented as far back as the early 1900s (Braarud, 1945; Braarud and Bursa, 1939; Hjort and Gran, 1900; Munthe-Kaas, 1967). Also, the extensive study conducted in 1962–64 documented that the upper water column was heavily eutrofied, and nutrient supply from land-based activities was one of the main sources (Munthe-Kaas, 1968). Our analysis shows that as the levels of chlorophyll-*a* decreased through the 1980s, the Secchi-depth increased. This is an expected relationship, as high biomass of phytoplankton is a major cause of reduced water clarity. However, the trends in Secchi-depth do not follow the trends in chlorophyll exactly. Possible explanations are increased outflow of dissolved organic matter runoff from rivers, which has been found to increase, especially in the eastern part of Norway during the period from 1986 to 2013 (Finstad et al., 2016) and led to darkening of coastal water (Aksnes et al., 2009). This change in turbidity should be studied further in order to determine the impact on primary production and water quality. During the same time as chlorophyll-*a* levels have decreased, the amount of nitrogen in surface water has also decreased steadily and still is. The levels of phosphorus decreased rapidly until around 1998, but have since then increased to the same levels as the beginning of the time series (1973). Model studies from the coastal zone of the North Sea indicate that nutrient loads cannot be linearly correlated to a reduction in primary production (Lenhart et al., 1997). However, it is likely that the reduction of nutrient loads has had an essential impact on the significant chlorophyll-*a* decrease during the study period. Our results further indicate that spring bloom amplitude is controlled by phosphorus. The reduced phosphorus concentration contributed to the decrease in chlorophyll-*a* from 1980s to 1990s. Interestingly, the increase in phosphorus since the 2000s seems not to have led to increased chlorophyll levels, possibly because of limitation from the low nitrogen. This indicates that nitrogen may have become more limiting earlier in the season in later years. To determine whether changes in chlorophyll-*a* level and turbidity are caused by anthropogenic pressures or is natural variability can be especially tricky in temperate fjords with high variation in salinity and temperature (Borja et al., 2016; Elliott and Quintino, 2007). However, in the inner Oslofjorden, the results obtained in this investigation are, to a large extent, coherent with what is expected after a reduction in anthropogenic nutrient load.

4.3. Management

The story about the reduced eutrophication and improved water quality of the Oslofjorden is an excellent example of how management initiatives can work and repair some of the old mistakes. The decrease in chlorophyll-*a* levels are likely related to management measures and improved cleaning systems at the sewage treatment plants, especially the introduction of nitrogen removal by biological treatment. The monitoring program was initiated due to concern about the effects of eutrophication of the fjord, but it is now also essential to study the effects of de-eutrophication after cleaning and how other variables such as inorganic particles and dissolved organic matter may affect the pelagic environment. The study station Dk1 in the inner Oslofjorden is not only one of the main stations of the monitoring program, but also a common sampling station included in many research projects in the inner Oslofjorden. Therefore, we managed to fill some of the gaps in the monitoring data with data from other research studies. Even though the main aim of a monitoring program may be the detection of a trend or the non-compliance with a water quality standard (de Jonge et al., 2006), in a rapidly changing environment with new threats and concerns, using monitoring data is essential not only to document the changes but to study how to improve and restore the environment (Cadée and Hegeman, 2002; de Jonge et al., 2006).

The observed improvement in the quality of the surface water through the 1980s (Magnusson et al., 1989; Paasche and Erga, 1988) was assumed to be due to improved sewage cleaning, but based on data available at that time it was not possible to be sure. The observed changes could also be natural fluctuations. Our long-term analysis confirms these early assumptions to be true and shows the long-term significant decrease in chlorophyll-*a* and the close relationship with nutrient levels. However, we also see that after the significant decline, phosphorus has increased since around 1998. We have seen how the reduction in phosphorus has contributed to decrease in the chlorophyll-*a* levels of the spring bloom. As phosphorus levels are increasing again it should be raised as a concern for management. We expect that if the nitrogen levels are kept low, this will most likely keep the chlorophyll levels low too. Due to this situation nitrogen may currently be the critical factor in controlling chlorophyll-*a* phenology in the inner Oslofjorden.

In this study, we have shown how the long-term monitoring dataset from the inner Oslofjorden can be used to understand how anthropogenic pressures contribute to eutrophication and changes in phytoplankton biomass. The analysis here are, however, only indications of biomass changes, and it is also important to understand whether the phytoplankton community composition is changing and how this affects marine biodiversity in the area. There is a growing concern about the local fish stocks in the fjord, as a decrease in the juvenile cod population is evident from the long-term beach seine monitoring (Tore Johannessen pers. com.). In 2019 the Norwegian Directorate of Fisheries closed all fishing of cod (*Gadus morhua*) in the Oslofjorden (Ministry of Trade Industry and Fisheries, 2019). In a rapidly changing environment, with temperature increase, salinity changes, and water darkening, we need this understanding when redesigning monitoring programs to meet future needs and ensure knowledge-based management.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.seares.2020.101925>.

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