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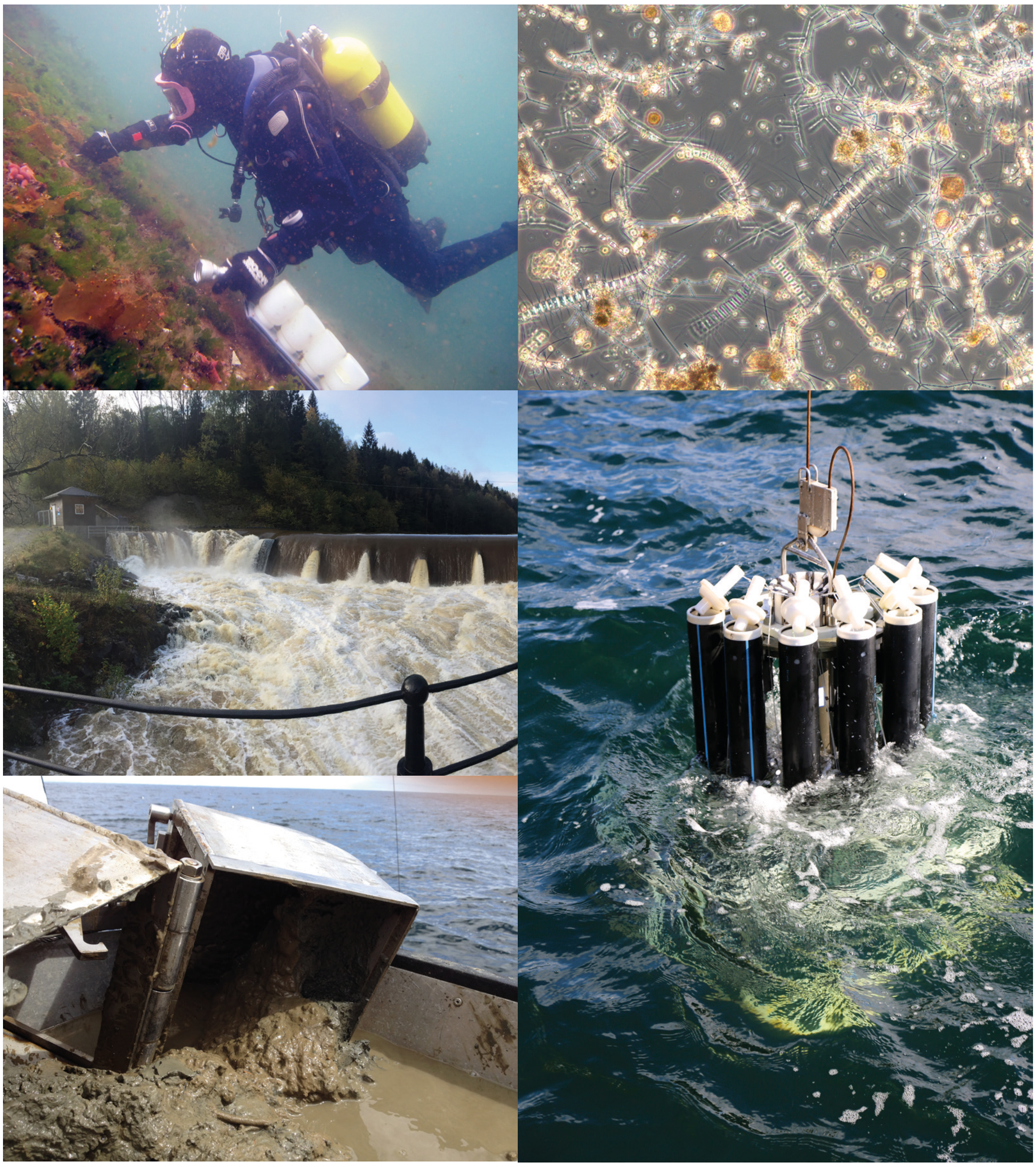
Synthesis of climate relevant results from selected monitoring programs in the coastal zone. Part 2: Quantitative analyses



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Summary

This report is Part 2 of the project Synthesis of climate relevant results from selected monitoring programs in the coastal zone (Klima-Overblikk). The overall aim of this report was to document changes over the period 1990-2016 in riverine loadings to Skagerrak and in coastal water quality and species composition. In addition, we investigated the relationships between changes in climate drivers (temperature, river discharge) and coastal responses in hydrography and changes in species composition in phytoplankton, hard-bottom and soft-bottom communities. We used long-term (approx. 26 years) coastal monitoring time series on hydrography, phytoplankton, hard-bottom communities and soft-bottom fauna from coastal Skagerrak, together with monitoring data on selected Norwegian rivers draining to Skagerrak.

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4. Coastal ecosystems	4. Kystøkosystemer

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Synthesis of climate relevant results from selected monitoring programs in the coastal zone

Part 2: Quantitative analyses

Preface

This report is part of the project «Synthesis of climate relevant results from selected monitoring programs in the coastal zone», that has been performed by the Norwegian Institute for Water Research (NIVA) on assignment for The Norwegian Environment Agency. The first phase of the project was completed in 2017 (see report: M-905/NIVA 7214), and was a qualitative assessment of climate-relevant results from selected monitoring programs.

The second phase of the project is presented in this report and involves quantitative analyses of selected time series from the Ecosystem monitoring in coastal waters (ØKOKYST) and the River monitoring program (Elveovervåkingsprogrammet).

The following people have contributed to this report:
Lars Johan Naustvoll, Institute of Marine Research (IMR), Flødevigen (plankton),
Øyvind Kaste, NIVA (rivers),
Guri S. Andersen, NIVA (hard-bottom communities, statistical analyses),
Hilde C. Trannum, NIVA (soft-bottom fauna),
Helene Frigstad, NIVA (hydrography, statistical analyses),
Dag Hjermann, NIVA (statistical analyses, plankton).

Gunhild Borgersen has contributed to data gathering from soft bottom databases. Janne K. Gitmark and Camilla W. Fagerli have contributed with data gathering, recoding and filtering of hard bottom data. Liv Bente Skancke has contributed with data gathering and processing for the river monitoring programme. Kai Sørensen has provided feedback on the report. Anne Deininger has summarized the main findings of the report in the graphical summary.

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Grimstad, 7. December 2018

Helene Frigstad
Project manager

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Summary

The overall aim of this report was to document changes over the period 1990-2016 in riverine loadings to Skagerrak and in coastal water quality and species composition. In addition, we investigated the relationships between changes in climate drivers (temperature, river discharge) and coastal responses in hydrography and changes in species composition in phytoplankton, hard-bottom and soft-bottom communities. We used long-term (approx. 26 years) coastal monitoring time series on hydrography, phytoplankton, hard-bottom communities and soft-bottom fauna from coastal Skagerrak, together with monitoring data on selected upstream Norwegian rivers draining to Skagerrak.

There have been significant upward trends in discharge and transports in rivers draining to Skagerrak, with the largest relative increase during the summer period (May-July). This confirms the trends reported for the Skagerrak region for the River monitoring program (Kaste et al. 2018). The temperature in the intermediate and deep coastal waters have increased significantly, while the upward trend for surface temperature is not significant, probably related to the large interannual variations in the upper water masses.

For hydrographic variables, we found the largest upward trends for suspended particulate organic material (POC, PON, TSM), which was observed for all depth layers. Using regression analyses, we found that the riverine total organic carbon concentration (TOC) and surface salinity were the most important explanatory variables in explaining this long-term trend. We hypothesized that the riverine organic material (which is mostly in dissolved form) aggregates to larger particles in the coastal zone, through a process called salinity-induced flocculation. Meanwhile, the largest downward trends were for the dissolved inorganic nutrients (DIN, PO_4). The reduction in inorganic nutrient concentrations in coastal Skagerrak follows reductions reported for many coastal regions, linked to management efforts to reduce eutrophication.

For the phytoplankton groups, we found a consistent and large decrease in dinoflagellates, which bloom in summer and autumn. This could explain the reduction in biomass (chlorophyll a) during these seasons, however no clear trend was found on an annual basis. There were reductions also in flagellates, while diatoms showed large interannual variations. The variables that accounted for most of the long-term decline in dinoflagellates were DIN, temperature and river suspended particulate matter (SPM). The effect of river SPM is harder to explain than the effects associated with nutrients and temperature, however it affects the dinoflagellates and flagellates in a negative way.

There was a pronounced change in the structure of the hard-bottom communities. There was a shift in the community towards fewer algal species (particularly red) and more species of filter feeders, which has been suggested to be related to reduced light availability and increased particulate loadings. Nutrient-rich particulate loadings may serve as food for filter feeders, which could possibly explain the increased presence of these animals in the hard-bottom fauna. There was also a significant decrease in the overall lower growth depth of the nine macroalgae species included in the MSMDI-index, which is connected to both reduced light availability and increased temperature. Temperature, TSM and POC were found to be important drivers of the change in community structure in hard-bottom communities.

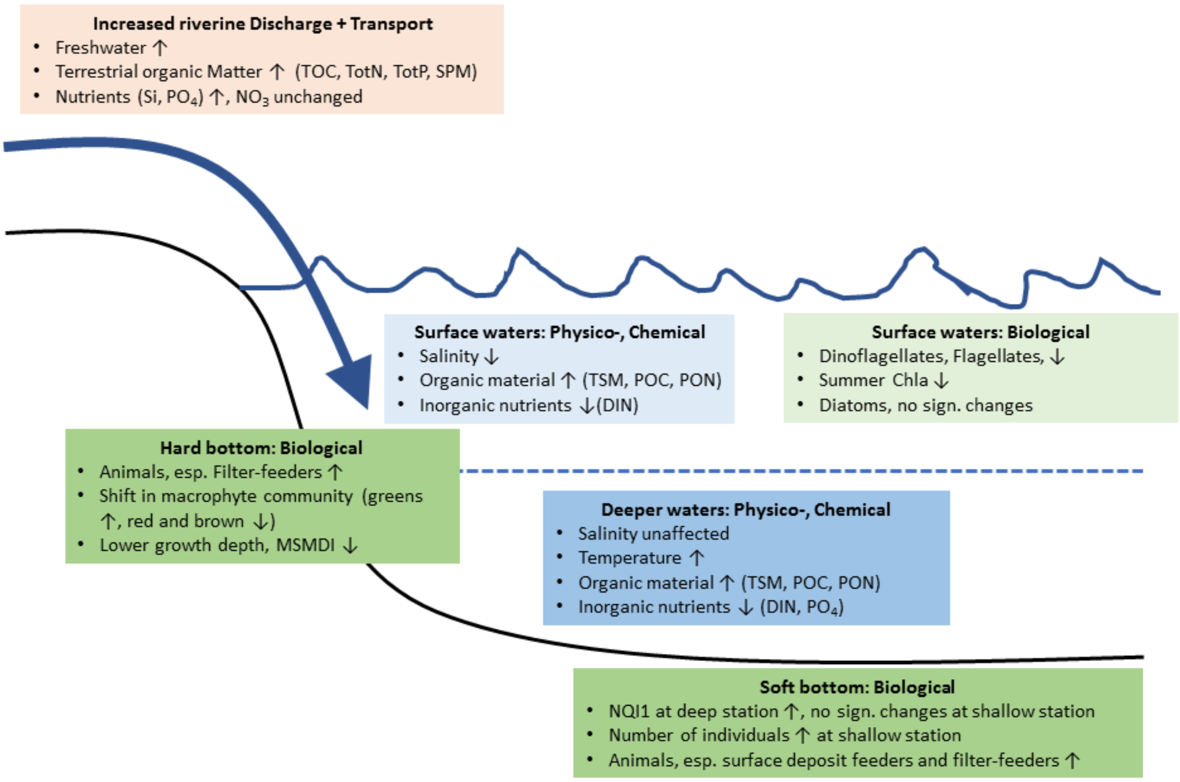
Similarly, there were substantial changes in the soft-bottom fauna. At the deep/outer station, an improvement in ecological condition was observed, evidenced by a reduction in the total abundance (number of individuals) and opportunistic species and an increase in species diversity. This finding is in accordance with previous studies, and interpreted as a response to the overall reduction in the inorganic nutrient (i.e. eutrophication) load. On the other hand, the abundance tended to increase at the shallow/most coast-near station, pointing to an increase in food supply. This finding accords with the identification of TSM as an important driver of the change in the faunal composition at this station. At the same time, there were parallel changes in species composition at both stations, pointing to the same underlying drivers. For both stations there was an increase in

species feeding on suspended material in the water column or on the sediment surface, such as bivalves, which indicates a change in the food source for the benthic communities. It seems likely that these changes are related to the increase in total and particulate suspended material, which sinks through the water column to the deeper layers and bottom sediments where they can be utilized by filter feeding and surface deposit feeding benthic species.

This works showcases the importance of maintaining time series to detect effects of long-term environmental changes. Some of these changes are intentional, such as the decrease in inorganic nutrient concentrations, while some are unexpected, such as the increase in suspended material in coastal waters caused by increased riverine discharge and transports. The latter is both caused by climate change (through increasing precipitation), but also owing to complex interactions with reduced sulfate deposition (i.e. acid rain) and land-use changes. These changes call out for implementing adaptive monitoring, where the monitoring programs evolve iteratively as new information emerges and the major drivers of the systems change.

In this report, we advise to include measurements of dissolved organic carbon and its chromophoric fraction (DOC and cDOM) and light profiles (including spectral composition) in the Ecosystem monitoring of coastal waters (ØKOKYST). This could be implemented by establishing study areas along the coast with stations in a land-ocean gradient, from the recipients of major Norwegian rivers draining to Skagerrak (complemented with high-resolution monitoring in the relevant river) and towards more open, exposed coastal areas. This would increase the knowledge on the relationship between riverine transport and the coastal responses, and build the knowledge basis needed for further development of the classification scheme and indices, and related surveillance monitoring programmes of the Water Framework Directive (WFD).

Graphical summary



Sammendrag

Tittel: Sammenstilling av klimarelevante resultater fra utvalgte overvåkingsprogram i kystsonen: Del 2 Kvantitative analyser
År: 2018

Forfatter(e): Helene Frigstad, Guri S. Andersen, Hilde C. Trannum, Lars-Johan Naustvoll, Øyvind Kaste og Dag Ø. Hjermann

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Formålet med dette arbeidet var å dokumentere endringer over perioden 1990-2016 i elvetilførsler til Skagerrak og i vannkvalitet og artssammensetning i kystområdene. Vi undersøkte forholdet mellom endringer i påvirkning av klimaendringer (temperatur, vannføring) og effekter på hydrografi og endret artssammensetning for planteplankton, hardbunn- og bløtbunnssamfunn. Vi brukte lange tidsserier fra overvåking (rundt 26 år) for hydrografi, planteplankton, hardbunn og bløtbunn fra kystnære områder i Skagerrak, i tillegg til tidsserier fra utvalgte norske elver som renner ut i Skagerrak oppstrøms fra kyststasjonene.

Det har vært signifikante økninger i vannføring og transport i elvene som renner ut i Skagerrak, og den største økningen ble funnet for sommerperioden (mai-juli). Dette bekrefter trendene som er rapportert for Skagerrak i Elveovervåkingsprogrammet (Kaste et al. 2018). Temperaturen i midlere og dypere lag av kystvannet økte signifikant, mens det ikke ble funnet signifikante endringer i de øvre vannlaget, sannsynligvis knyttet til høyere variasjon mellom årene.

For de hydrografiske variablene, så var de største økningene for suspendert partikulært organisk materiale (POC, PON, TSM), som økte i alle vannlagene. Med hjelp av regresjonsanalyser, fant vi at den totale organiske karbonkonsentrasjonen i elvene (TOC) og saltholdigheten i det øvre vannlaget var de viktigste forklaringsvariablene for denne trenden over tid. Vår hypotese var at det organiske materiale i elvene (som er mest i løst form) aggregerte til større partikler i kystvannet, gjennom en prosess kalt salt-indusert flokkulering. Derimot ble den største reduksjonen over tid observert for de uorganiske næringssaltene (DIN, PO_4). Denne reduksjonen i næringssalter i kystvannet i Skagerrak har sammenheng med reduksjoner rapportert for andre kystområder, og er knyttet til tiltak for å redusere eutrofiering.

For planteplankton, så fant vi en betydelig reduksjon i dinoflagellater, som har hovedsakelig har oppblomstringer om sommeren og høsten. Dette kan ha forklare reduksjonen i biomasse (klorofyll a) som ble observert for disse sesongene, selv om det ikke ble funnet noen trend for biomasse på årlig nivå. Det var også en reduksjon i flagellater, mens det for kiselalger var stor mellomårlig variasjon. De variablene som kunne forklare mest av nedgangen i dinoflagellater var DIN, temperatur og suspendert partikulært materiale (SPM) i elvene. Effekten av det suspenderte materiale på planteplanktonet er ikke kjent, men det påvirket dinoflagellatene og flagellatene på en negativ måte.

Det var en tydelig endring i sammensetning av hardbunnssamfunnene. Det var en endring mot færre algearter (spesielt rødalger) og flere arter med filtrerende dyr, som man tror henger sammen med redusert lystilgang og økt partikkelbelastning. Næringsrike partikler kan være en kilde til mat for filtrerende organismer, og bidra til å forklare økningen av denne typen dyr på hardbunn. Det var også en signifikant reduksjon i den nedre voksegrensen for de ni makroalgene inkludert i MSMDI-indeksen, som har sammenheng med redusert lystilgang og økt temperatur. Temperatur, TSM og POC ble alle funnet til å være viktige påvirkningsfaktorer for endringen i artssammensetning for hardbunnssamfunn.

Det var tilsvarende endringer i artssammensetning for bløtbunnsfauna. På den dype, ytre stasjonen, så var det en bedring i økologisk tilstand, vist ved en reduksjon i antall individer og opportunistiske arter, og en økning i artsmangfold. Disse funnene er i samsvar med tidligere studier, og blir tolket som en effekt av den reduserte eutrofibelastningen. På den andre siden, så var det en økning i antall individer på den grunne, kystnære stasjonen, som kan indikere en økning i næringstilgang. Dette kan ha sammenheng med at TSM ble funnet til å være en viktig påvirkningsfaktor for endringen i artssammensetningen på denne stasjonen. På et overordnet nivå, var det parallelle endringer i artssammensetning for begge stasjonene. Det var en økning i arter som spiser suspendert materiale i vannsøylen eller på overflaten av sedimentene, slik som muslinger, som kan indikere en endring i næringstilgang for de bentiske samfunnene. Det er sannsynlig at disse endringene har sammenheng med økningen i totalt og partikulært suspendert materiale, som synker gjennom vannsøylen til de dypere vannlagene og sedimenterer på havbunnen, hvor de kan bli utnyttet av organismer som filtrerer eller spiser på overflaten av sedimentene.

Dette arbeidet fremhever viktigheten av å bevare lange tidsserier for å avdekke effekter av miljøpåvirkninger over tid. Noen av disse endringene er ønskede og et resultat av forvaltningstiltak, slik som reduksjonen i uorganiske næringssalter, mens andre er uventede, slik som økningen i suspendert materiale i kystvannet på grunn av økt avrenning og transport i elvene. Det sistnevnte er både forårsaket av et endret klima (gjennom økt nedbør), men henger også sammen med kompliserte samvirkninger mellom redusert sulfatdeponering (sur nedbør) og endringer i landskapet. Disse endringene aktualiserer betydningen av adaptiv overvåking, hvor overvåkingsprogrammene kan endres etter hvert som ny kunnskap tilføres og de viktigste påvirkningsfaktorene på kystøkosystemene endres seg.

I denne rapporten anbefaler vi at det inkluderes overvåking av løst organisk karbon (DOC), den fargede komponenten av dette (cDOM) og lysprofiler (inkludert spektral oppløsning) i Økosystemovervåking i kystvann (ØKOKYST). Dette kan gjennomføres ved at det opprettes studieområder for land-hav interaksjoner, fra elveutløp (koplet med høy-oppløselig overvåking i elven) og utover gradienten mot mer åpne og eksponerte kystområder. Dette ville gi økt kunnskap om forholdet mellom elvetransport og responser i kystøkosystemet, og begynne å bygge det kunnskapsgrunnlaget som er nødvendig for å videreutvikle klassifiseringssystemet, indeksene og basisovervåking i henhold til Vanndirektivet.

1 Introduction

Coastal ecosystems are among the most productive global ecosystems (Nixon 1988, Cloern et al. 2014), and provide at least 40% of the of the value of the world's ecosystem services (Costanza et al. 1997, Barbier et al. 2011). These transitional zones are uniquely influenced by processes from both land and sea, and the high productivity can in part be attributed to fueling from nutrient run-off from land (Nixon 1988, Cloern and Jassby 2012). However, coastal ecosystems are also under accelerating pressures from human activities and climate change, with implications for water quality and provision of important ecosystem services (Halpern et al. 2008, Cloern et al. 2016).

Overview of large-scale drivers and responses in the Skagerrak region

The Skagerrak and the North Sea have densely populated catchment areas and human activities lead to heavy impacts, such as eutrophication, contaminants, non-indigenous species and marine litter (OSPAR 2017). In addition, the region is experiencing effects of climate change, such as ocean warming and species displacements (Rinde et al. 2017) and ocean acidification (Jones et al. 2018). Historically, eutrophication has been a major concern and management efforts to reduce inorganic nutrient loadings has led to improvements in eutrophication status in several coastal areas of the North Sea and Skagerrak (Carstensen et al. 2006, Vermaat et al. 2008, Norderhaug et al. 2016).

Correspondingly, in the Norwegian coastal waters of Skagerrak there has been a long-term decrease in the inorganic nutrient concentrations, mainly due to a reduction in the nutrients advected from the southern North Sea (Aure et al. 1998, Frigstad et al. 2013). However, there was an increase in the suspended organic material (dissolved and particulate) over the same time period (Frigstad et al. 2013), which was hypothesized to be related to the increased riverine loads and the reported "darkening" of coastal Skagerrak and the North Sea (Aksnes and Ohman 2009, Dupont and Aksnes 2013). There were reports of significant changes in the phytoplankton and zooplankton community around 2002 and poor recruitment in selected fish species (Anonymous 2012, Johannessen et al. 2012). There was a shift from sugar kelp (*Saccharina latissima*) to ephemeral algae on rocky-bottom substrates around the same time period (Moy and Christie 2012), which was attributed to effects of high summer temperatures, as well as aggregated factors related to eutrophication, such as particle load, sedimentation and high growth of opportunistic algae and epibionts (Sogn Andersen et al. 2011, Sogn Andersen et al. 2013, Norderhaug et al. 2015). A decrease in the lower growth depth of several macroalgae has also been indicated in Skagerrak (Moy et al. 2017, Naustvoll et al. 2018, Sogn Andersen et al. In Press). The status of the sugar kelp forest has improved in recent years, especially in exposed coastal areas, however there is concern that climate change will negatively affect kelp forests in the future (Norderhaug et al. 2015, Sogn Andersen et al. In Press). The soft-bottom fauna in Norwegian coastal waters showed improved status (increased species richness) since 1990, believed to be related to a reduction in inorganic nutrient concentrations in the water masses (Trannum et al. 2018).

The Norwegian rivers draining to Skagerrak have shown increased discharge over the last 25 years, yet while the inorganic nutrient concentrations have decreased, there has been an increase in the loads of organic material (de Wit et al. 2016, Kaste et al. 2018). These changes correspond to increased inputs of terrestrial organic material reported for many boreal and arctic regions (Solomon et al. 2015, Creed et al. 2018), which is often referred to as "browning". The drivers might vary both with time and region, but important contributing factors are increased precipitation, reduced atmospheric sulfate deposition and land-use changes (Monteith et al. 2007, de Wit et al. 2016).

Background and aim

This report builds on the conclusions and recommendations from Part 1 of this project (Frigstad et al. 2017), where we gave a qualitative overview of climate relevant results from published reports from selected monitoring programs. Climate variability can affect biogeochemical and ecological processes in various ways, and the responses can be direct, indirect (mediated through their environment), have temporary lags or be non-linear in nature. Examples of direct effects of climate change from the above-mentioned report, were impacts on species composition and physiology due to increasing ocean temperature and the decrease in seawater pH due to increased atmospheric pCO2. An example of an indirect effect of climate change, is the increase in river run-off entering coastal ecosystems. The increase in river discharge can in large be attributed to climate-related increase in precipitation, however the associated effects in coastal ecosystems can potentially be confused with eutrophication. Coastal responses to increased riverine loading can be hypothesized to be a decrease in salinity and water clarity (Secchi depth), increase in suspended dissolved and particulate matter in the water column and increased sedimentation on hard- and soft-bottom substrates. Increased particle loads, sedimentation and reduced water clarity can negatively affect the lower growth depth of macroalgae, while the soft-bottom fauna can be negatively impacted if the organic loads becomes very high. Thereby, climate change can have an impact on the eutrophication status, through changes in riverine transports of organic matter and nutrients, and thus have an indirect (but often unquantifiable) impact on biological quality elements (as defined through the Water framework directive (WFD) classifications). We emphasized in Part 1 that long-term consistent time series are necessary in order to disentangle these complex relationships, especially if the aim is to differentiate between natural variation and climate change or other human-induced drivers.

In this work, we use four long-term (approx. 26 years) coastal monitoring time series on hydrography, phytoplankton, hard-bottom communities and soft-bottom fauna from coastal Skagerrak, together with monitoring data on selected Norwegian rivers draining to Skagerrak. The aim of the quantitative analyses in this work is twofold; firstly we will document and test the significance of the trends in riverine loadings to Skagerrak and in coastal water quality and species composition. Secondly, we will investigate the causal relationships between changes in climate drivers (temperature, river discharge) and changes on observed coastal responses in hydrography and changes in species composition in plankton, hard-bottom and soft-bottom communities.

2 Methods

2.1 Study area and data

The Skagerrak is situated in the North-East Atlantic Ocean, between Denmark, Sweden and Norway. It has a complex hydrography, but the circulation of the surface water is on average cyclonic, and consists of the Jutland Current along the west coast of Denmark, which mixes with the Baltic Current, local river run-off and more saline Atlantic Water from the west to create the Norwegian Coastal Current (Sætre 2007).

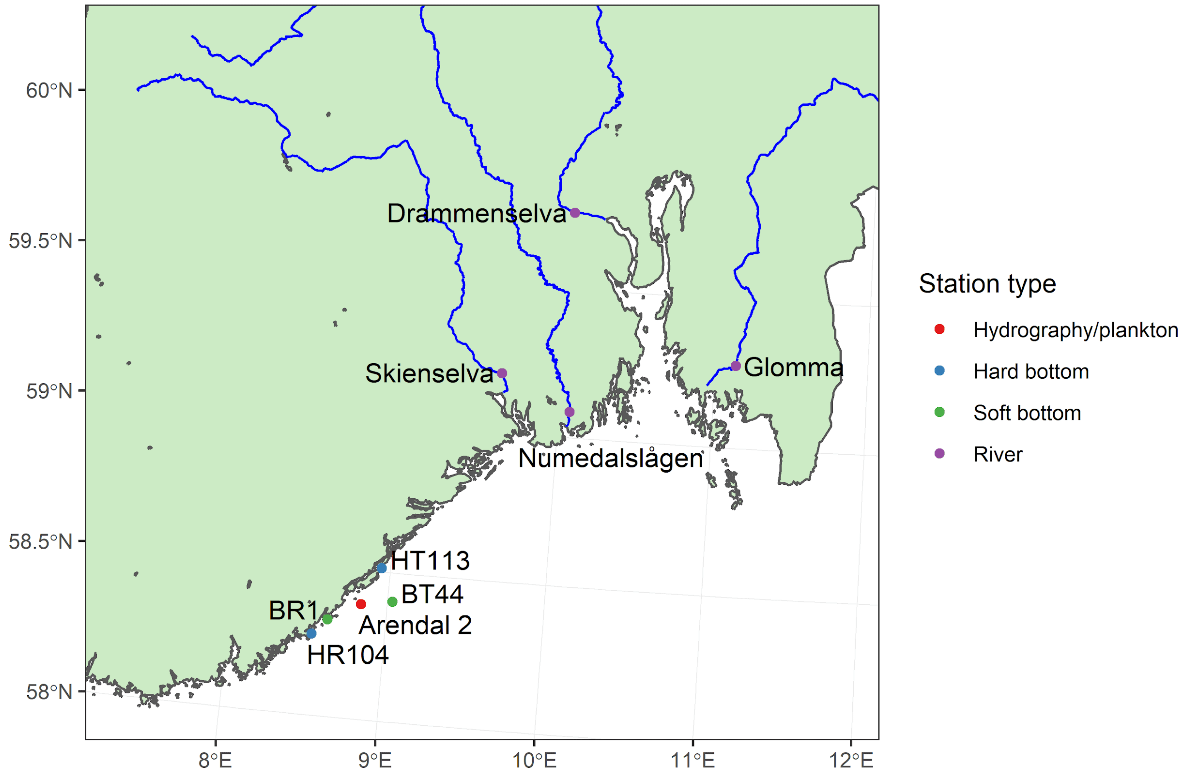


Figure 1. Location of time series stations.

In 1990, the Norwegian Environment Agency established the Norwegian Coastal Monitoring Programme in Skagerrak. The programme was revised in 2012/2013, and the current version called Ecosystem monitoring of coastal waters - ØKOKYST (Fagerli et al. 2018, Naustvoll et al. 2018) is designed to map and monitor the environmental status in Norwegian waters according to the Water Framework Directive (WFD). The stations selected for this work have the longest consistent time series in the coastal monitoring programme and the various station types are located close enough to facilitate interpretation between changes in hydrography and hard- and soft-bottom stations (see location of stations in Figure 1). The hydrography (1990-2016) and phytoplankton (1994-2016) data are taken from the Arendal station 2 (VT5; 58.3870 N 08.8330 E), which is located at 75 m depth 1 nautical mile off the coast and sampled approximately 20 times per year. The parameters included in the hydrographical part of the programme are: temperature, salinity, oxygen, Secchi depth, dissolved inorganic nitrogen (DIN), orthophosphate (PO_4), silicate (Si), total nitrogen (TotN), total phosphorus (TotP), Chlorophyll *a* (Chla), particulate organic carbon (POC), particulate organic nitrogen (PON), particulate organic phosphorus (POP) and total suspended matter (TSM). Observations of TSM was missing for the period 2012-2013 (see Figure A1), and these values were interpolated using the zoo package (Zeileis and Grothendieck 2005). From 2013, the measurements of POC, PON, POP and DIN in the deep layer (50 and 75m) were discontinued. For a detailed description of the programme and analytical procedures for the monitoring period from 1990 to 2016 see Moy et al. (2017).

The phytoplankton data has been analyzed according to the Utermöhl method (Sournia 1978) and according to the standard NS-EN 15972:2011. All analyses have been performed using invert light microscope. The phytoplankton analyses have been performed by two laboratories during the monitoring period, 1994-2012 and 2013-2016. However, the method for concentration and enumeration has been the same over the whole period. The samples have been collected biweekly from March to September, and monthly during the winter periods. Samples have been analysed to the highest taxonomic level possible with the described methods. In this study the phytoplankton data has been aggregated to 13 taxonomic classes and 3 main phytoplankton groups (diatoms, dinoflagellates and flagellates). In the period 1994-1999 the phytoplankton samples were taken as a mixed sample for 0-30 m, and from 2000 to 2016 for one single depth (5 m).

The hard bottom species data are from dive transects conducted on stations HR104 (Prestholmen; 58.2732 N 08.5372 E) and HT113 (Tromøy; 58.5132 N 08.9445 E) annually since 1990. The surveys are conducted from a maximum depth of 30 m and up to the surface. Semi-quantitative registration of abundance (0: absent, 1: single specimen, 2: scattered, 3: common, and 4: dominating) of all macroalgal and faunal species (or taxa) has been performed along transects by divers specialized in marine floral and faunal taxonomy. Registrations of all species visible (approximately 0.5 m each way from the diver position, i.e. 1 m^2 at each depth) were made at every meter from 1 m above to 4 m below surface and for every second meter from 4 m depth and to the maximum depth. The surveys were performed in summer (May-June). Some species have changed name over time, and some of these were registered under both names. These entries were collapsed, and the newest species name was used. Some species that previously were registered lumped together on higher taxonomic levels, have more recently been differentiated and vice versa. These species were all aggregated to ensure consistency over time. After these aggregations, the time-series dataset contained a total number of 481 unique species/groups. The Multi Species Macroalgae Depth Index (MSMDI) serves as an indication of eutrophication and increased concentrations of particulate matter in the water. It is based on the lower growth depth of a few easily recognized macroalgal species, and the index species are selected based on their known responses to reduced light conditions. For Skagerrak, the species are *Chondrus crispus* (krusflik), *Coccotylus truncatus* (hummerblekke), *Delesseria sanguinea* (fagerving), *Furcellaria lumbricalis* (svartkluft), *Halidrys siliquosa* (skolmetang), *Phycodrys rubens* (eikeving), *Phyllophora pseudoceranoides* (krusblekke), *Rhodomela confervoides* (teinebusk) and *Saccharina latissima* (sukkertare). The lower growth depth of each of these macroalgal species is estimated as the maximum depth to which the abundance was recorded as scattered or higher each year. The EQR value from the MSMDI-index has been calculated for the whole time-series in the Coastal Monitoring Programme and these data were used in the test of time trends (Mann-Kendall, see Chapter 2.2). The species diversity was calculated by the Shannon–Wiener index (Shannon and Weaver 1963) using the logarithm base of 2 (H'log2). The Pielou's evenness index (J') was calculated by dividing the Shannon-Wiener index (H') by the species richness (Pielou 1966). The Shannon-Wiener index reflects how many different types (species) there are in a dataset (community), simultaneously taking into account how evenly the basic entities (individuals) are distributed among those types. The Pielou's evenness index (0 - 1) refers to how close in numbers each species/group in an environment is. In other words, it quantifies how equal the community is numerically. The less evenness in numbers between the species in the community (clear difference in dominance), the lower the J' is.

The soft-bottom fauna data are from the coast-near shallow station BR1 (Grimstad) at 50 m depth (58.3253 N 08.6295 E) and the outer deep station BT44 (Arendal) at 350 m depth (58.4038 N

09.0312 E). The sampling started in 1990, and we have used data through 2016. Sampling has been conducted with a 0.1 m^2 Day grab or a 0.1 m^2 van Veen grab in May or June each year. The fauna was sieved on a 1mm screen. Through time, either four or eight grabs were sampled, but for the purpose of the present work four grabs were used. All organisms were identified to species or lowest taxon possible. In this context, all values were averaged per 0.1 m^2. The raw taxon data matrix was carefully inspected for inconsistencies in the identifications, including changes in taxonomy. The same stations were sampled for percent sediment fine fraction (i.e. % particles < 0.063 mm) and Total Organic Carbon (TOC, mg/g). The field-work and processing were performed according to guidelines for quantitative sampling and sample processing of marine soft-bottom macrofauna (NS-EN ISO 16665:2013). Due to outsourcing of analyses and some deviations in methodology, we have removed the TOC data from 2014 and the sediment fine fraction in 2012. In the present work, the multivariate species matrix was used in the analyses. In addition, species richness (S), number of individuals (N), the Shannon-Wiener diversity index (H'log2) (Shannon and Weaver 1963) and NQI1 – Norwegian Quality Index (Molvær et al. 2009) were calculated. Both H' and NQI1 are included in the WFD monitoring system for Norwegian coastal waters. NQI1 was calculated with the formula applied in Borja et al. (2000).

The river data are from the River monitoring program (Kaste et al. 2018), which has been funded by the Norwegian Environment Agency since 1990. All major rivers upstream of the Arendal area is included in this study (with catchment area given in parenthesis): Glomma (41918 km^2), Drammenselva (17034 km^2), Numedalslågen (5577 km^2), and Skienselva (10772 km^2) (marked in Figure 1, see monthly discharges of individual rivers in Figure A2). All rivers are sampled monthly during the period 1990-2015. Chemical parameters included in this study comprise nitrate (NO_3-N), total nitrogen (TotN), phosphate (PO_4-P), total phosphorus (TotP), total organic carbon (TOC), suspended particulate matter (SPM) and silicate (Si). For analytical methods, limits of detection (LOD) and quantification (LOQ), see Kaste et al. (2018). The time series for Si start in 1995, whereas the TOC data are included from 1992. For all other parameters, data are collected from January 1990. Missing TotP data during the period 1998-2003 are replaced by interpolated values based on the last and the first measured value in the time series. Daily water discharge measurements have been used for the calculation of element transport. Discharge data have been provided by the Norwegian Water Resources and Energy Directorate (NVE). Since the hydrological stations are usually not located at exactly the same sites as the water quality sampling, the water discharge at the water quality sampling sites have been calculated by up- or downscaling, proportional to the respective drainage areas. Calculations of riverine loads are done according to procedures described in Kaste et al. (2018).

2.2 Statistical analyses

All statistical analyses were performed using the R statistical software (R CoreTeam 2018). All plots were made using the ggplot2 package (Wickham 2016). The time series with monthly (or higher resolution) were aggregated into annual and seasonal averages, using the mean values for hydrography and plankton and sum for rivers. In order to capture phytoplankton bloom for all years, spring was defined as the period from February to April for rivers, hydrography and plankton data (i.e. season 1 (spring) from February to April, season 2 (summer) from May to July, season 3 (fall) from August to October and season 4 (winter) from November to January. For hydrography we aggregated into surface (0, 5, 10m), intermediate (20, 30m) and deep (50, 75m) layers.

A non-parametric Mann-Kendall test was applied to all variables in testing for a significant monotonic time-series trend (Mann 1945). The test was applied on the annually and seasonally averaged data, using the rkt package in R (Marchetto 2017), and the results are visualized in Figure 13 (annual) and Figure A13 (seasonal), and summarized in Table B1.

Detrended correspondence analysis (DCA) (Hill and Gauch 1980) was performed using the vegan package in R (Oksanen et al. 2018) to produce ordination diagrams. The ordination axes are gradients in species composition and represent hypothetical ecological gradients. Along these hypothetical gradients, each plot (species survey unit) and species is placed to optimize the fit to the data assuming an underlying unimodal relationship between species and gradients (Terbraak and Prentice 1988). The positioning of plots along the main ordination-axis (depicting the longest latent gradient in species compositions) was used for further statistical analysis. The positioning of species along the same main axis, the species score, is a model representation of the species optimum within the multidimensional space of the dataset. The ordination axes and the scores can be interpreted in relation to the environmental gradients that strongly correlates with the axes. Species with optimums on opposite ends of the gradient are less likely to occur together in the ordination diagram. Species with scores closer to the center of the gradient (0) are more likely to be present along larger parts of the gradient. This is the rationale behind our interpretations of species abundance and changes in species compositions. In our case, the main ordination axis was highly correlated with time, and therefore the species scores was also viewed in relation to time (Chapter 3.3). For the hard-bottom dataset one analysis comprising both stations was performed. For the soft-bottom datasets each station was treated in a separate analysis, based on the knowledge that there are distinct differences in species composition between the two sites.

We used regression models to investigate the relationships between changes in climate drivers (temperature, riverine discharge and transports) and responses in hydrography and changes in species composition in plankton, hard-bottom and soft-bottom communities for coastal Skagerrak. For hydrography we analyzed the variation in annual means of selected relevant response variables from the significant upward/downward trends from the Mann-Kendall test (Figure 13), and from reported changes in Norwegian coastal waters (Aksnes et al. 2009; Frigstad et al., 2013). As possible explanatory variables, we used a set of response variables from hydrography, river discharge and transports and the winter NAO index. The set of explanatory variables was selected to reduce correlation among variables (guided by correlation matrices in Figures A3 and A4), and based on our understanding of the relationship among variables. The following set of explanatory variables were used: River TOC, River TotN, River SPM, Winter NAO, Temperature, Salinity, DIN, PO_4, TotP, TotN, Chla and Secchi depth. In general, the observations from the same depth layer as the response was used for the explanatory variables. We analyzed the variation in the annual means of the three phytoplankton groups (diatoms, dinoflagellates and flagellates) separately. The same set of explanatory variables was used, however the chla concentration was excluded due to high correlations with plankton abundance. For the regressions of changes in hydrography and plankton, linear models (lm) was used and we ran a stepwise selection process to select the best explanatory model, using the Bayesian information Criterion (BIC) as implemented in the MuMIn package in R (Barton 2018). When both the response and explanatory variables have strong time trends (consistently decreasing/increasing), interpretation of the result is more uncertain; an explanatory variable with a strong time trend may enter because it actually is the cause of the decrease/increase, or just because it also happens to have a similarly strong time trend. In these cases, we performed extra stepwise analyses including Year as an additional explanatory variable, which effectively corresponds to removing the consistent time trend (i.e. detrend) from the data. If an explanatory variable is significant both with and without Year as an additional explanatory variable, this strengthens the belief that this variable is causally linked to the variable of interest.

For the modelling of change in hard- and soft-bottom communities the selection of environmental variables to include was executed in three steps. First, from each pair of explanatory environmental variables with a correlation coefficient larger than 0.79, one was removed from the set. Second, variables with no significant correlations with the DCA-ordinations were also removed, as calculated by the envar-function using 999 permutations (Oksanen et al. 2018). The rationale being that these did not explain any part of the observed change in the communities. All river variables were excluded from the set of explanatory variables by this process. Effects of changes in riverine discharge and transports were therefore assessed via the influence on hydrographic variables (as tested in Chapter 3.4.1). For the regression analysis of changes in species composition proxied by DCA, a linear mixed effects model (lmer) was used for hard bottom data (including station as random factor), while linear models (lm) were used for the soft bottom data (one for each station). Stepwise model selection was performed by lmerTest in all cases, to find the best reduced model (similarly to the selection process for hydrography and phytoplankton).

3 Results

3.1 Time series plots

The time series shown in this chapter are annual averages (shown with a Loess smoothing function), while the seasonally averaged data for rivers, hydrography and plankton are shown in Appendix A (Figures A5-A12).

3.1.1 Rivers

There are large variations in discharge among the rivers included in this study (see Figure A2), and the discharge in the Glomma is approximately one order of magnitude larger than Numedalslågen, Skienselva and Drammenselva.

In general, there is an increase in discharge over time for the rivers draining to Skagerrak upstream of the coastal monitoring stations (Figure 2). The transports of PO_4, Si, SPM, TOC, TotN and TotP all show increasing trends over time, with some interannual fluctuations. The transport of NO_3 is fairly stable over the time period.

There were several flood events during the autumn of 2000, and this flood is clearly evident in Figure 2, with exceptionally high discharge and transports of NO_3, Si, SPM, TOC and TotN.

Seasonal variations in element transports are largely determined by seasonal patterns in river flow, and the flow volumes were generally 1.5-2 times higher in summer (season 2; May-July) compared to the other seasons (Figure A5). This period captures the flood events related to snow melt in Glomma and Drammenselva generally occurring in May (Figure A2). This results in correspondingly high transports of TOC, NO_3, TotN and TotP during this particular season (Figures A6 and A7). The most notable long-term changes during the various seasons, is that while the winter (November-January) discharge and transport appear to be gradually increasing over time, there is a shift towards markedly higher discharge and transports during the summer season from 2010 onwards.

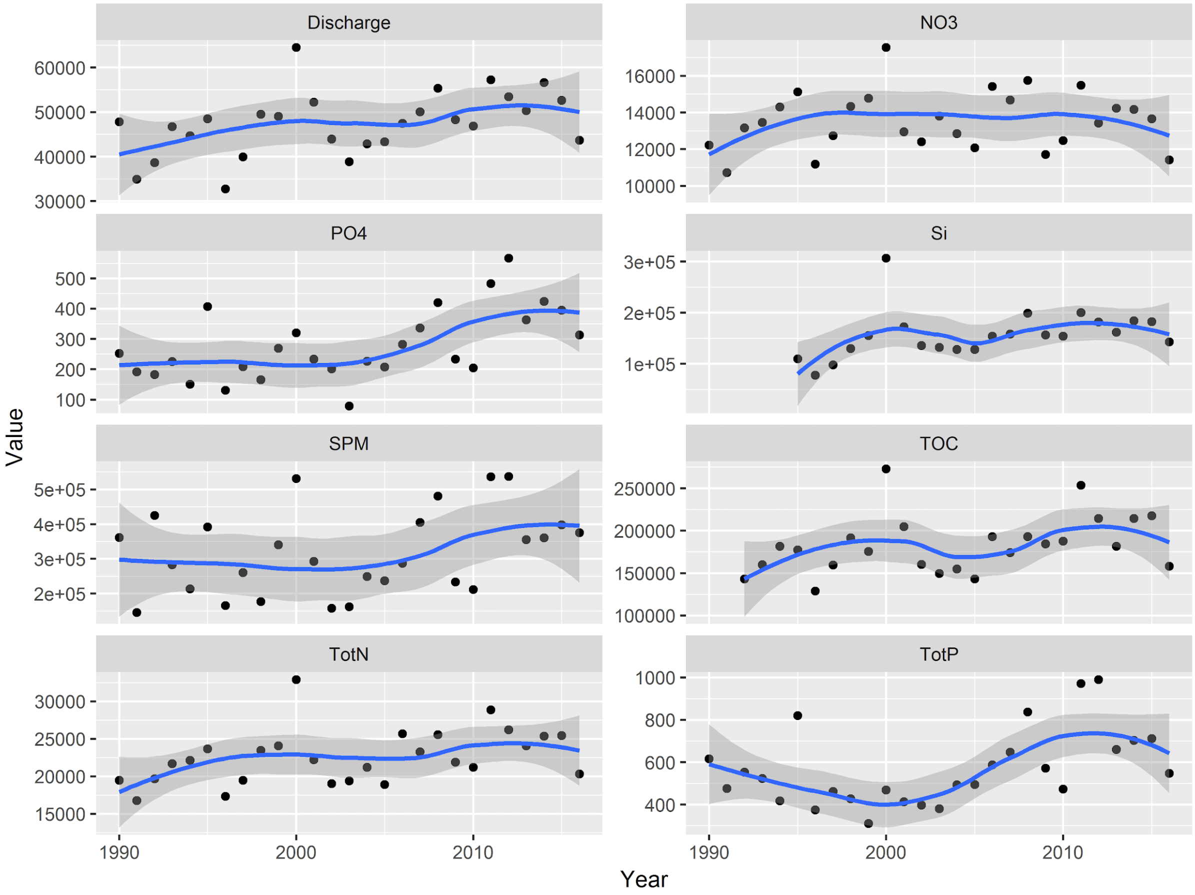


Figure 2. Total discharge (million m3) and transports (tons) summarized for major rivers draining to Skagerrak (Glomma, Drammenselva, Numedalslågen and Skienselva).

3.1.2 Hydrography

The temperature at the Arendal station increased over the period 1990-2016 for all depth layers (Figure 3), with high temperatures at the start of the monitoring period, around 2000 and from 2013 to 2016. The temperature in the deeper layer (50-75m) shows less interannual variation, and has had a gradual increase since around 2000. The salinity is highest at depth, with values around 34, 33 and 29 in the deep, intermediate and surface layers, respectively. There is a marked decrease in salinity in the surface layer in the period 2010 to 2016. The oxygen concentrations show similar temporal variations as temperature, with a stronger decrease from 2013-2016.

There is an overall decrease in the DIN and PO_4 concentrations over time in all depth layers (Figure 4). For DIN there was a sharp increase at the start of the monitoring period, with a maximum around 1995, followed by a decrease in the period 1995-2010, and more stable concentrations between 2010 and 2016. The PO_4 reduction over time is more gradual, and appears to be stronger in the intermediate and deep layers. The Si concentrations shows considerable variation between years and depth layers.

There were no apparent changes over time in the Chla concentrations (Figure 5), while TotN have slightly higher concentrations between 2000 and 2005. The concentrations of TotP are highest in the deep layer, and appears to be decreasing over the time period. The Secchi depth decreased from around 9 to 7m between 1990 and 2000, however it increased between 2010 to 2016 and returned to around similar levels as in 1990 (between 8-9m).

The concentrations of POC, PON and TSM generally increased over time in all depth layers (Figure 6). The PON and POP concentrations increased rapidly to around 2000 in the surface layer, and have stable or slightly decreasing concentrations for the remainder of the time period.

The seasonal variations in hydrographic variables over time are shown in Figures A8-A11, and the most notable seasonal changes are that while the surface salinity in winter (November-January) has decreased gradually over time, there has been a sharper reduction in the summer values since around 2010. The reductions in DIN and PO_4 over time is primarily in the winter months, while the increase in POC, PON and TSM over time is occurring over the winter to summer (November-July) period.

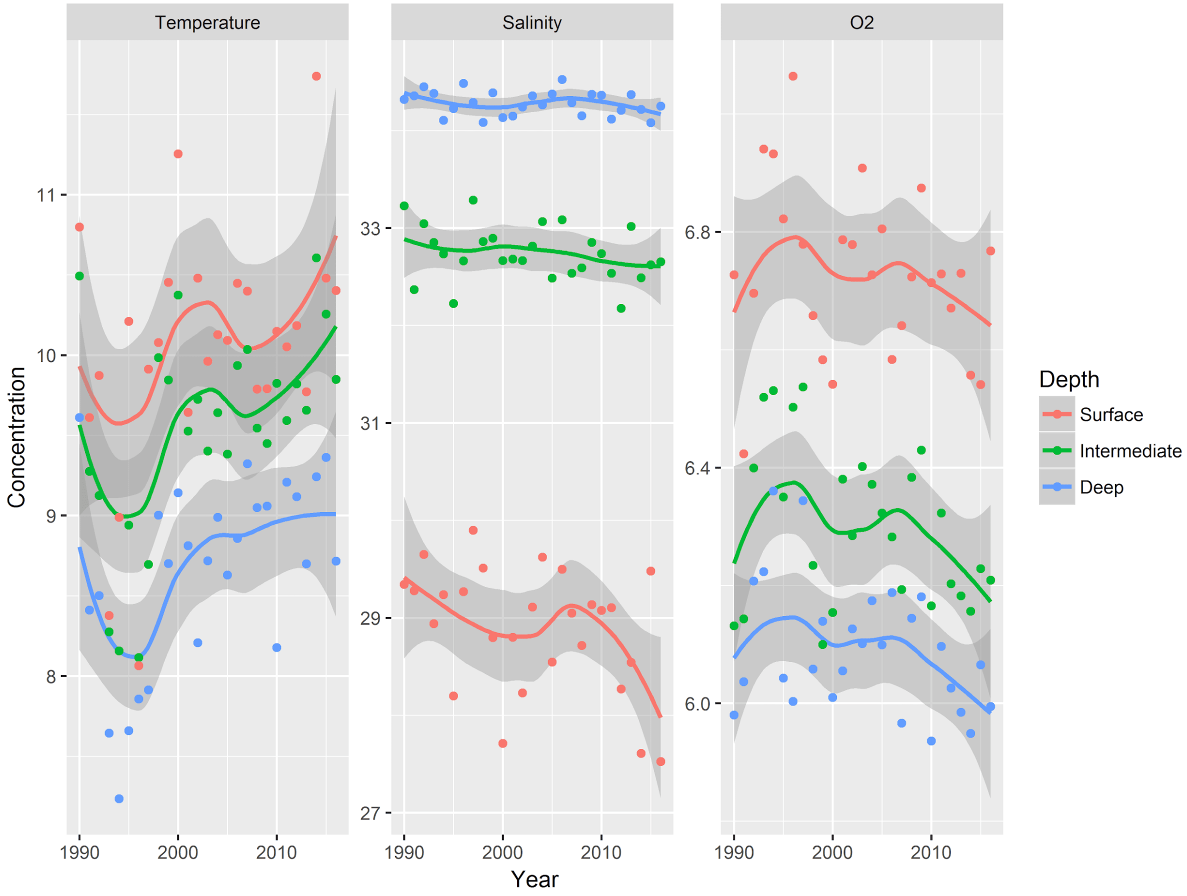


Figure 3. Time series of temperature (ºC), salinity (PSU) and oxygen (ml/l) for surface (0-10m), intermediate (20-30m) and deep (50-75) layers at the Arendal station (VT5).

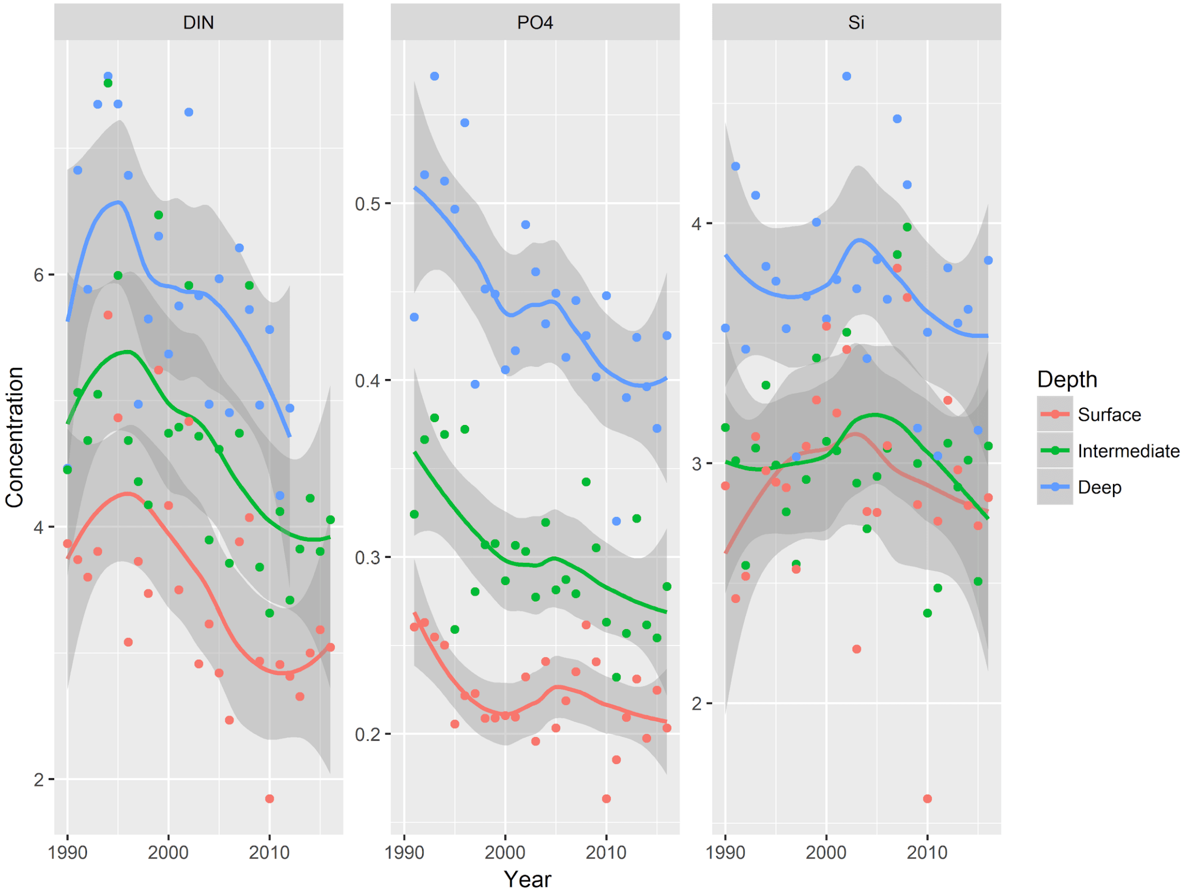


Figure 4. Time series of DIN, PO_4 and Si (all in µmol/l) for surface (0-10m), intermediate (20-30m) and deep (50-75) layers at the Arendal station (VT5).

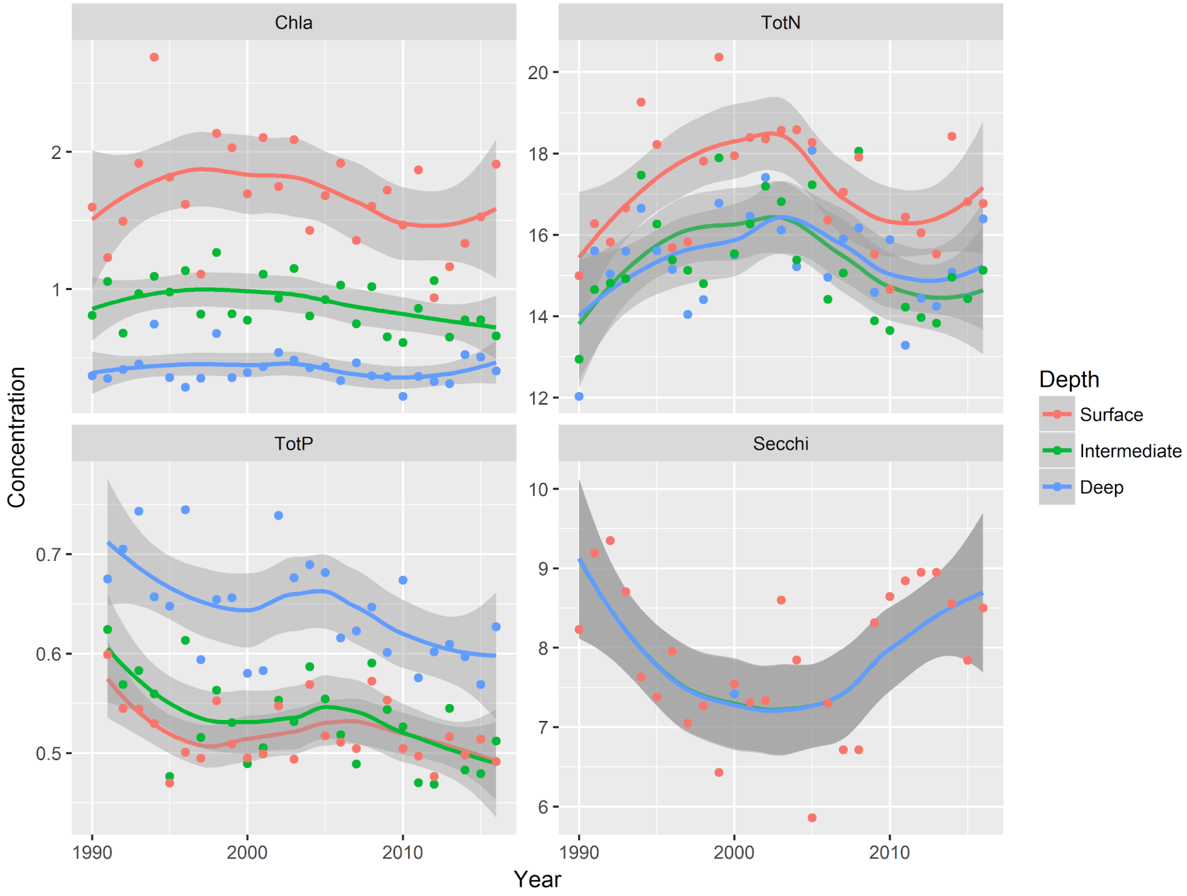


Figure 5. Time series of Chla (µg/l), TotN, TotP (both µmol/l) and Secchi depth (m) for surface (0-10m), intermediate (20-30m) and deep (50-75m) layers at the Arendal station (VT5).

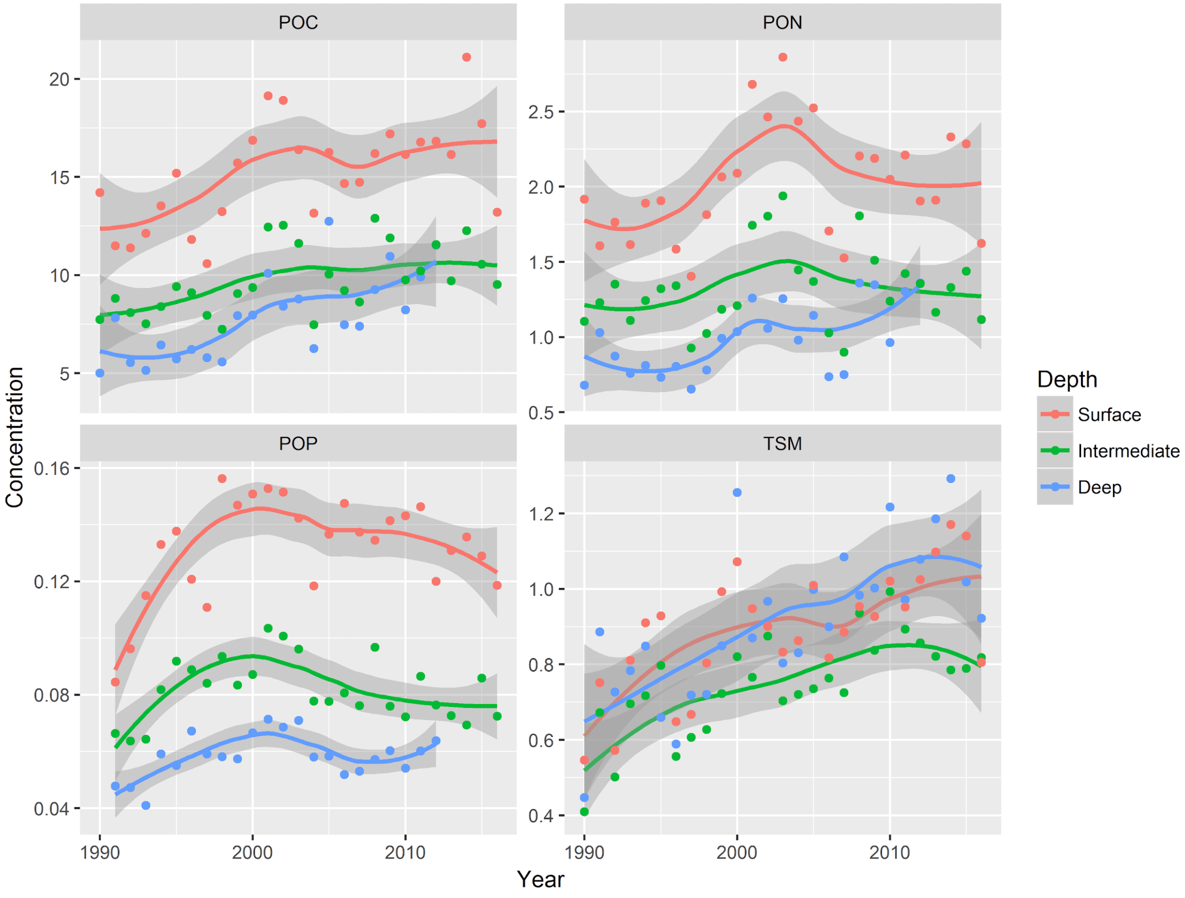


Figure 6. Time series of POC, PON, POP and TSM (all in µg/l) for surface (0-10m), intermediate (20-30m) and deep (50-75) layers at the Arendal station (VT5).

3.1.3 Phytoplankton groups

The phytoplankton species data has been aggregated into three main groups, diatoms, dinoflagellates and flagellates, where the latter group is composed of several different phytoplankton classes. The time series of the main phytoplankton groups at the Arendal station is shown in Figure 7, and there is considerable interannual variation for all groups.

There is a seasonal succession in the phytoplankton composition (see Figure A12). Diatoms are dominant and abundant during the spring period, with a maximum during the annual spring bloom in February- March. In some years, diatoms will form smaller blooms during the summer and in the autumn. Dinoflagellates are present throughout the year but is most abundant during the summer and autumn months. Smaller flagellates are present throughout the whole year with minimum abundance during the winter months and maximum in early spring, through the summer and early autumn.

For dinoflagellates there is a general decrease over time, the abundance was higher during the 1994-2001 period, however the group shows a noticeable and sustained reduction since 2002. The reduction in dinoflagellate abundance has occurred during all times of the year, both during the seasons where they are most abundant (summer and autumn), as well as the other seasons.

The flagellates group shows interannual variations, however as a whole there is a decrease from 1994 to 2012, but their numbers in the period 2013-2016 has been almost on a par with their abundance in the 1990s. The recovery in the later years has been especially strong in spring, where abundance historically has been lower than in summer and autumn.

Diatoms, which are mostly present in spring, do not show a marked trend over time, but display more a pattern of multi-year fluctuations. Some of the last years have seen a high abundance of diatoms also in summer, but it is too early to say if this is part of a trend.

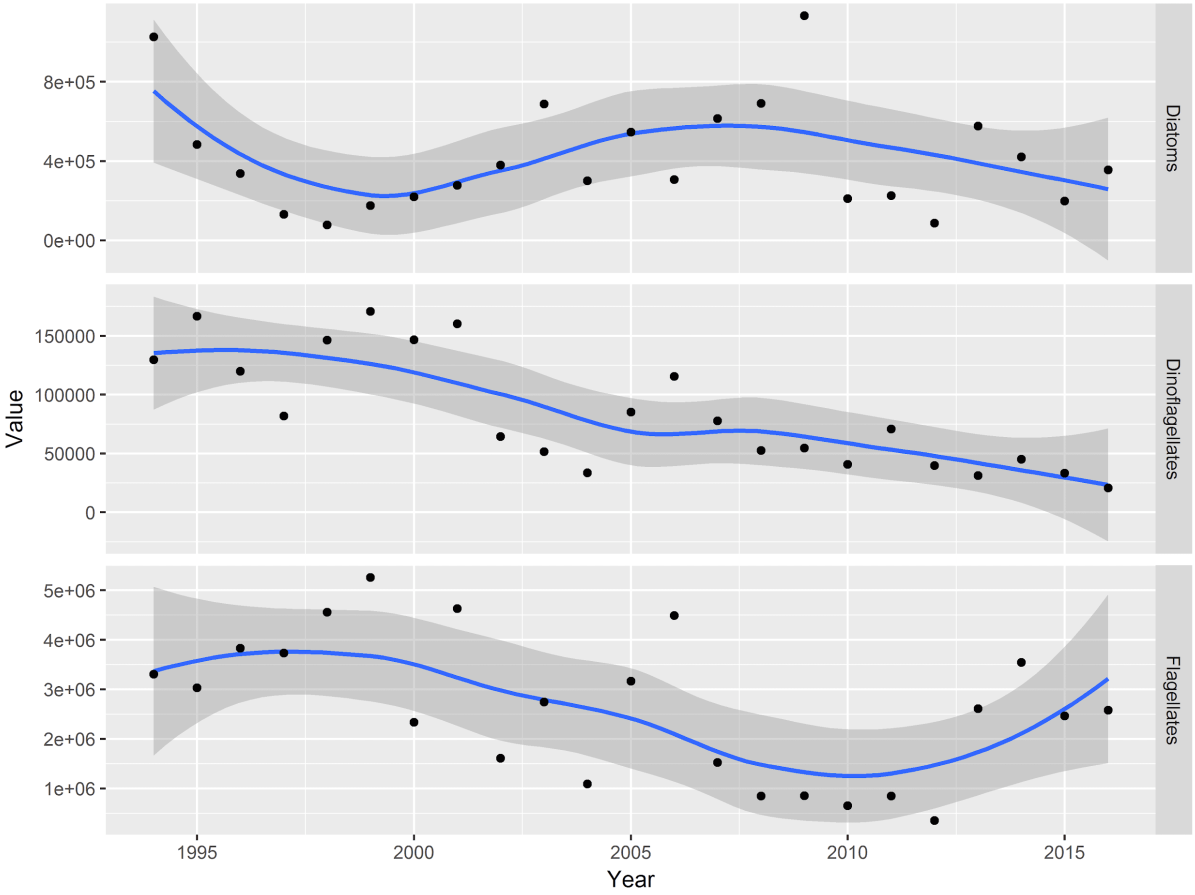


Figure 7. Time series of the main phytoplankton groups diatoms, dinoflagellates and flagellates (cell/l) at the Arendal station (VT5).

3.1.4 Hard-bottom communities

The data shows that there has been changes in the structure of the hard bottom species communities over time (1990 - 2016). The number of algal species recorded (red, brown and green) reached a maximum just before year 2000, and decreased towards 2016. The number of faunal species peaked at approximately the same time, and decreased somewhat before increasing again from year 2005 and onwards (Figure 8).

The species richness is higher now than in the early 1990s, but has decreased since around year 2000 (Figure 9). Both diversity indices (the Shannon-Wiener and the Pielou's) peaked between year 2000 and 2005, meaning that species diversity was the highest and also that the presence of dominant species was less prominent in this period (Figure 9). Both diversity indices are similar when comparing the data from 1990s to the surveys of more recent years, although the species diversity was a bit lower in the early 1990s.

The overall change seems to have been a shift from more algal species towards more faunal species, with minor changes in the evenness (i.e. the dominance-structure) within the community.

Changes in lower growth depth of certain macroalgal species at a location over time is an indication of changes in light conditions. The lower growth depth of the nine macroalgae species included in the MSMDI have generally become shallower over time (Figure 10), resulting in the suggested decrease in the ecological status judged by the MSMDI (Naustvoll et al., 2018).

Figure 8. Time series of number of species in different hard-bottom groups (animals and macroalgae, the macroalgae were also separated into red, brown and green algae) for stations HT113 (Tromøya N) and HR104 (Prestholmen).

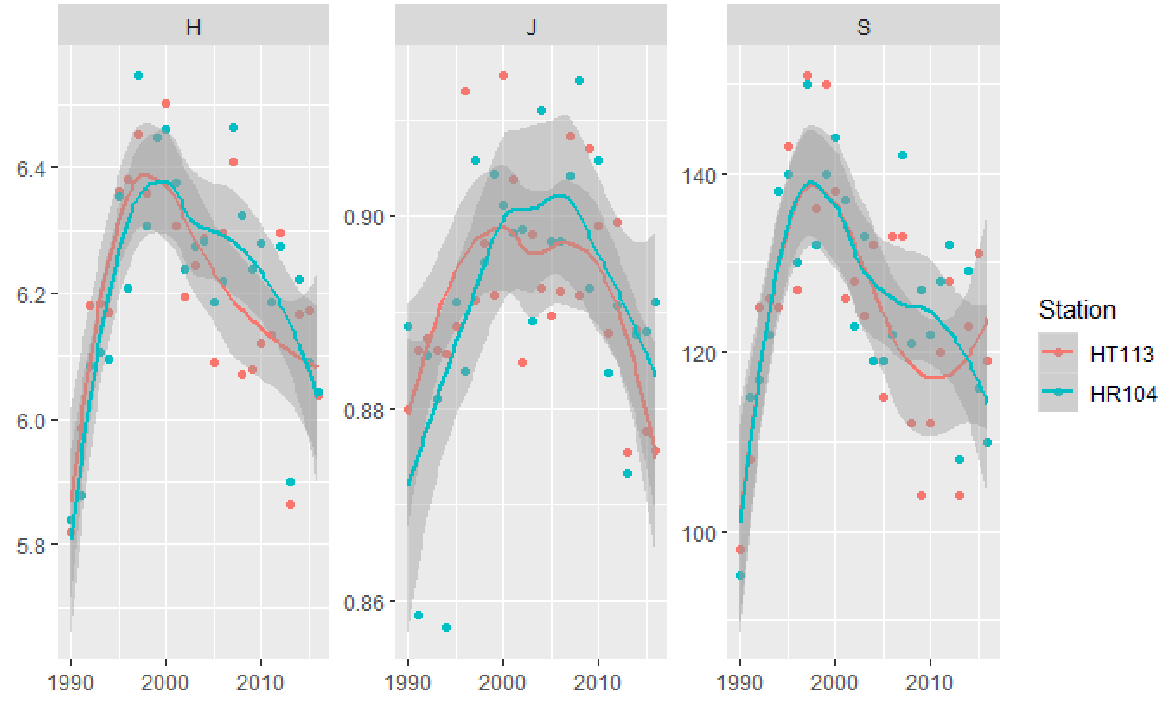


Figure 9. Time series of the diversity indices Shannon-Wiener (H') and Pielou's evenness (J') and overall species richness (S) in number of species.

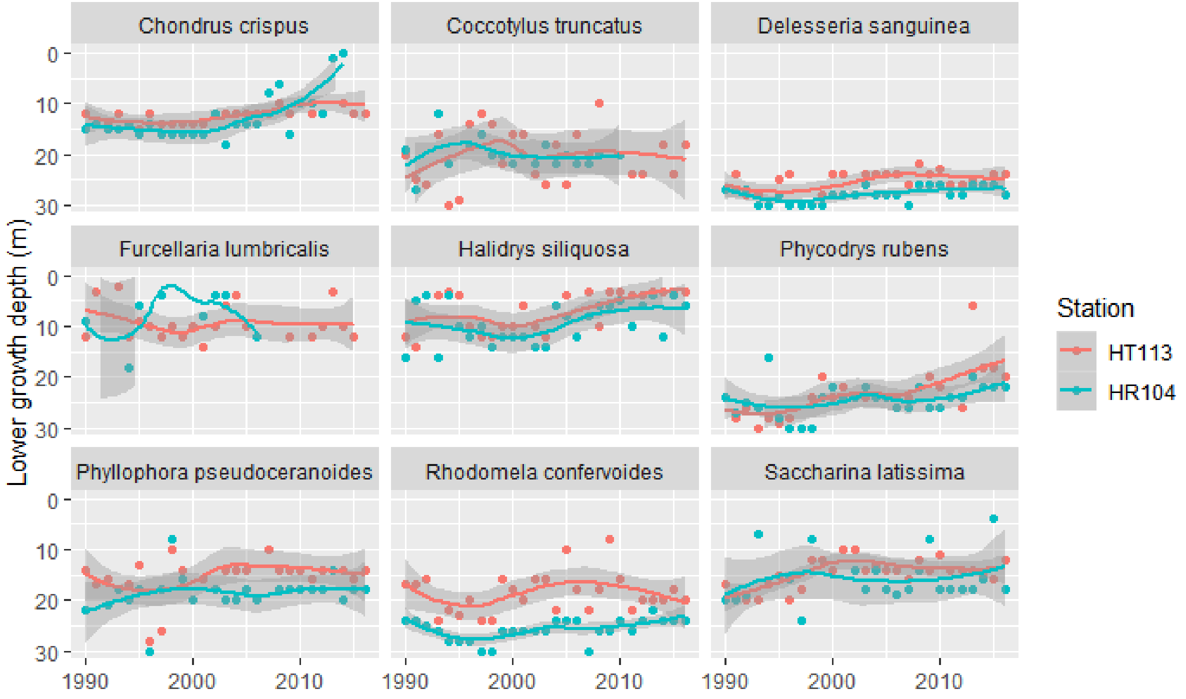


Figure 10. Time series of lower growth depth for the 9 species included in the MSMDI-index for stations HT113 (Tromøya N) and HR104 (Prestholmen).

3.1.5 Soft-bottom fauna

At the shallow station BR1 there was a tendency of an increase in number of species and number of individuals, particularly after 2010 (Figure 11). At the same time, the variation has been large the last years, particularly in number of individuals. For H' and NQI1 there was no clear trend during the monitoring period, but both parameters had a weak increase towards year 2000 and then during the last years. A strikingly similar curve was observed for TOC. As expected, there was no change in grain size during time; i.e. the sediment itself did not change.

At the deep station BT44 there was an increase in number of species and the two diversity indices (Figure 12). The number of individuals declined, particularly until 2000, although it has increased slightly the latest years. For TOC, there appeared to be somewhat lower values in the 1990s than later in the period. Again, grain size did not vary systematically. The lower variation in the first part of the period can be explained by the fact that 4 replicates were sampled earlier (1990-1997 and in 2002-2004) and the points are a mean of these three, but only one replicate was collected in the other time-periods.

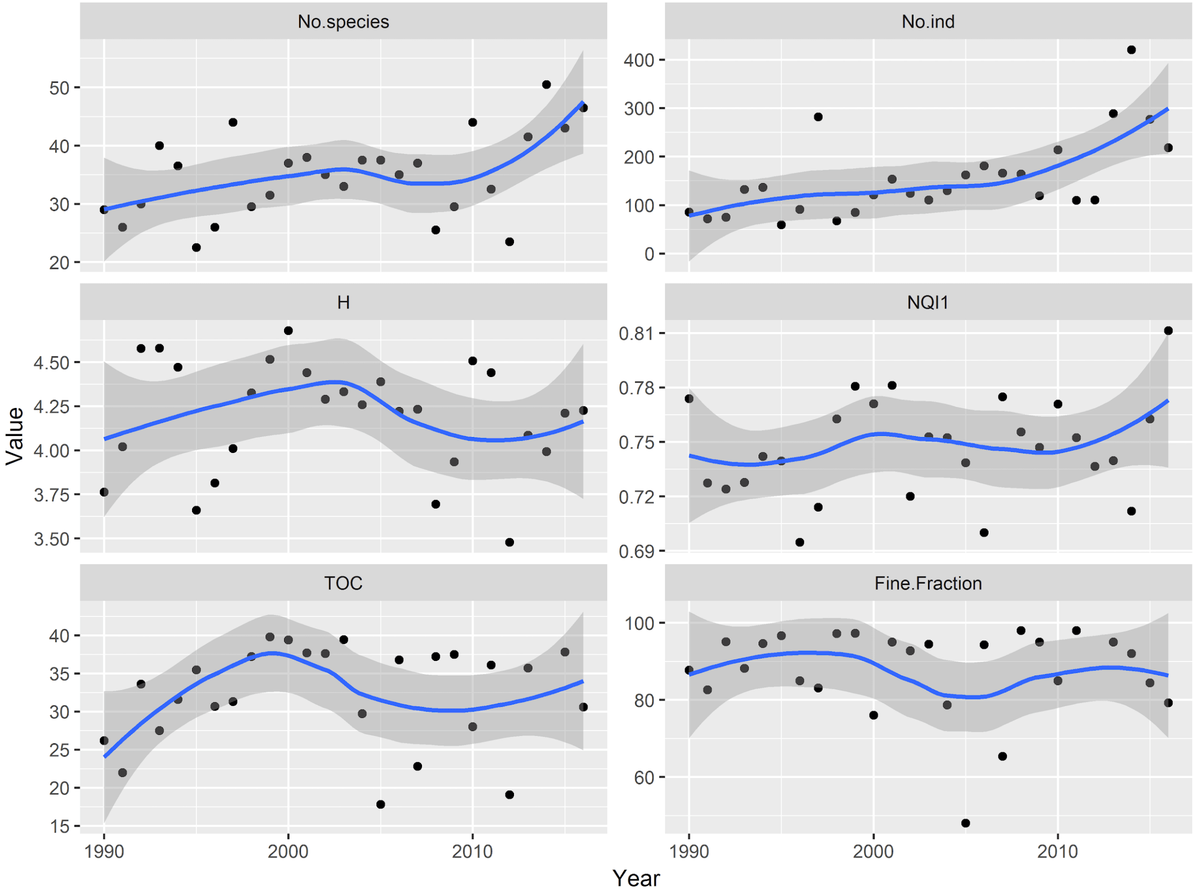


Figure 11. Time series of number of species and individuals, indices H' and NQI1 and the TOC-concentration and fraction of fine sediments (%<63um) for the shallow station BR1 (Grimstad). The biological parameters are mean values of four grabs.

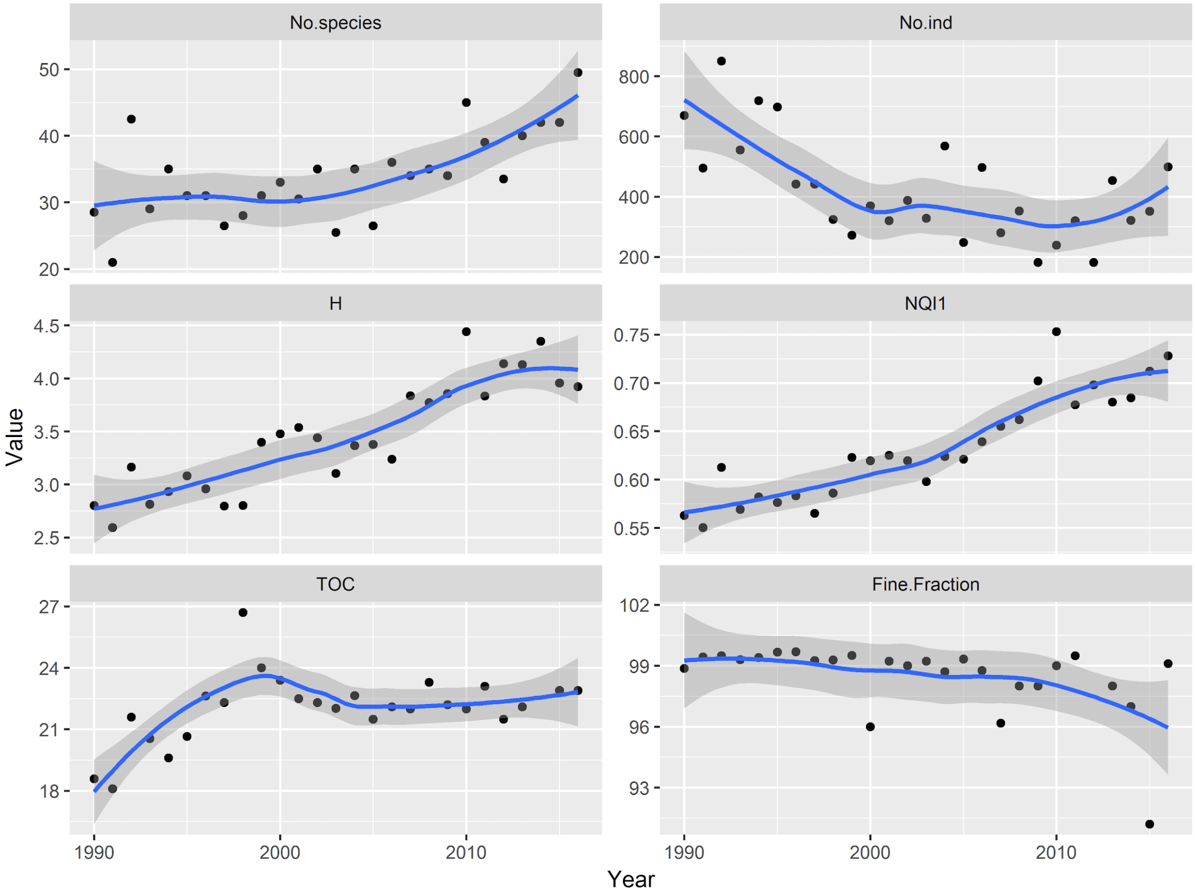


Figure 12. Time series of the number of species and individuals, indices for H' and NQI1 and the TOC-concentration and fraction of fine sediments (%<63 um) for the deep station BT44 (Arendal). The biological parameters are mean values of four grabs.

3.2 Time series trends

We tested for the presence of monotonic time series trends using a non-parametric Mann-Kendall test on annually aggregated data for all variables in the hydrography, plankton and river datasets (Figure 13, summarized in Table B1). A monotonic upward (downward) trend means that the variable consistently increases (decreases) through time, but the trend does not have to be linear.

There were significant upward trends for discharge and all transports for the rivers draining to Skagerrak. The SPM transport was also increasing (with approx. 2 % per year), however the trends for SPM and NO_3 were not significant.

The variables with the largest upward trends for hydrography was the POC, PON and TSM of the deep layer, which all increased by around 2-3% per year. The TSM and POC also increased significantly in the intermediate and surface layer, although with slight lower annual percentages. The temperature also increased significantly over time for the deep and intermediate layers, while the temperature in the surface layer also showed an increase, however this was not significant. There was a small but significant downward trend in salinity in the surface layer, while there were no significant changes in the salinity of the intermediate and deep layers. The TotP and PO_4 of the intermediate and deep layers showed significant downward trends, together with the DIN in all depth layers.

The largest downward trends over time in all variables tested were for the flagellates and dinoflagellates phytoplankton groups (-10-8 % per year), while there was no significant change in the diatoms.

The macroalgal index based on lower growth depth (MSMDI) had significant downward trends for both stations, while the soft-bottom index NQI1 had a significant upward trend at the deep station BT44.

The seasonal Mann-Kendall test is shown in A13, and confirms the observation from the time series plots of seasonal river discharge and transports (A5-A7), that there is a stronger upward trend in discharge and transports for the summer (May-July) period. The downward trend in Chla is also strongest in the May-July period.

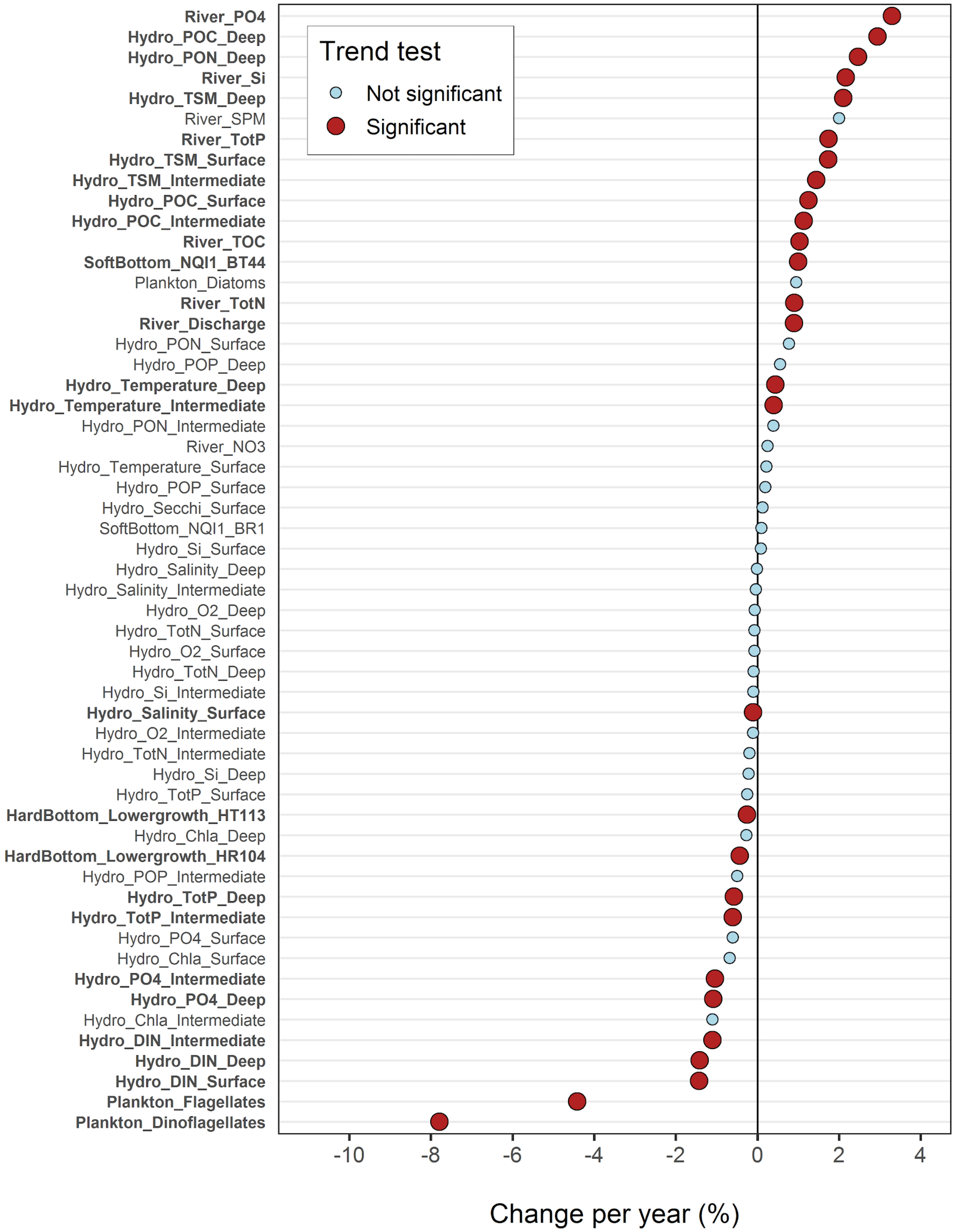


Figure 13. Time trends of annually aggregated data for all variables in the hydrography, plankton and river datasets, as well as the lower growth limit (based on the MSMDI index) for hard-bottom macroalgae and the NQI1-index for soft-bottom fauna. The trends (Theil-Sen slope) are given in percentage change in the mean quantity per year. Red dots and bold types indicate significant trends (Mann-Kendall trend test, $p < 0.05$). The actual numbers are given in Appendix table B1.

3.3 Ordinations and changes in species composition

3.3.1 Hard-bottom

The main ordination axis from the DCA (i.e. DCA1) shows that the overall structure of the hard-bottom communities (that is the number of species, which species and the abundance of each species) in the depth range 0-30 m has changed over time (Figure 14). The community structure changed more or less gradually in the 1990s, before more rapid changes occurred in the 2000s. The more recent surveys may indicate that the changes are now slowing down (at least in HT113), but the validity of this pattern will not be established for yet some years.

The community changes are interpreted in light of the species scores also obtained from the DCA. A species score is an estimation of the species' optimum along the DCA-axis (a theoretical gradient), that is; where the species is likely to have been the most abundant.

Because the main DCA-axis in our analysis is strongly correlated with time, the species with the most extreme scores on either end of the main ordination axis (DCA 1) represent the most distinct differences between early and late surveys. These are species likely to have gone, come or changed substantially in abundance over time. Species with low DCA scores were probably more abundant at the beginning of the monitoring period, while species with high scores are likely to be more abundant today. Among the macroalgae, the most prominent difference between early and recent surveys seems to be a decrease in several red algal species and an increase in some green algae (Figure 15). The introduction of the black-listed species *Heterosiphonia japonica* is also evident, and this red algae has been recorded in increasing amounts since it was first recorded in 2004. Among animal species, a change in filter feeders has been the most apparent change (Figure 16). The low axis score of *Mytilus edulis* may suggests that blue mussels were registered to a greater extent in the earliest surveys. This is in concurrence with notes of reductions in blue mussel populations along the southern coast of Norway, a potential large-scale change that is yet poorly documented.

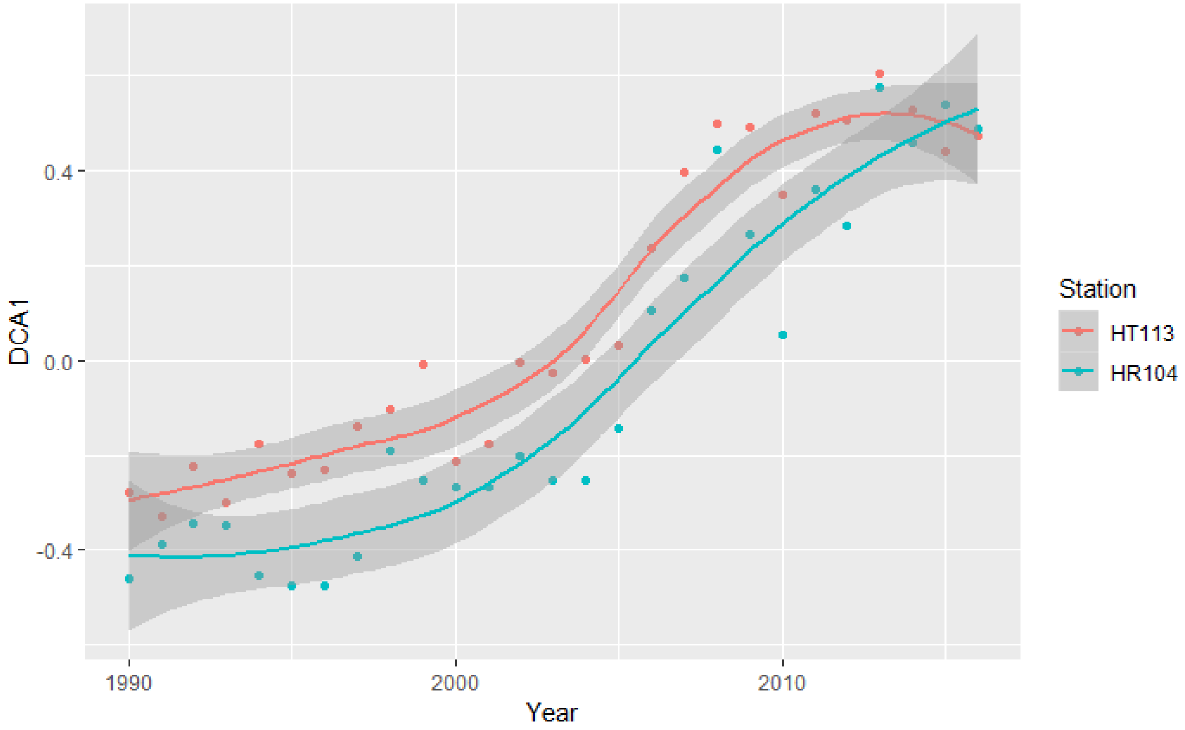
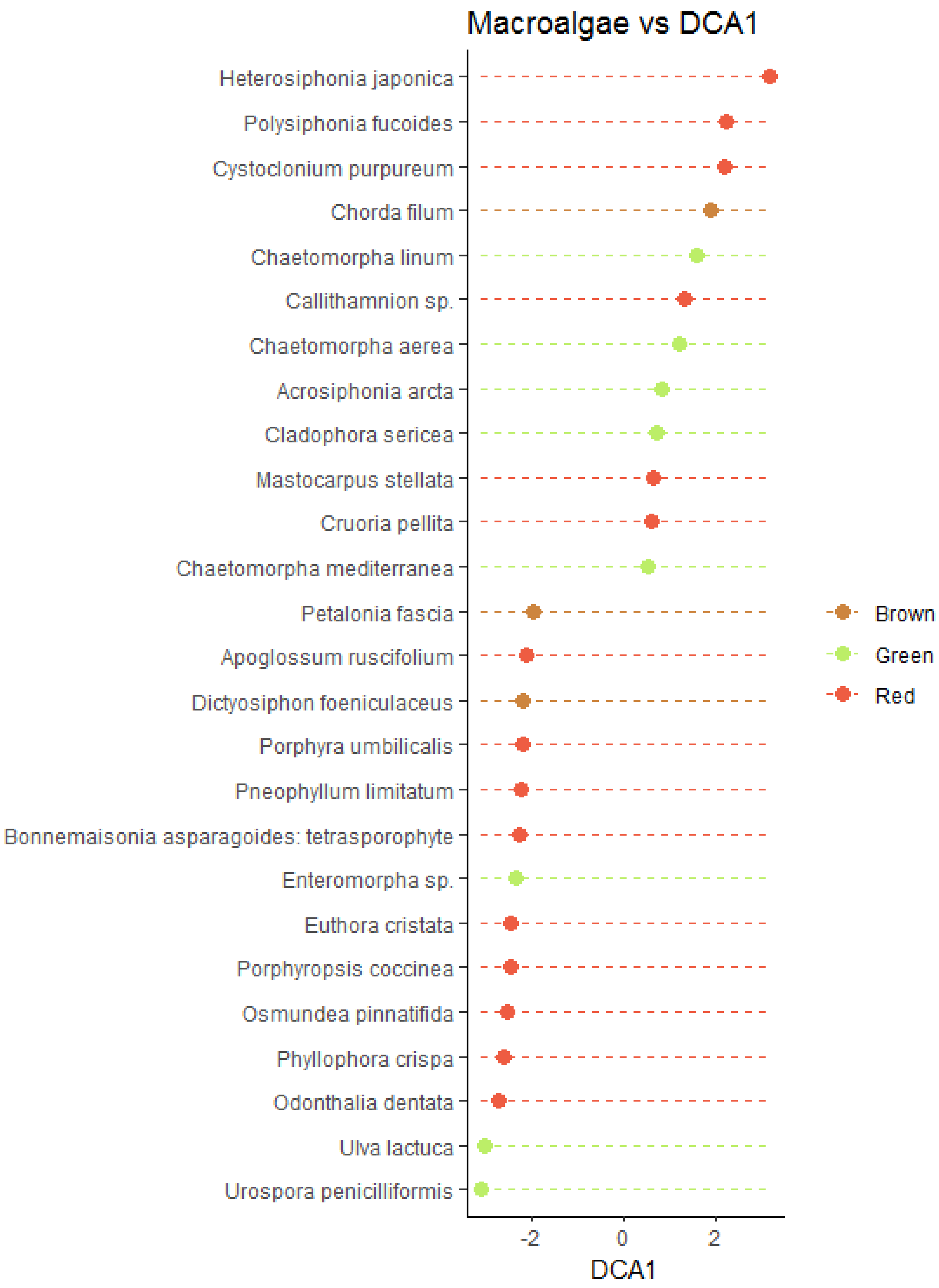
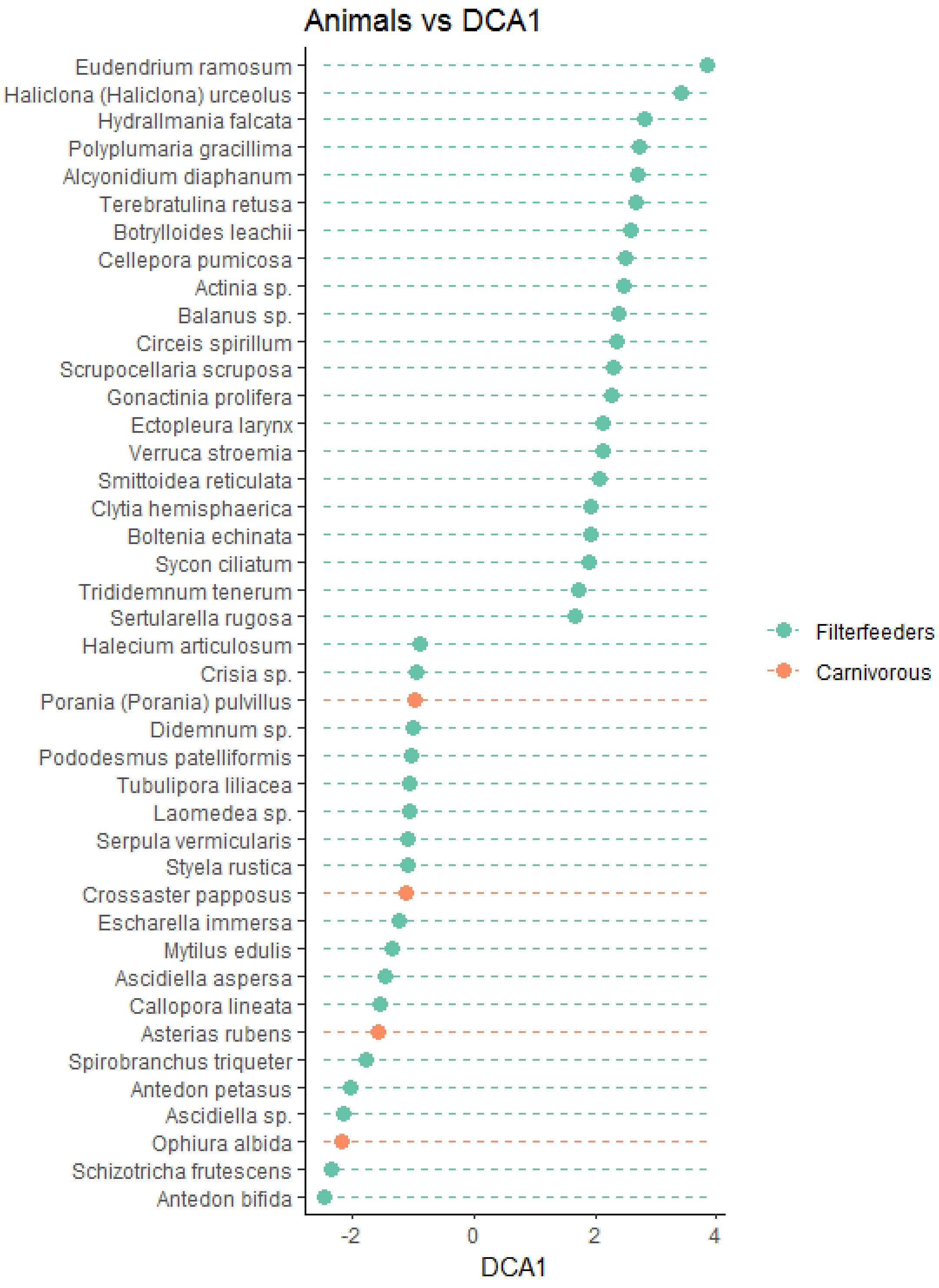


Figure 14. Main ordination axis (DCA1) of hard bottom communities from 0-30 m depth at HT113 (red) and HR104 (blue) versus year.



source: Macroalgae subset (smallest and largest 10 % of DCA-scores)

Figure 15. Species scores obtained from DCA for macroalgae species versus DCA1.



source: Animal subset (smallest and largest 10 % of DCA-scores)

Figure 16. Species scores obtained from DCA for macroalgae species versus DCA1.

3.3.2 Soft-bottom fauna

The DCA of soft bottom fauna (Figure 17) shows that the species composition changed over time at both stations. The main ordination axis (DCA1) is assumed to represent this temporal trend. At the deep station BT44 there was a consistent trend over the entire time period. At the shallow station BR1 there was not any profound change from 1990 to approximately 2002, but from then a clear trend occurred.

As for the hard-bottom communities, the changes in species composition over time is interpreted from the species scores obtained from the DCA. Again, the species with the most extreme scores on either end of the main ordination axis (DCA 1) represent the most distinct differences over time. At the shallow station BR41, eight of the ten particularly increasing species were molluscs, which for some reason have been benefited (Figure 18). From the list, it does not appear to be a clear trend in the sensitivity of the species; there were both sensitive and more tolerant species in both time-periods, which accords with the finding above that there was not any clear trend in the NQI1-index over time (Figure 11).

On the deep station BT44, again molluscs seem to have been benefited during the later part of the study period. Further, there appeared to be a trend with a decrease of tolerant species over time (with the exception of the increase in the tolerant mollusc *Thyasira sarsi*). As an example, the small opportunistic annelids *Heteromastus filiformis* and *Notomastus latericeus* was far more abundant in the first years of the monitoring period than in the last years (Figure 19), which is in line with the reduced eutrophication load. The trend for the *H. filiformis* was also documented by Trannum et al. (2018). On the other hand, more sensitive species like tube-building annelids (e.g. maldanids; *Rhodine loveni* and Euclymeninae indet.) increased.

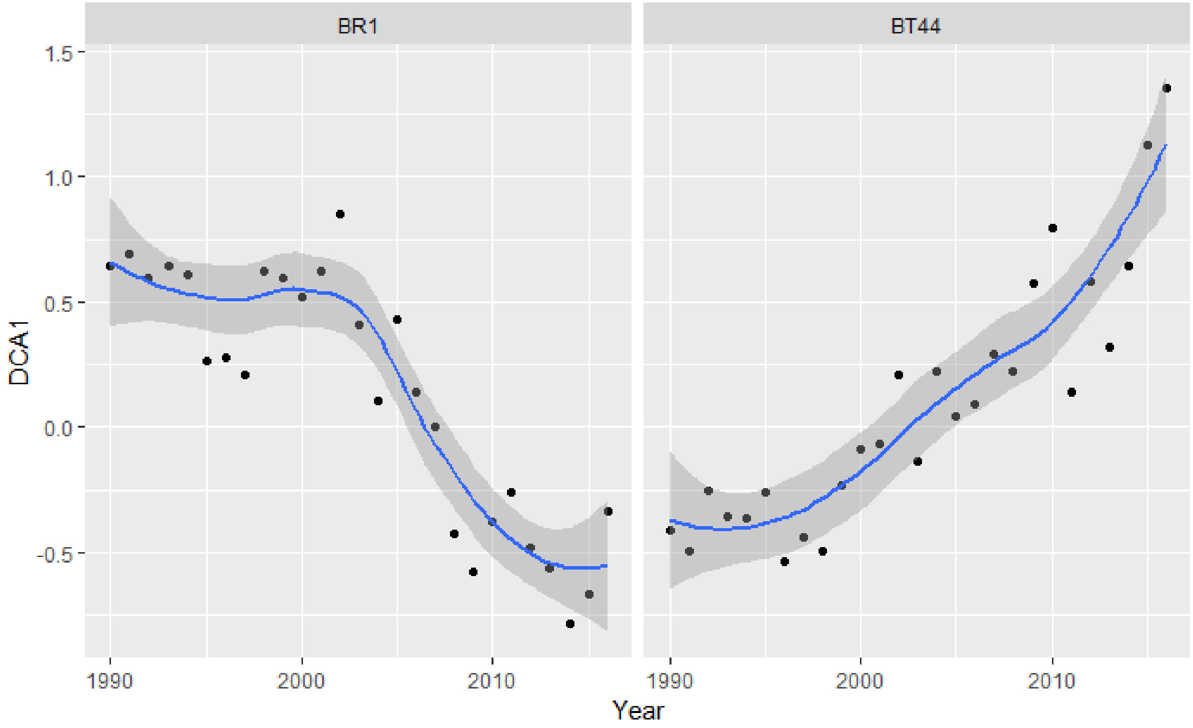
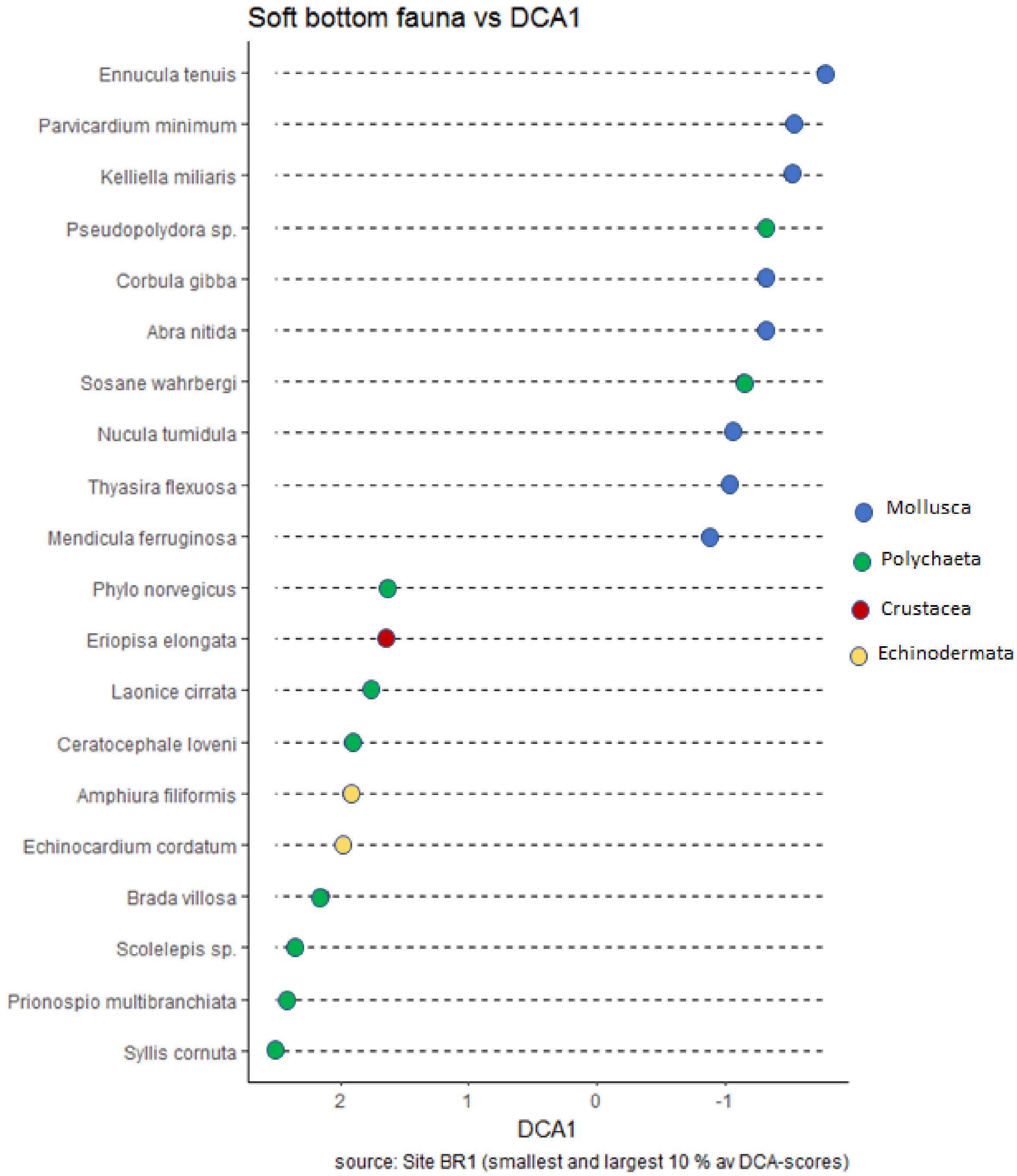
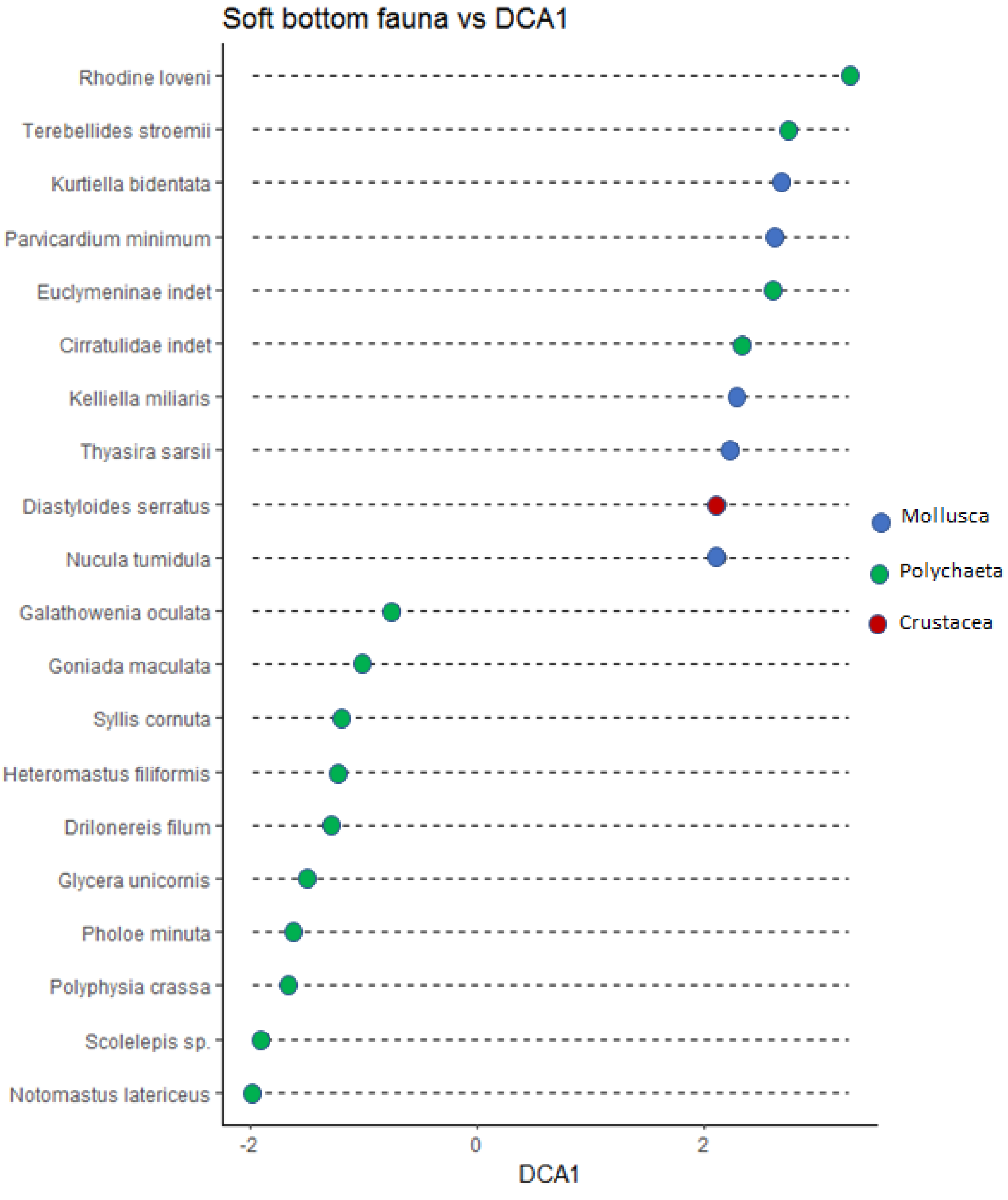


Figure 17. Main ordination axis (DCA1) for the shallow soft bottom fauna station BR1 (left) and the deep station BT44 (right) versus year.



source: Site BR1 (smallest and largest 10 % av DCA-scores)

Figure 18. Species scores obtained from DCA for soft-bottom fauna versus DCA1 for the shallow station BR1.



source: Site BT44 (smallest and largest 10 % av DCA-scores)

Figure 19. Species scores obtained from DCA for soft-bottom fauna versus DCA1 for the deep station BT44.

3.4 Regression analyses

3.4.1 Hydrography

For hydrography, we analyzed the variation in annual means of POC, TSM, PON and salinity, and as possible explanatory variables we used a set of selected variables from rivers, hydrography and the winter NAO index (see detailed description in Sect. 2.2) From 2013, the measurements of POC, PON, POP and DIN in the deep layer (50 and 75m) were discontinued, and these variables were therefore excluded from the regression analyses. There were generally high correlations between the measurements in the deep and intermediate layers (see Figure A3), and we therefore used the intermediate values as proxies where necessary. In models for the deep or intermediate layers, we used the measurement of the same variable from the surface layer as an additional explanatory variable.

For POC the best model explaining the annual mean concentrations included surface salinity and riverine transports of TOC and SPM (Figure 20). The strongest relationships was with surface salinity, and secondly with river transport of TOC. In general, the POC concentration in the surface layer was higher at low salinities, and increased with riverine transport of TOC. The relationship with SPM transport was uncertain ($p > 0.05$). A similar relationship was found for the surface TSM concentrations (Figure 21), where the best model included surface salinity and river TOC.

High concentration of PON in the surface layer, was associated with high TotN and low DIN concentrations, respectively (Figure 22). Increasing PON with decreasing DIN concentrations could reflect biological uptake and incorporation into organic matter. However, as the analysis is performed on annual, this is probably related to the opposite direction of trends for these two variables (see Figure 12), where the PON is increasing, while the DIN is decreasing over the duration of the monitoring period. The PON concentration shows a positive relationship with TotN, which is natural as increasing PON concentration also implies increasing total nitrogen (i.e. TotN).

For the POC, TSM and PON in the deeper layers, the concentration in the surface layer was the most significant explanatory variable, with concentrations in the deeper layer increasing as the surface concentrations increased (data not shown).

For salinity in the surface layer, we used river discharge and the winter NAO as explanatory variables, and rather surprisingly only the river discharge was retained in the best model (Figure 23). The salinity in the surface layer decreased with increasing discharge, however the total amount of variation described by the model was quite low ($R2 = 0.21$).

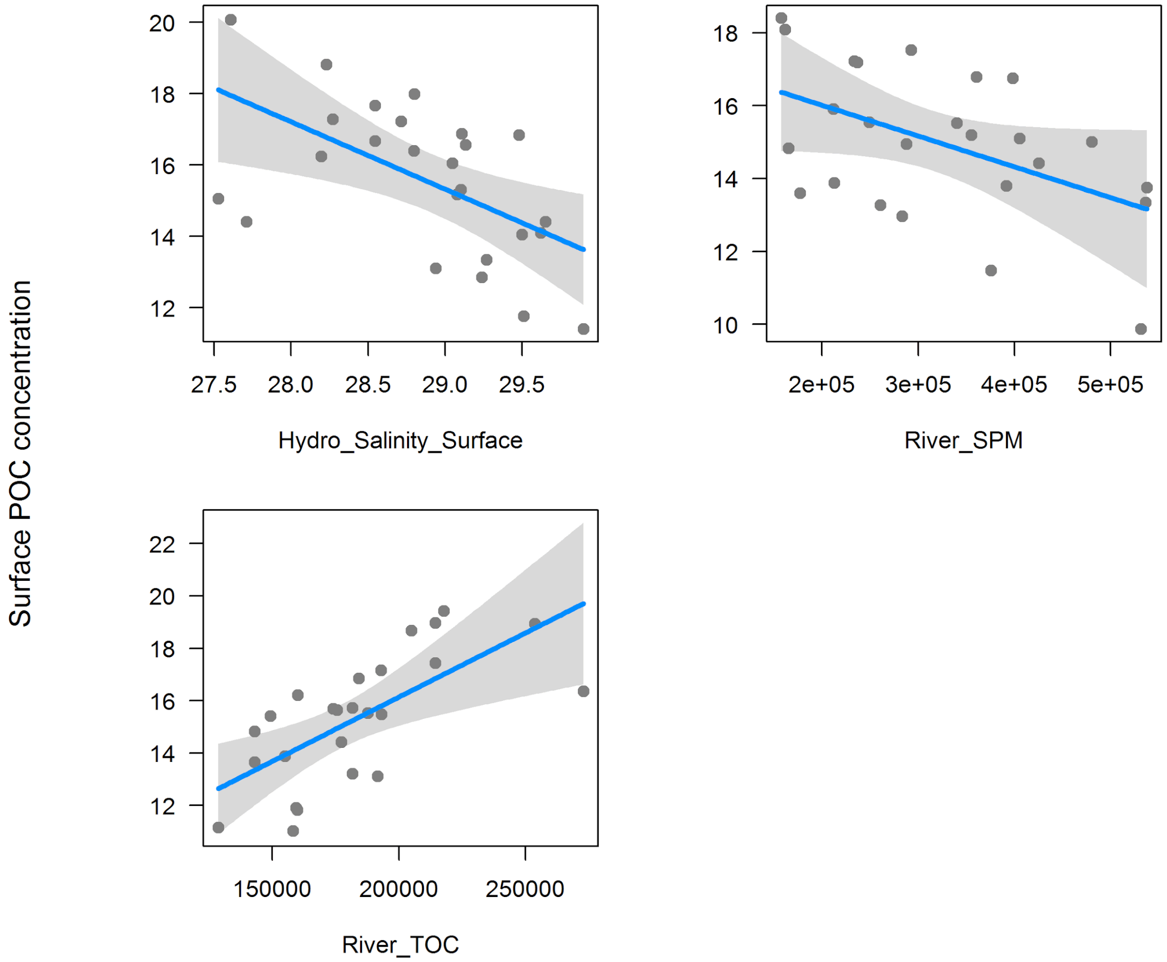


Figure 20. Variables affecting the annual mean POC concentration in the surface layer (model R2 = 0.52).

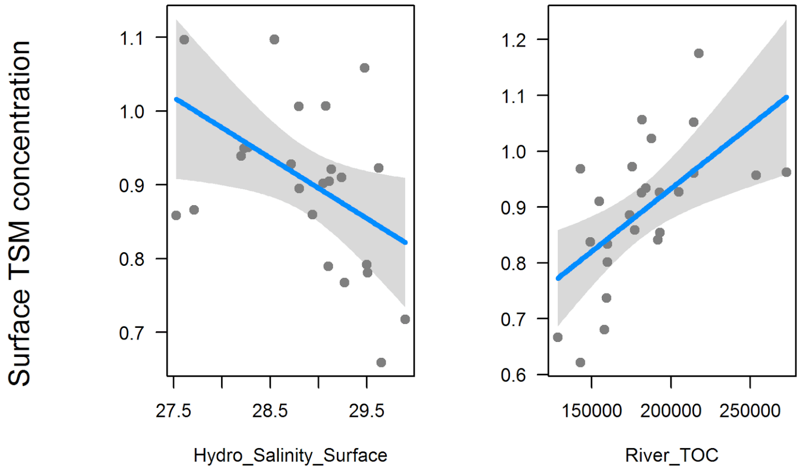


Figure 21. Variables affecting the annual mean TSM concentration in the surface layer (model R2 = 0.51).

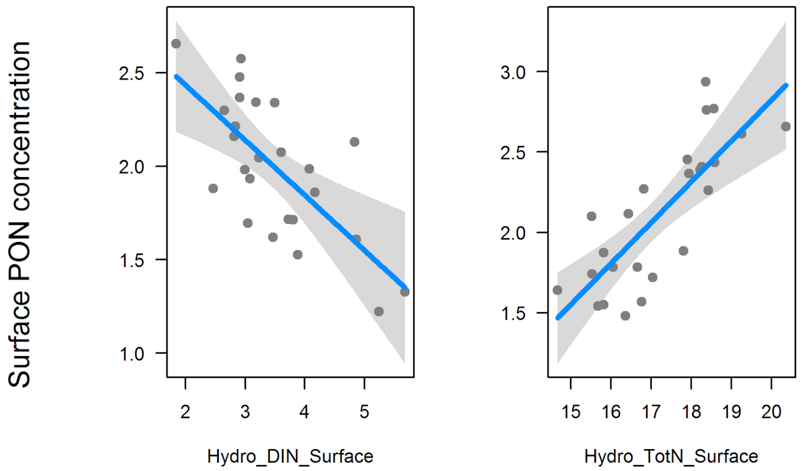


Figure 22. Variables affecting the annual mean PON concentration in the surface layer (model R2 = 0.51).

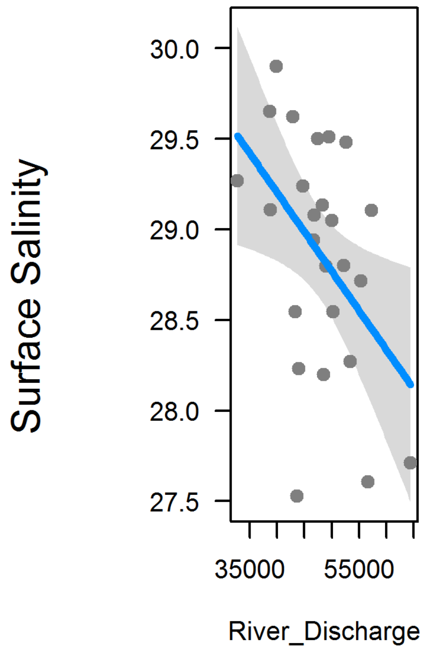


Figure 23. Variables affecting the annual mean salinity in the surface layer (model R2 = 0.21).

3.4.2 Plankton

We analyzed the variation in the annual means of the three phytoplankton groups (diatoms, dinoflagellates and flagellates) separately. As possible explanatory variables, we used the same set of variables used for hydrography, however we excluded the Chla concentration, as this is a measure of plankton abundance (see description in Sect. 2.2). We did, however, allow Secchi depth as a potential explanatory variable, although low Secchi depth (= low visibility in the water) can be a result of high plankton abundance. However, Secchi depth is also affected by the particulate and dissolved organic matter from rivers, which can potentially have a feedback effect on phytoplankton productivity (through shading). We therefore included Secchi depth in the analyses, as it can be both an effect and a cause for changes in phytoplankton abundance.

High abundance of diatoms was associated first and foremost with high phosphate (PO_4) concentration in the surface water, thereafter with low salinity and low silicate concentrations (Figure 24). If we include Year as an explanatory variable, which corresponds to analyzing detrended data, phosphate is still significant, which increases the likelihood that phosphate is causally linked to diatom abundance.

The best model explaining mean annual dinoflagellate abundance consists of six variables (Figure 25). The three strongest relationships are the positive relationship between dinoflagellates and river TOC and the negative relationships with marine surface phosphorus (TotP) and Secchi depth. These three variables were also significant in a detrended analysis (including Year as an explanatory variable). Furthermore, there is a positive association with marine dissolved inorganic nitrogen (DIN), and negative associations with sea water temperature and river suspended particulate material (SPM). The increase in SPM and the decrease in DIN could each account for 30-35% of the observed decline in dinoflagellates, while the increase in temperature could account for 21%. River TOC has increased, and as it is positively associated with dinoflagellates, it is counteracting the negative effects of changing SPM, DIN and temperature.

The best model explaining mean annual flagellate abundance consists of three variables (Figure 26). High flagellate abundance is associated with low levels of total nitrogen (TotN), low levels of river suspended material (SPM), and low Secchi depth. The latter may (as mentioned above) be an effect rather than a cause. None of these variables were chosen if we removed the temporal trend from the data, which indicates that this result should be treated with some caution.

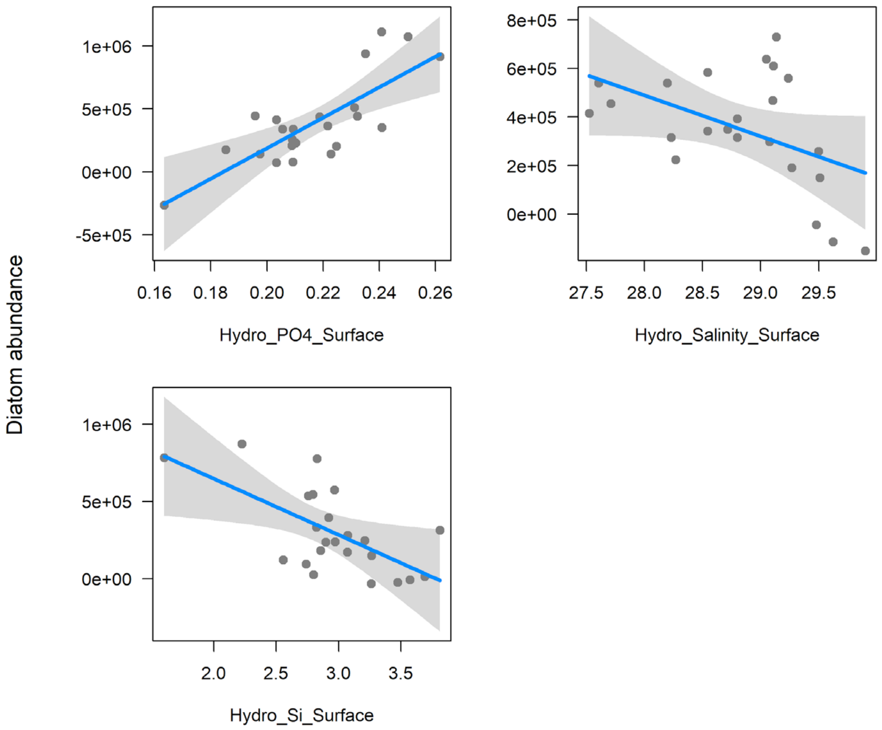


Figure 24. Variables affecting the annual mean diatom abundance (model R2 = 0.45).

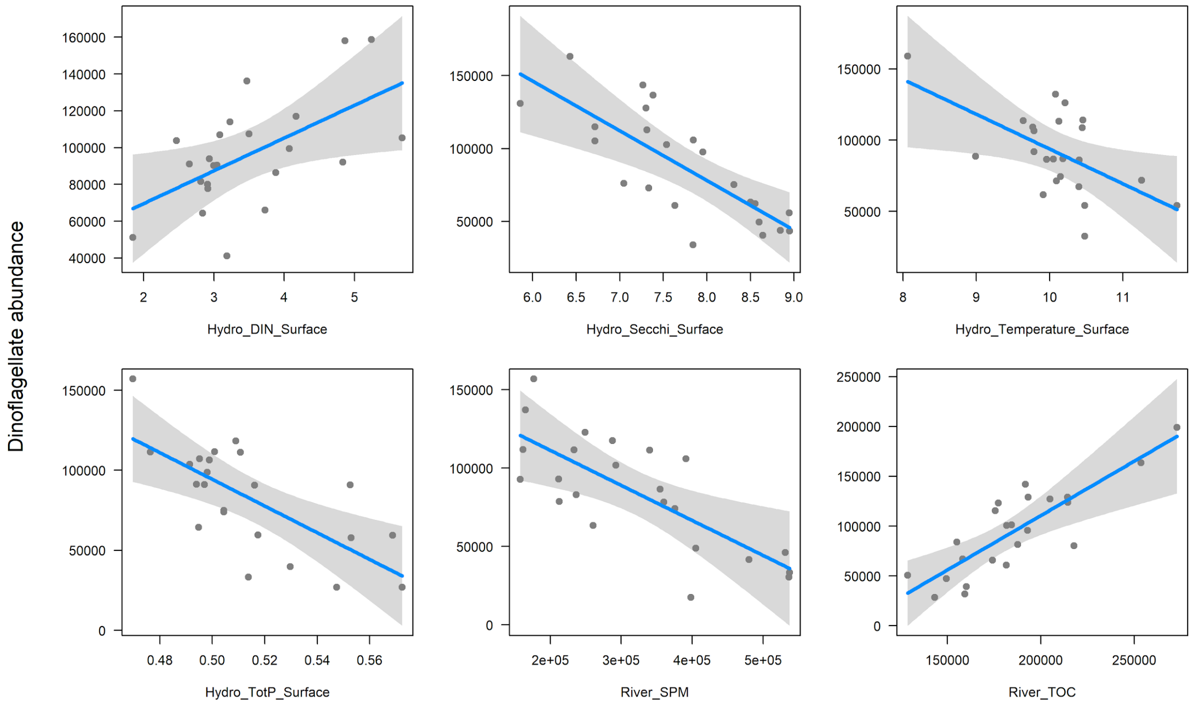


Figure 25. Variables affecting the annual mean dinoflagellate abundance.

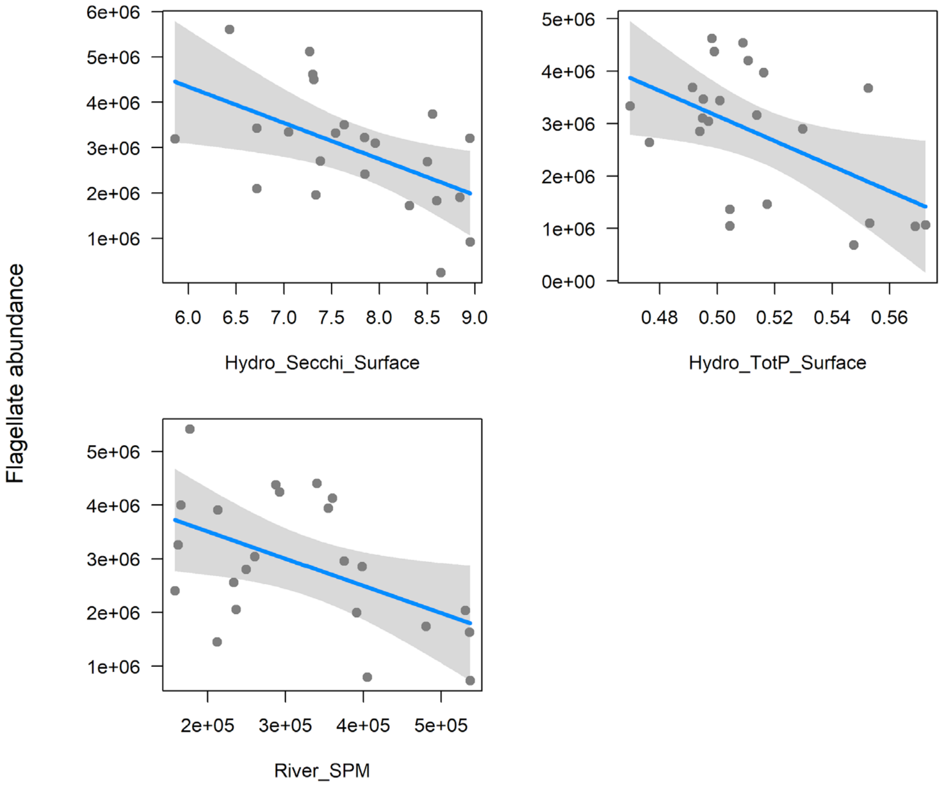


Figure 26. Variables affecting the annual mean flagellate abundance.

3.4.3 Hard-bottom

For the modelling of change in hard-bottom communities the selection of environmental variables to include followed the procedure outlined in Chapter 2.2. The best model describing changes in the hard-bottom communities on stations HT113 and HR104 included Chlorophyll-a (intermediate), POC (intermediate), Temperature (intermediate), Tot N (deep) and TSM (intermediate).

Temperature, TSM and POC seem to have driven changes towards larger DCA-values, while chlorophyll a and Tot N in deeper waters seems to have driven changes towards lower DCA-values. The strongest drivers in opposite directions appear to have been TSM and TotN. These explained a considerable part of the temporal change in species composition (Figure 27).

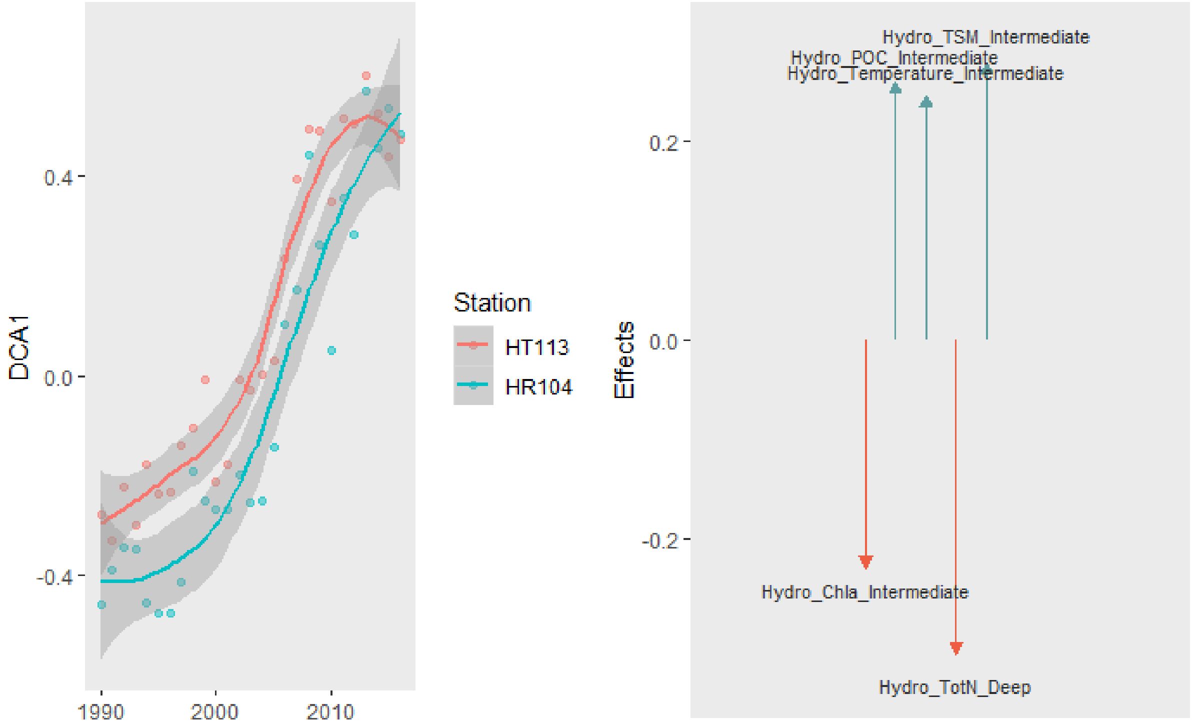


Figure 27. The relationship between changes in hard bottom species composition (the main ordination axis) and environmental drivers (R2 = 0.65).

3.4.4 Soft-bottom

For the modelling of change in soft-bottom communities the selection of environmental variables to include followed the procedure outlined in Chapter 2.2. Nine variables were included in the best models describing the changes in species composition on the two soft-bottom sites. Only POP (intermediate), Tot N (deep) and TSM (intermediate) explained significant parts of the pattern in community change, and only for the shallow station BR1 (depth 50 m). POP and Tot N seem to have driven changes towards larger DCA-values, while TSM seems to have driven changes towards lower DCA-values (Figure 28, notice the reversal of the x-axis compared to Figure 27). None of the environmental variables were significant in describing changes in species composition for the deeper (350 m depth) station BT44 (R2 = 0.47).

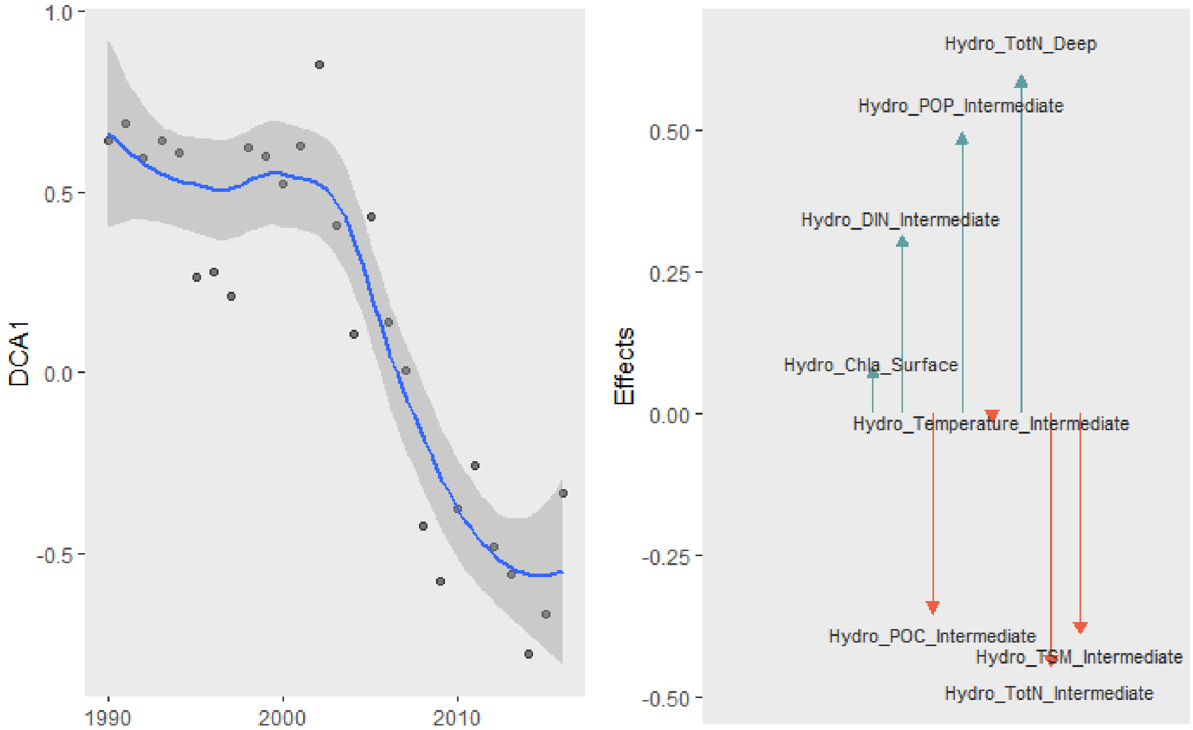


Figure 28. The relationship between changes in soft bottom species composition for the shallow station BR1 (the main ordination axis) and environmental drivers (R2 = 0.65).

4 Discussion

The overall aim of this work was to document changes in the period 1990-2016 in riverine loadings to Skagerrak and in coastal water quality and species composition, and secondly to investigate whether there was any relationship between climate drivers (temperature, river discharge) and the observed coastal responses. This work shows that there have been significant upward trends in discharge and transports in rivers draining to Skagerrak (except for NO_3), with the largest relative increase during the summer period (May-July). This confirms the trends reported for the Skagerrak region for the River monitoring program (e.g. Kaste et al. 2018). The increase in riverine discharge and transports during summer is especially evident from 2010. The temperature in the intermediate and deep coastal waters have increased significantly over the time period, while the upward trend for surface temperature is not significant, probably related to the large interannual variations in the upper water masses.

Long term trends in coastal suspended material and the relationship with riverine transports
The largest upward trends for hydrographic variables were shown for POC, PON and TSM, with concentrations increasing between 40-78% for all depth layers over the 26-year time series. The regression analyses showed that surface salinity and river TOC were the explanatory variables that were most relevant in describing the long-term change. The concentrations of TSM and POC in the water column increased with increasing riverine TOC concentration. The relationship with salinity is probably not causal, however illustrates that high POC and TSM concentrations are most frequent at low salinities, and probably more related to the effect that riverine discharge has on the salinity of the coastal water masses. The salinity in the surface layers also has a downward trend over time, and the river discharge was found to be the most significant explanatory variable for this long-term trend. There was no significant effect of the NAO on salinity or any of the other tested hydrographic variables. This was a bit surprising, considering the wide-ranging effects of the NAO on weather and current patterns, and the multitude of marine time series which have been found to be linked to NAO (Hurrell et al. 2013). The increase in suspended material and decrease in salinity is in accordance with what has been reported for the Norwegian coastal current previously (Aksnes and Ohman 2009, Frigstad et al. 2013), and shows that these trends are sustained up to the present. In general, higher loads of suspended material (especially terrestrial derived humic material) are connected to higher light attenuation (i.e. decreasing Secchi depth), which has been termed darkening. Darkening of coastal waters has been observed for both the Baltic and Skagerrak regions (Sanden and Hakansson 1996, Aksnes and Ohman 2009).

The riverine TOC is largely comprised of dissolved organic carbon (DOC; Kaste et al. 2018), and the particulate fraction in the riverine waters is comparable low. The total or dissolved fraction of organic carbon (DOC or TOC) is not monitored at the Arendal station (or the coastal surveillance program in general), therefore a direct link between the riverine TOC and coastal POC or TSM cannot be made. There could hypothetically be a link between the riverine SPM (suspended particulate matter) and coastal water TSM (total suspended matter), as they are both a measure of particles (organic and inorganic) retained on a filter. However, the riverine particles are generally believed to be high in inorganic silt material, that sediments out of the water column fairly rapidly when it mixes with seawater. In the regression for TSM, no clear link with river SPM was found. However, there is a possible mechanistic link between the riverine dissolved material and the particulate material in the coastal waters through flocculation, where terrestrially derived humic dissolved organic material aggregates to larger sized particles through various processes when it crosses a salinity gradient, such as in coastal regions (Buffle et al. 1998, Sondergaard et al. 2003). This process can create particles that are larger than the operational definition of 0.45 µm separating the dissolved and particulate fractions (i.e. what is retained on the filter). This causal links needs further investigations into the various processes involved, and also requires measurements of dissolved organic carbon (DOC) in the coastal regions to document the potential salt-induced flocculation of dissolved material into particulate material where fresh- and seawaters meet. The largest upward trends in suspended material were generally for the deep and intermediate layers, where the surface concentrations were the most significant explanatory variables. This would suggest that the suspended material in the deeper layers originates from the surface layers, and sediments out of the surface layer through various processes.

In this study, we did not find a significant change in the mean annual Secchi depth. As described for the regression results for plankton (Chapter 3.4.2), the Secchi depth can be affected by a multitude of processes in the water column, where a long-term increase in suspended material in the water column would act to reduce Secchi depths (less light penetrating into water column), while a reduction in plankton (especially large, compact dinoflagellates) could act to increase Secchi depths (more light penetrating into water column). A more precise method to determine the underwater light climate and its effects of pelagic and benthic processes (such as the lower growth depth of macroalgae), would be to measure profiles of the total light available and the spectral composition (i.e. diffuse attenuation coefficients for the photosynthetically active radiation (kd PAR) and at specific wavelengths). This would allow for examining the effect of DOC (or specifically the chromophoric fraction, cDOM) on the underwater light climate, which has been shown to be related to riverine transports in Norwegian coastal waters in Skagerrak (Kristiansen and Aas 2015).

In freshwaters, increased terrestrial organic matter (especially the dissolved organic fraction) is recognized as having strong impacts on aquatic productivity and ecosystem functioning, and can act both to reduce productivity due to reduced light availability (Thrane et al. 2014) and stimulate production by increasing carbon and nutrients available for bacteria and phytoplankton (Hessen et al. 1990). There is considerable transformation of this dissolved organic material, and especially the chromophoric fraction (cDOM), as it is transported along the aquatic continuum from catchments, to headwater streams, via lakes and rivers, and until it finally enters the coastal zone. These processes along the aquatic continuum gradually act to turn the pool of terrestrial dissolved organic matter less reactive (i.e. less available for biology), and processes believed to be important in the transformation of dissolved material in marine ecosystems are the above-mentioned salt-induced flocculation, photodegradation and bacterial degradation (Massicotte et al. 2017). However, less is known about the transformations and fate of terrestrial organic matter in the coastal zones than in freshwaters, and this is currently a field of high scientific activity. Processes that require more knowledge and further investigations are the composition of the terrestrial dissolved material and the effect on the total and spectral composition of light in the water column, bioavailability of the carbon, nitrogen and phosphorus fractions and the effect on the autotrophic/heterotrophic metabolic balance of the coastal system (i.e. on the phytoplankton vs. bacterial processes).

Reduction in inorganic nutrient concentrations

The largest downward trends for hydrographic variables over the 1990-2016 period were for the DIN and PO_4 concentrations for all depth layers. Previous analyses of the contribution of inorganic nutrients of various advected water masses to Arendal station (Aure et al. 1998, Frigstad et al. 2013), has shown that it is particularly reductions in nutrients advected from the German Bight and the southern North Sea that contributes to this long-term nutrient reduction. There is a general decrease in inorganic nutrient loadings and eutrophication status reported for many regions of the North and Baltic Seas, linked to the management efforts to reduce eutrophication (Carstensen et al. 2006, Vermaat et al. 2008, Norderhaug et al. 2016). This overall reduction in eutrophication forcing, termed oligotrophication (Nixon 1995), is not the focus of the present work, however some implications for management and monitoring programs aimed at effects of eutrophication are discussed below. Naturally, a reduction in inorganic nutrients can have an impact on autotrophs (e.g.

phytoplankton and macroalgae), and should in general lead to a reduction in primary production and biomass. However, an increase in other human induces drivers (e.g. climate change) and natural variability, will simultaneously act on the ecosystems, and may mask potential effects due to the reduction in inorganic nutrient loading.

Long term trends in plankton species and biomass

There was no clear trend for Chla on an annual basis, however, there was a significant decrease in the summer Chla concentrations in surface and intermediate layers. These seasonal changes are linked to changes in the abundance of the three main groups of plankton: Diatoms, which have their main bloom in spring (February-April), has the smallest changes over time, while the summer- and autumn-blooming dinoflagellates has seen a large and consistent decrease over time. This decrease in dinoflagellates is potentially reflected in the reductions in the overall biomass (Chla) during the summer period. Flagellates, blooming in spring to summer, has also experienced a decrease, but somewhat less dramatic and consistent compared with dinoflagellates.

The abundance of dinoflagellates was about 3.5 to 4 times higher in the start of the time series as in the end, which is a quite dramatic change. The variables that account for most of the long-term decline in dinoflagellates is river SPM (suspended particulate matter) and marine dissolved inorganic nitrogen (DIN), who each account for 30-35% of the decline in dinoflagellates. The negative effect of the approximately 40% decrease in DIN is expected, as dinoflagellates are poor competitors of nutrients. The link with river SPM (which has increased approximately 60%) is harder to explain, however it affects the dinoflagellates in a negative way. The third variable to affect dinoflagellates negatively is temperature; the increase in temperature is, according to the model, responsible for 21% of the decrease in dinoflagellates. (It should be noted that we have used *additive* models, thus, we measure the effect of one variable after the effect of all the other variables has been taken into account. We also find a close positive relationship between dinoflagellates and river TOC. Dinoflagellates are partly mixotrophs, and it is possible that high TOC load from rivers acts as a source of energy for nano- and microplankton, which again can be a source of food for dinoflagellates. It should be noted that the TOC load is also correlated to river discharge, which leads to increased stability of the water column. This is supported by a study by Hinder et al. (2012), who observed reduction in the abundance of selected species of dinoflagellate in the period 1960-2009, with a marked change around 2003. In their study, the reduction in dinoflagellates was linked to increased surface temperature and the increased surface wind, working on the stability of the surface water. Thus, the positive effect of the TOC variable may include a positive effect of discharge itself. However, river TOC explains year-to-year fluctuations in dinoflagellates, not the long-term decline. On the contrary, the increasing river TOC has counteracted the negative effects of the decreasing DIN. Also Secchi depth, which has been increasing, is negatively related with dinoflagellate abundance, but this is probably an effect, not a cause, of the abundance of dinoflagellates, which are large cells with a substantial effect on light penetration.

The abundance of flagellates decreased with about 75% until 2012, but their numbers in the period 2013-2016 has been almost on a par with their abundance in the 1990s. Flagellates are a functionally and taxonomically very heterogeneous group, which may be affected in diverse ways by the changes in environment. It can be noted that the three variables that are found to affect flagellates - river suspended particulate matter, marine total phosphorus, and Secchi depth, are also all among the variables that were found to affect dinoflagellates, and in the same direction. As with Secchi depth, it is likely that a large abundance of dinoflagellates and flagellates is the cause of low levels of water phosphorus, rather than vice versa. The consistent effect of river suspended particulate matter, however, supports the finding that river suspended particulate matter affects the dinoflagellate and flagellate phytoplankton group negatively.

While diatoms show no strong long-term trend, their year-to-year fluctuations are positively associated with the concentrations of phosphorus. This is consistent with the consensus that diatoms are more dependent on higher levels of nutrients than dinoflagellates and flagellates. Diatom blooms also tend to occur when salinity is low, i.e., when the water has stabilized in spring and when nutrient availability is still high after the vertical mixing of the water column during winter. It may appear paradoxical that there is a negative, not a positive association with silicate, as building diatom shells depend on silicate in the water. However, the explanation is likely to be that in years with big diatom blooms, the growth of diatoms depletes the water concentrations of silicate. Thus, silicate concentration is in this case an effect and not a cause of diatom abundance.

Long term trends in hard-bottom communities

The DCA shows that there has been pronounced changes in the structure of the hard-bottom communities over time, and that a rapid change in the overall community structure was onset around year 2000 (Figure 14). During the 1990s both animal and algal species increased evenly in numbers, leading to increased species diversity (measured by H') in the hard-bottom communities. However, after year 2000 the species diversity (H') and the evenness between the species groups (J') was reduced (Figure 9). While animal species continued to rise in numbers, the number of algal species declined (Figure 8). The reduction in species evenness also indicate that some species increased in dominance during this period, although the change was relatively small. The DCA (15 and 16) and the species count plots (Figure 8) revealed that the rapid change included a structural shift towards increased abundance of some green algae and filter feeders, and decreased abundance of some brown and red algae.

The community shift towards fewer algal species (particularly red) and a structural shift towards more species of filter feeders in Skagerrak has previously been suggested attributed to reduced light availability and increased particulate loadings (Moy et al. 2017). The monitoring data shows that the lower growth depth of several of the nine macroalgae species included in the MSMDI-index was reduced over time (Figure 10), and the general trend was significant (Figure 13), which is a strong indicator of reduced light availability. Changes in the lower growth depth of macroalgae is also influenced by temperature. Increased temperature leads to increased metabolism, which in turn demands more energy. To meet this demand, more light and/or more efficient photosynthesis is required. The ability of the macroalgae to regulate the latter is limited, especially under temperature stress (Sogn Andersen et al. 2013), and increased temperature is thus likely to reinforce the negative effects of light reductions on most macroalgae. Our results from the DCA-ordination and the regression model clearly establishes the link between the overall hard bottom community changes and these drivers (Figure 27). The change in community structure was strongly driven by TSM, POC and temperature, all of which have increased significantly over time. The increase in the number and abundances of sessile hard-bottom animal species in Skagerrak has been attributed to increased substrate availability, mainly due to reductions in lower growth depth and the density of macroalgae (Moy et al. 2017). Further, nutrient rich particulate loadings may serve as food for filter feeders, possibly explaining the increased presence of these animals in the fauna. These suggestions are also supported by our analyses, pointing to TSM and POC as important drivers.

Other drivers linked to the change in community structure were TotN and Chla (Figure 27). The concentrations of TotN peaked somewhere in between 2000 and 2005 (Figure 5), but did not show any significant downward or upward trend over time. Nitrogen strongly influences macroalgal community structure, which is why macroalgal indices are included in the monitoring of ecological status in relation to eutrophication. Particulate nitrogen (PON), which is also included in TotN may be expected to have effects similar to POC and TSM. The explanation for the estimated effect of increased TotN driving the community towards the structure observed in the 1990s is a bit counterintuitive, since the pattern of change is opposite. The link is in itself not surprising, but the underlying mechanism(s) is a bit difficult to disentangle. Chla did not show a clear trend over time, and the link between this parameter and the hard bottom communities is unclear.

Increased freshness in the surface layer may contribute to a competitive advantage for some green algae. Although salinity did not explain any significant part of the overall change in community structure over time, the increased occurrence of some green algae towards the end of the series may be related to the downward trend in salinity.

Long term trends in soft-bottom communities

At the shallow station BR1 there was a tendency of an increase in number of species and number of individuals, particularly after 2010, while for H' and NQI1 there were no clear trend during the monitoring period, although both parameters had a weak increase towards year 2000 and then during the last years (Figure 11). No significant overall trend was observed for NQI1 for this station (Fig. 13). The deep station BT44 showed an increase in number of species and the two diversity indices throughout the monitoring period (Figure 12). The number of individuals declined, particularly until 2000, although it has increased slightly the latest years. Generally, a decrease in number of individuals is positive, i.e. reflecting a decreased eutrophication load. The positive trend in NQI1 observed was significant (Fig. 13). It was very interesting that number of individuals tended to decrease at the deep station, but increase at the shallow station. Thus, this may indicate that the nutrient load has been decreasing far from the coast, but increased closer to land.

The DCA of soft bottom fauna (Figure 17) indicated that the species composition underwent a consistent change during time at both stations. In accordance with the trend in NQI1, the change occurred during the entire time-period at the deep station BT44, while at the shallow station BR1 there was no consistent change during the first ten years approximately, but after that a clear trend was evident. The changes in the faunal composition documented in the multivariate space concurs with findings by Trannum et al (2018) for the same stations.

Notably, at the shallow station BR41, the majority of the increasing species were molluscs (Figure 18). There were both sensitive and more tolerant species in both time-periods, which accords with the finding that there was not any clear trend in the NQI1-index over time (Figure 11). On the deep station BT44, on the other hand, there appeared to be a trend with a decrease of tolerant species and increase in more sensitive species over time, which is in line with the general reduced eutrophication load. The small opportunistic annelids *Heteromastus filiformis* and *Notomastus latericeus* was far more abundant in the first years of the monitoring period than in the last years (Figure 19). The declining trend for the *H. filiformis* was also documented by Trannum et al (2018). On the other hand, more sensitive species like tube-building annelids (e.g. maldanids; *Rhodine loveni* and Euclymeninae indet.) increased. This development is indeed reflected in the positive trend in NQI (Figure 12).

The finding at both stations with an increase in species living in a tube or shell was also recorded in Trannum et al (2018) in the analysis of the same stations as well as four more stations along the Skagerrak coast. Several of these increasing species feed on organic matter on the sediment surface and/or as filter feeders rather than as subsurface deposit feeders like e.g. *Heteromastus filiformis*. For example, the molluscs *Gorbula gibba, Parvicardium minimum* and *Mendicula ferruginosa* and the polychaete *Sosane wahrbergi* are filter feeders (i.e. filter particles from the water column). The mollusc *Kelliella miliaris*, which increased at both stations lives partly as a filter feeder and partly as surface deposit feeder. The same applies for the tube-building polychaete *Pseudopolydora* sp. The polychaete *Terebellides stroemi* and the crustacea *Diastyliodes serratus* are surface deposit feeders. Thus, this shift in feeding mode may suggest a change in the food source pointing to more particulate food in the water column or the sediment surface, although this is still not fully verified. In line with our findings, Kroncke et al. (2011) recorded a similar increase in small molluscs in the southern North Sea from 1986 to 2000, which also was interpreted as an increased food supply.

Another finding was that carnivore/omnivore species (i.e. predators, including forms that may eat plant food and detritus in addition to prey organisms) seem to decline over the monitoring period. Examples are the polychaetes *Glycera unicornis*, *Goniada maculata* and *Ceratocephale loveni*. This finding accords with the findings for hard-bottom communities. Typically, in a pollution-gradient there are most carnivore species under higher levels of disturbance, as described in the classical work by Pearson and Rosenberg (1978). The decline of carnivores supports the conclusion of a general decline in the eutrophication load. In a follow-up work we will particularly work with functional changes during the monitoring period in relation to environmental changes (Oug et al., in prep).

At the shallow station BR41, changes in nutrients seem to have driven changes in the faunal composition. POP and Tot N seem to have driven changes towards larger DCA-values (Figure 28), i.e. influencing the faunal composition in the first part of the monitoring period. Here it is important to be aware that for dissolved nutrients the effects will be indirect (i.e. “via” plankton). The finding with nutrient-driven changes for the soft bottom fauna along the Skagerrak coast concurs with Trannum et al. (2018), where decreased nutrient levels were associated with an increased species richness. TSM was found to have the opposite effect, i.e. determining the community structure in the last part of the time period. TSM may be composed of not only organic matter, but also particles of inorganic material e.g. arising from river run-off. Particulate nutrients can fuel the benthic communities more directly than inorganic dissolved nutrients, and it seems likely that the finding with an increase in number of individuals and species living of particulate matter in the water column or on the sediment surface can be linked to TSM. At the same time, the level is below the level where detrimental effects occur as the number of species in fact increased slightly. Moderate increases in the nutrient supply may give enrichment effects until oxygen depletion starts to occur (Pearson and Rosenberg 1978).

For the deep station BT44, no significant explanatory environmental variables were found. Probably, the shallowest/most coast-near station will be more directly influenced by changes in the uppermost water-column including changes in riverine inputs, while for the deep station the responses will be more complex and time-lagged. It is also important to be aware that the deepest station (350 m depth) was much deeper than the hydrographic sampling depth (max 75 m), which thus can reduce the explanatory power. However, the same increase in species feeding on the sediment surface as the shallow station was recorded, pointing to some of the same mechanisms of change.

It should also be noted that some of the changes in abundance also possibly can reflect climate-induced changes in the species distribution patterns. E.g. the bivalve *Gorbula gibb*a previously had its core distribution in the southern North Sea, but has increased northwards (Kroncke et al. 2011), in accordance with the increase observed in the present study. However, studies of distribution patterns have been outside the scope of the present work.

The overall conclusion for soft bottom is that substantial changes in the faunal composition occurred along the time-period. At the deep/outer station an improved ecological condition was observed, which is interpreted as a response to the overall reduction in the eutrophication load. Also, a reduced abundance through time was recorded here. On the other hand, at the shallow station the abundance increased. Thus, this may indicate that the nutrient load has been decreasing far from the coast, but increased closer to land. In addition, an interesting finding was that we observed an increase in species feeding on the sediment surface or from the water column (filter-feeders) throughout the monitoring period at both stations. This can possibly be linked to the increase in suspended particulate matter observed, which is reflected in an altered origin of the sedimenting material on the seafloor.

Limitations of approach

This study is naturally limited to understanding the effect of explanatory variables included in the analyses. We have not included any measure on the strength of the circulation within Skagerrak, or changes in inflowing water masses from the Atlantic Ocean, the North Sea or the Baltic Sea. For instance, organic matter is also increasing in the Baltic water (Wikner and Andersson 2012), and the outflow of water from the Baltic Sea is quite variable. However, apart from the difficulties of obtaining such time series of good quality and sufficient length, including even more potential explanatory variables increases the risk of obtaining spurious results (i.e., variables that by chance happen to correlate with the variables we want to explain). We did, however, include the North Atlantic Oscillation (NAO) index, which relates to the wind patterns in the North Atlantic and is also strongly linked to wind and current patterns in the North Sea area. The NAO index influences the inflow of Atlantic water to the Norwegian Sea and furthermore the influx of Atlantic water to the North Sea (Winther and Johannessen 2006). Furthermore, NAO has shown to be linked to various time series of the North Sea, e.g. phyto- and zooplankton (Alvarez-Fernandez et al. 2012) and fish (Stige et al. 2006, Engelhard et al. 2011), as well as species richness of soft-bottom communities (Trannum et al. 2018). NAO is also linked to the volume of water exchange between the North and Baltic Seas through the Danish Sounds (Lehmann et al. 2002). The inclusion of the NAO index, should therefore capture some of the potential effects of interannual and long-term variation in circulation and inflow of water masses to the Arendal station.

The analyses in this works is mainly performed on annually aggregated data. While this is enough to capture a lot of the dynamics for benthic (soft- and hard-bottom) organisms, one year is a very long time scale for phytoplankton, which may experience large changes during a few weeks. The year will usually start with high concentrations of nutrients in the water in spring, which then will decrease quickly in the spring bloom as nutrients are taken up by the plankton. During summer, nutrients will to varying degrees be recirculated, released to the water and sink out during the succession of different species of plankton. An analysis of annual means, averaging all the dynamics within a year, can obviously not fully describe all these processes, and therefore the interpretation of the results requires some caution. However, the purpose of this study is to give an overview of the large-scale changes occurring in this area on a decadal time scale.

The surveys of hard-bottom substrate were performed by diving. Two experts within the fields of marine floristic and faunal taxonomy performed the dives and the observations of macroalgae and animals respectively. Observations during diving is highly dependent on weather conditions, wave action and water turbidity. Much wave action and bad weather may obstruct observations near the surface because water motions disturb the diver, and because spending much time tossed about near bare rock and boulders may become too risky. Murky waters reduce visibility and thereby the probability of observing all species present. Some species may be more easily missed than others, which introduces data biases. Finally, changes in personnel over time may affect the frequency of some species registrations, because specialized expertise is required to recognize and separate some very similar species. These factors contribute to bias and uncertainty. It was not possible to formally analyze the hard-bottom data with regards to changes in personnel, but overlapping data does exist and this can be done in the future by using a larger subset of the data contained in NIVA databases. For plankton, the sampling protocol was changed in 2000. Before 2000, a mixed sample from 0-30 m depth was used, from 2000 onwards a sample at 5 m depth was used. Although this certainly had some effect on the composition of plankton, the effect has probably been moderate compared to the main patterns seen in the data (e.g. the decrease of dinoflagellates).

This naturally applies to all data types included in this report (hydrography, plankton, hard- and soft-bottom), where errors and increased uncertainty may be introduced through changes in methodology over time (e.g., personnel, analytical procedures, frequency in sampling, etc.), however caution has been taken in the preparation of data and the analyses to the extent it has been possible (see Chapter 2.1 and 2.2).

Implications for coastal management and monitoring programmes

Eutrophication is the classical environmental problem in coastal systems, and formed the basis for establishment of the Water framework directive (WDF) and the related surveillance monitoring programs (such as ØKOKYST). Although eutrophication (as defined by inorganic nutrient concentrations) has decreased in many coastal regions, this has not resulted in good environmental status for several indices, especially in inner sheltered coastal areas (Norderhaug et al. 2016, Fagerli et al. 2018, Naustvoll et al. 2018). Duarte et al. (2009) has described this failure to return to reference status following nutrient reductions in long-term monitoring sites for several coastal areas around the globe. This failure is proposed to be a result of the cumulative effects of multiple changes in environmental conditions and interactions over the time period in question, in effect shifting the baseline conditions of the ecosystem. However, it is emphasized that the failure to return to reference conditions should not be interpreted as evidence for that nutrient reductions have been ineffective. Importantly, efforts to reduce nutrient inputs have haltered further eutrophication, and acted to reduce the overall vulnerability and damage to the ecosystem. Duarte et al. (2009) advices that instead of focusing on returning the system to a particular past state or reference conditions (which is highly unlikely), focus should be on the ability of the ecosystem to maintaining key ecosystems services to society.

In this work, we have shown that the riverine discharge and transports have increased, and that this has had an effect of the suspended particulate material in the water column. In order to better understand the effects of this terrestrial organic matter on the coastal ecosystems, it would be beneficial to include measurements of dissolved organic carbon and the chromophoric fraction (DOC + cDOM), in addition to light profiles (including spectral composition) in the ØKOKYST programme, to examine the effects of this material on the underwater light climate. This would give a better understanding of the effects that increased suspended material has on light conditions, and in turn the effects that this could have on phytoplankton and the lower growth depth and species composition of macroalgae. In addition, the increase in suspended material appears to affect both hard- and soft bottom communities, through benefitting the organisms that are able to utilize this particulate material as an energy/food source. The inclusion of total nitrogen (TN) in soft-bottom sediments in the ØKOKYST monitoring programme from 2017 will be helpful, as it will enable us to indicate a possible source of the organic material (through the C:N ratio). The current monitoring programs have little focus on fauna in the hard-bottom communities, however the analyses of the species lists indicate that there is a shift in the faunal composition over time. This needs to be explored further, and potentially an indicator for the change in faunal composition connected to documented changes in particle loading, and the observed increase in sedimentation, could be developed.

In order to more accurately establish the relationship between river run-off and coastal responses, the ØKOKYST monitoring programme could be expanded with stations in inner coastal areas (recipients of major rivers included in this work), and establish study areas along the coast with stations in a land-ocean gradient (complimented with higher resolution monitoring in the relevant river). The increased suspended material in coastal waters may also influence the acidification state of the waters, through remineralization of organic matter to inorganic carbon and other processes, and a closer link between stations in the ØKOKYST and the Ocean Acidification programme would be an advantage.

As emphasized in the recommendations in Part 1 of this project (Frigstad et al. 2017), it is important to preserve the existing long-time series in the monitoring programmes, and that these are kept consistent in terms of location, frequency of sampling and methodology. This includes yearly sampling of benthic communities.

Our analyses also show that long-term species datasets, acquired by registrations on fixed stations over time, may reveal the introduction of new species and also the point in time of establishment. The species list can also be used for detecting reduction in abundances, as illustrated for blue mussels in this report. The species lists for plankton, hard- and soft-bottom communities thereby represents a resource that is currently not fully utilized.

5 Conclusion

Large changes have occurred in the Skagerrak coastal ecosystem over the last decades. Approximately half of the time series shown in Fig. 13 display significant changes over time; in addition, the species composition of the bottom-living flora and fauna has changed considerably. The rivers draining to Skagerrak discharge more freshwater into the coastal region, and carry a substantially larger load of phosphate (PO_4/TotP), organic carbon (TOC), nitrogen (TotN) and suspended particles (SPM). In the coastal Skagerrak waters, we observe an increase in particulate organic carbon (POC), particulate organic nitrogen (PON) and total suspended matter (TSM) throughout all seasons and depth layers. At the same time, the water is steadily becoming warmer (more pronounced in the deeper layers) and fresher (in the surface). However, the concentrations of inorganic nutrients, i.e., phosphate (PO_4) and inorganic nitrogen (DIN), have decreased. The plankton community has changed quite dramatically, with a decline in flagellates and dinoflagellates being reduced to a fraction of their former abundance. In the hard-bottom habitats, the lower depth of algae is creeping upwards, reducing the number of red-algae species with over 50%, and algae are to some degree being replaced by animals, such as filter-feeders. Soft-bottom communities are also changing, with an increase in tube- and shell-living organisms (such as mollusks), and apparently a shift towards species that feed on suspended particles in the water or on the surface of the sediment, rather than below it. This indicates a change in the nutrient sources for the benthic communities. Further, the abundance decreased at the deep, outer station, but increased at the shallow, coast-near station, which indicates an increased nutrient supply towards the coast.

How are these phenomena linked? When we look across the different time series and the separate statistical analyses, some patterns emerge. A clear pattern, is the link from river TOC to coastal waters, where it is one of the factors leading to the increasing concentrations of POC and TSM. It is hypothesized that the dissolved organic material from the rivers aggregates into larger particles in the coastal zone, and that these particles sediments from the surface layer into the deeper waters. The total suspended material in the coastal waters, in turn, appears to be linked to the changes seen in both hard-bottom and soft-bottom communities, being a statistically significant factor for the major changes (the first DCA axis) in both systems. It therefore seems likely that the increased amount of suspended material has been involved in this shift, with a benefit to organisms being able to utilize these particles as an energy source in both hard- and soft-bottom communities. In contrast, there is a negative effect, mediated through reduced light availability, on certain macroalgae species (especially red) and on the overall lower growth depth of the species included in the MSMDI-index, which is reinforced by an increase in temperature (increasing metabolism). Among the plankton, river TOC appears to be positive for dinoflagellates and flagellates, but the increase in TOC load has been counteracted by negative effects of an increasing load of riverine SPM (suspended particulate matter).

This works showcases the importance of maintaining long time series in order to detect effects of long-term environmental changes. Some of these changes are intentional, such as the decrease in inorganic nutrient concentrations, while some are unexpected, such as the increase in suspended material in coastal waters caused by increased riverine discharge and transports. The latter is both caused by climate change (through increasing precipitation), but also owing to complex interactions with reduced sulfate deposition (i.e. acid rain) and land-use changes. These changes call out for implementing adaptive monitoring, where the monitoring programs evolve iteratively as new information emerges and the major drivers of the systems change.

In this report, we advise to include measurements of dissolved organic carbon and its chromophoric fraction (DOC and cDOM) and light profiles (including spectral composition) in the Ecosystem monitoring of coastal waters (ØKOKYST). This could be implemented by establishing study areas along the coast with stations in a land-ocean gradient, from the recipients of major Norwegian rivers draining to Skagerrak (complemented with high-resolution monitoring in the relevant river) and towards more open, exposed coastal areas. This would increase the knowledge on the relationship between riverine transport and the coastal responses, and build the knowledge basis needed for further development of the classification scheme and indices, and related surveillance monitoring programmes of the Water Framework Directive (WFD).

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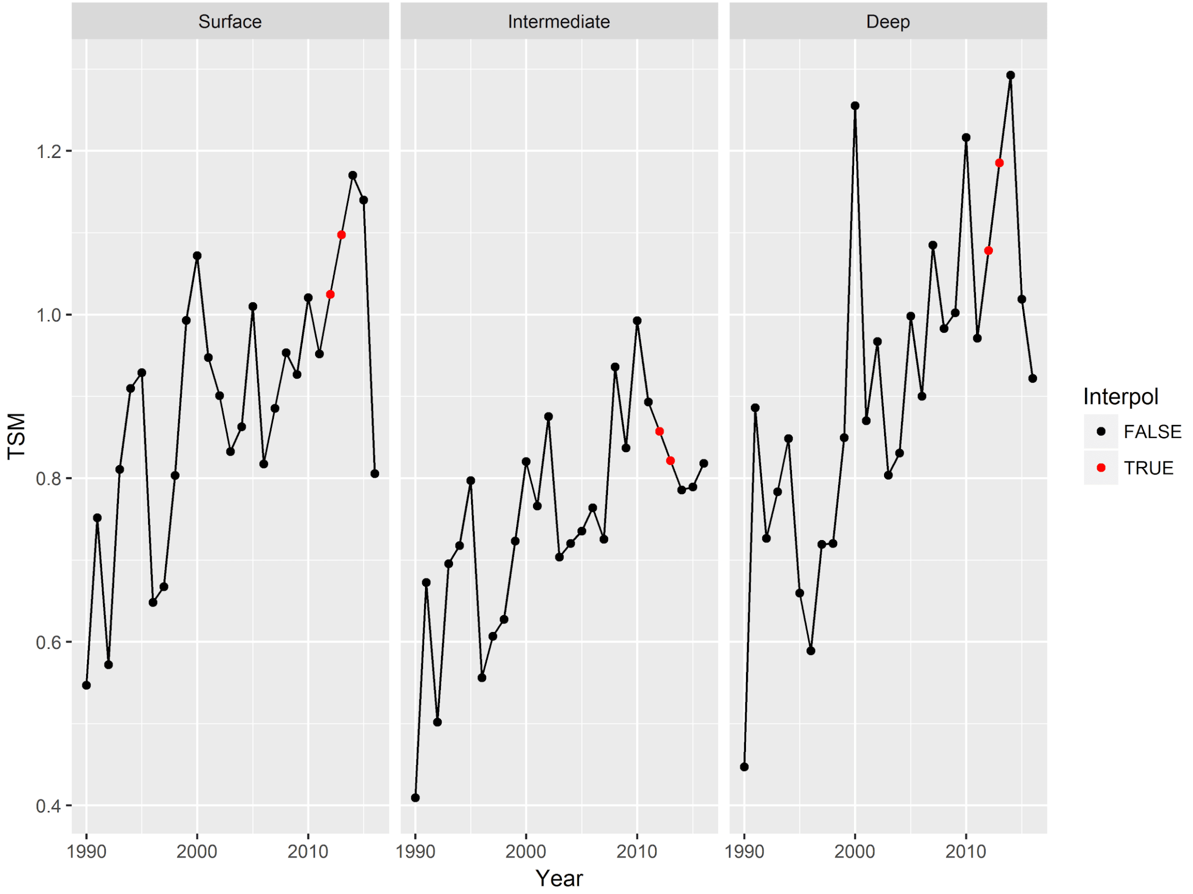
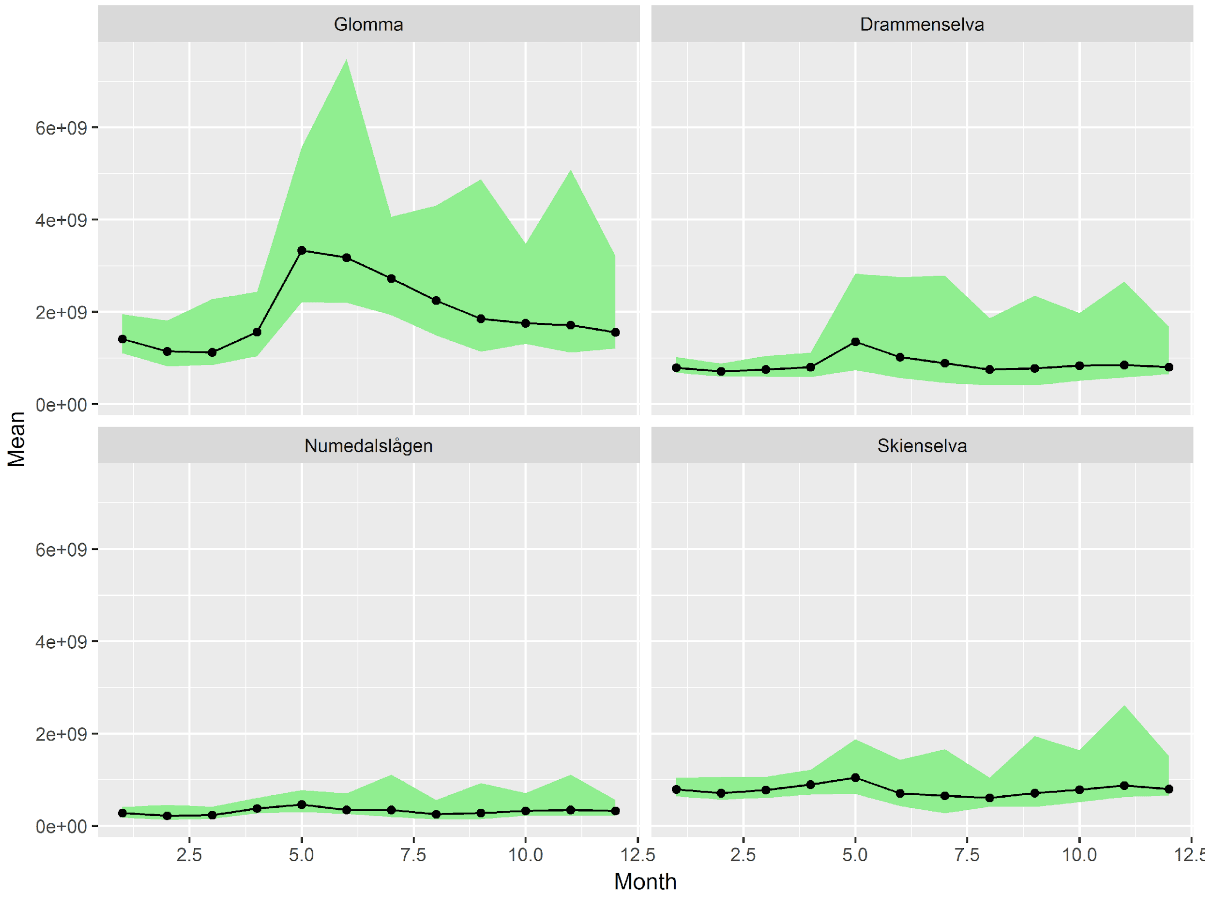
Appendix A. Additional plots



A1. Interpolation of missing observations for TSM during the period 2012-2013 (red dots).



Plot A2. Monthly mean discharge for individual rivers Glomma, Drammenselva, Numedalslågen and Skienselva.

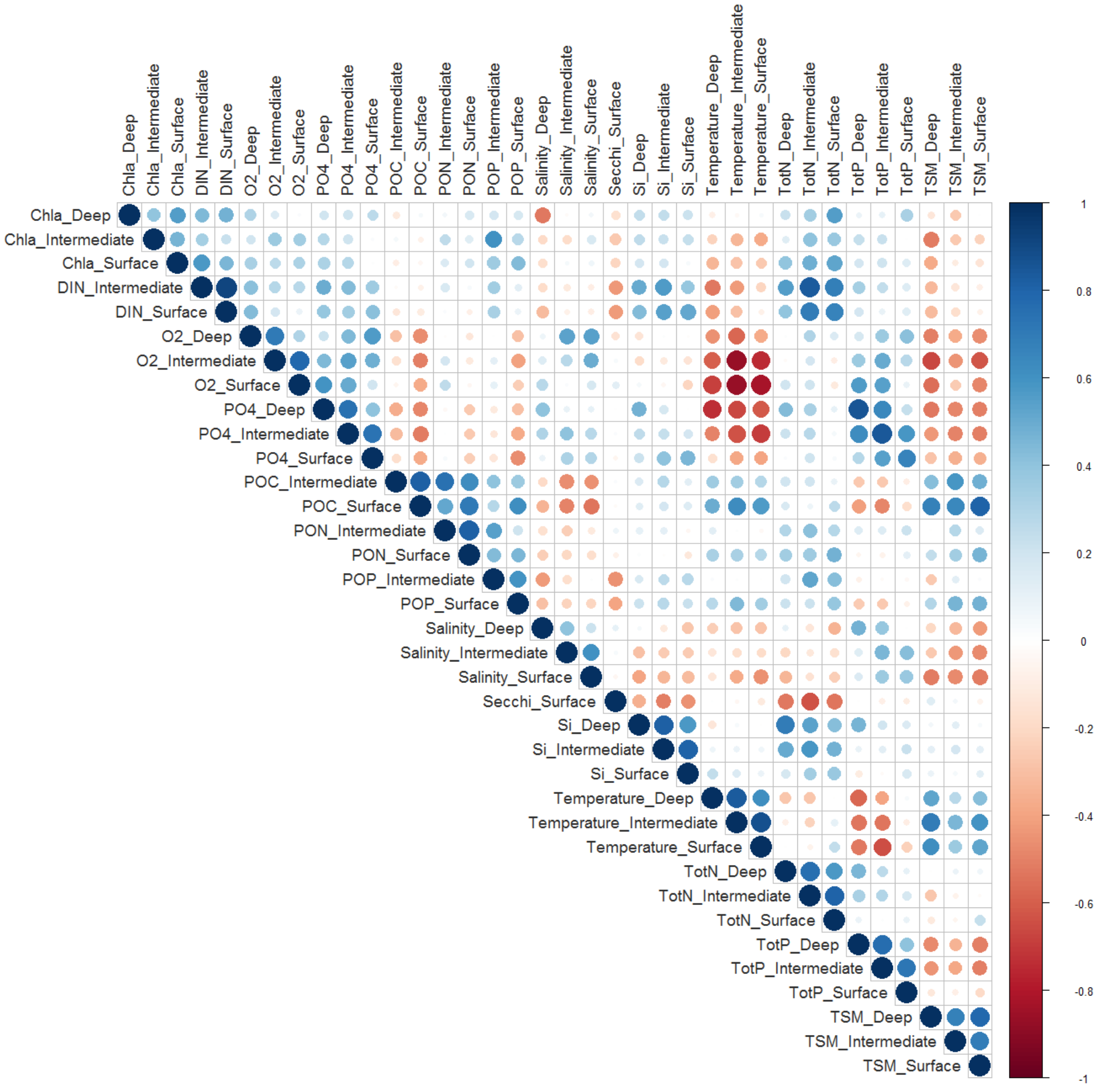


Figure A3. Correlation matrix for hydrographic variables.

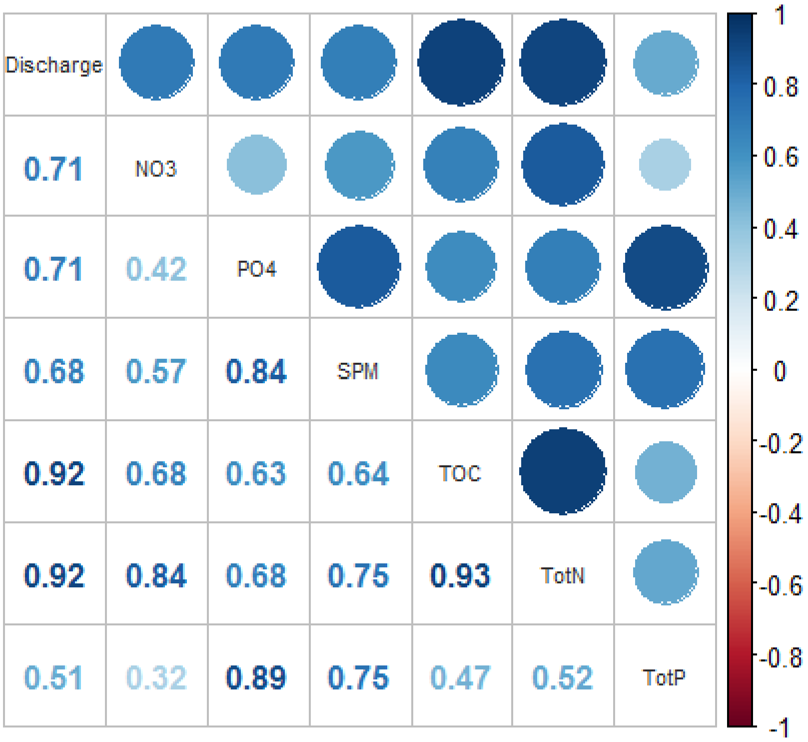
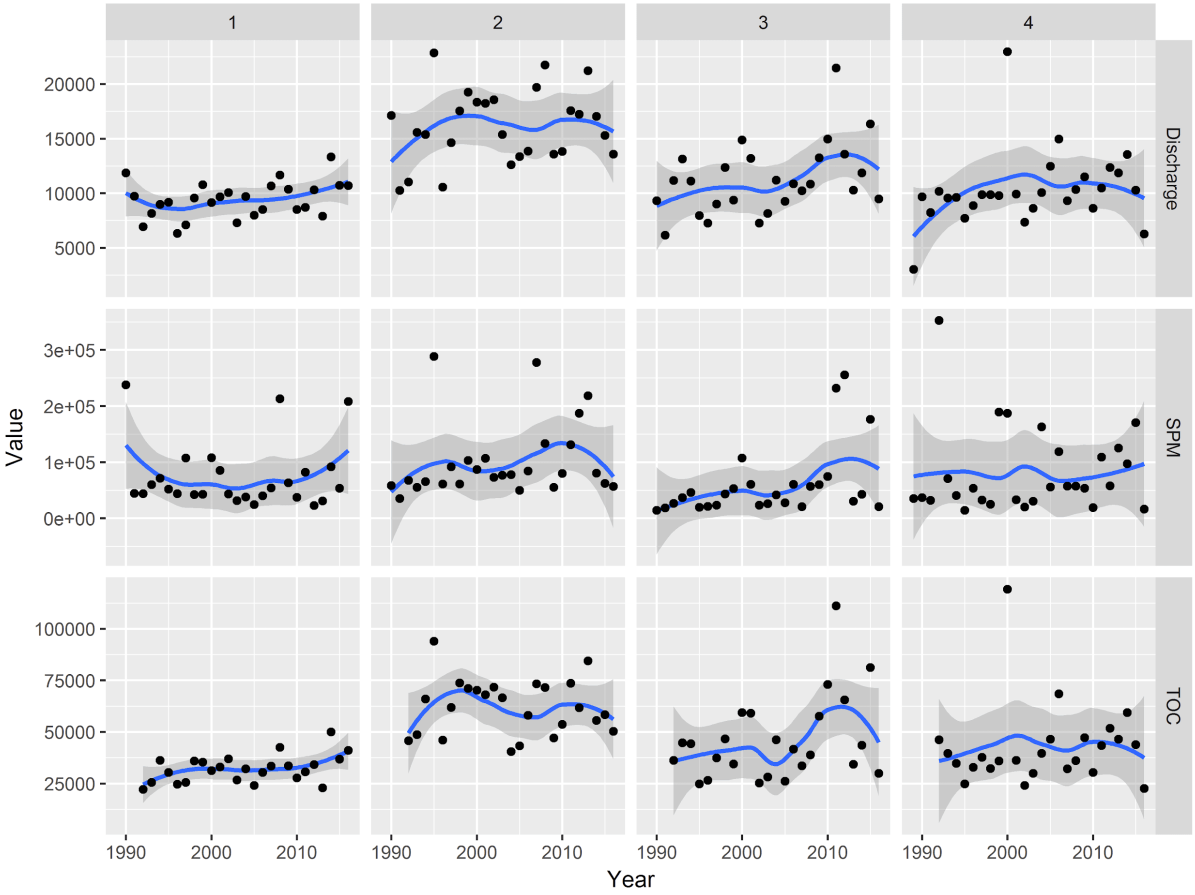
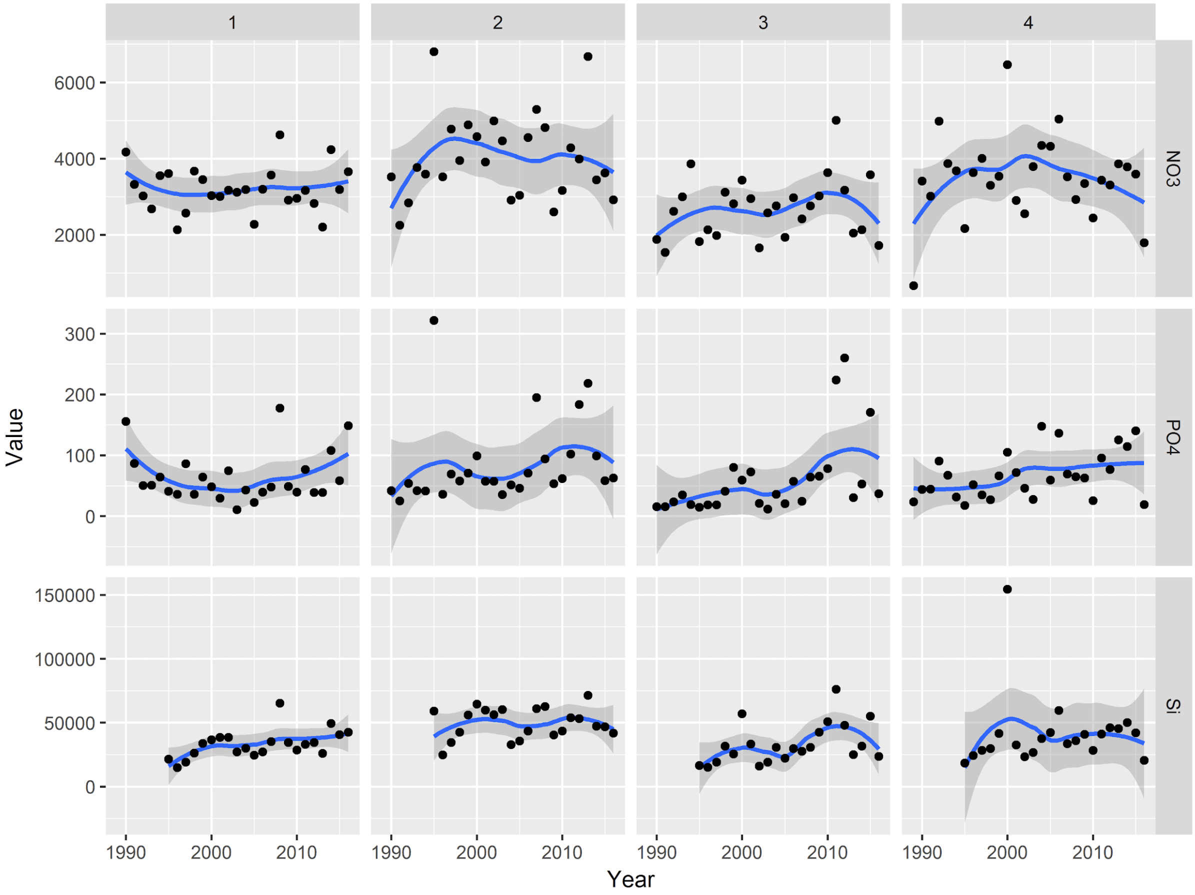


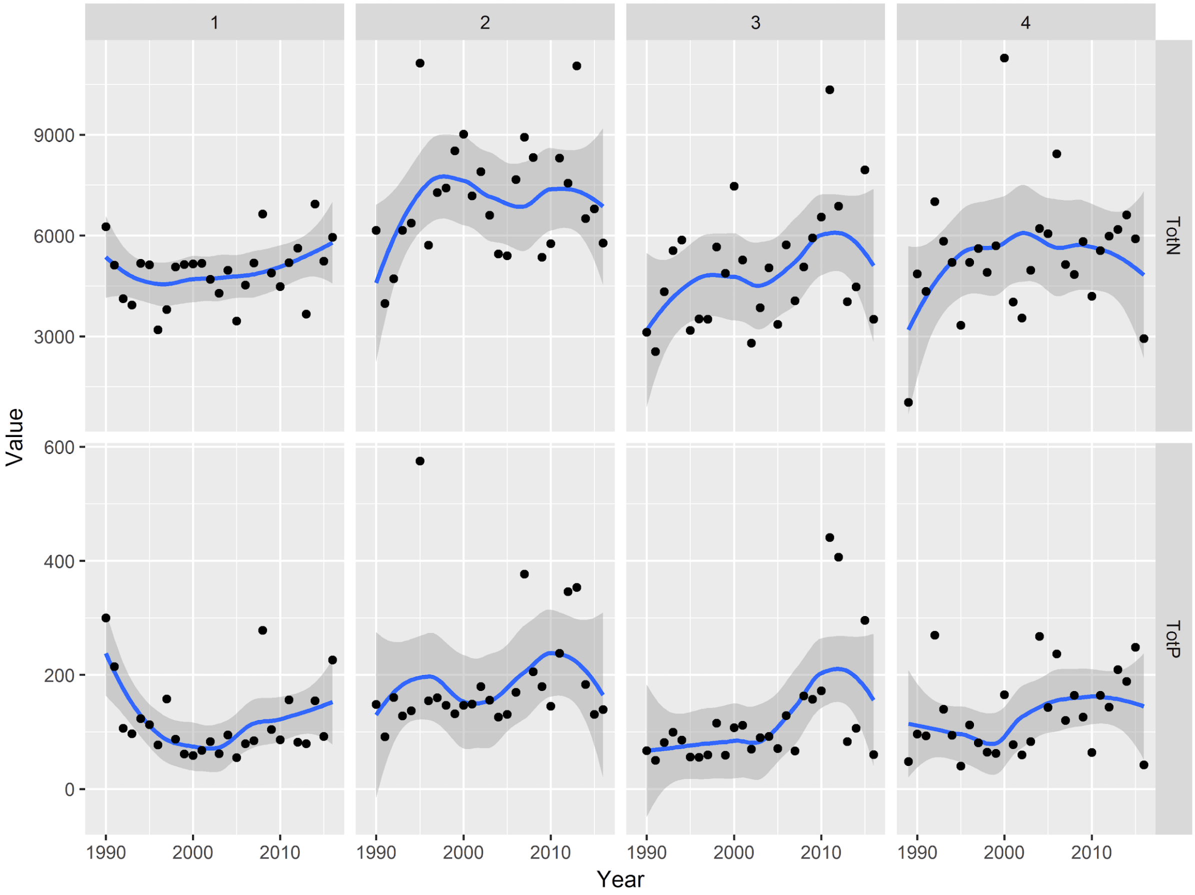
Figure A4. Correlation matrix for river variables.



Plot A5. Seasonal discharge (mill km3) and transports of TOC and SPM (tons) for major rivers draining to Skagerrak



Plot A6. Seasonal transports of NO_3, PO_4 and Si (tons) for major rivers draining to Skagerrak

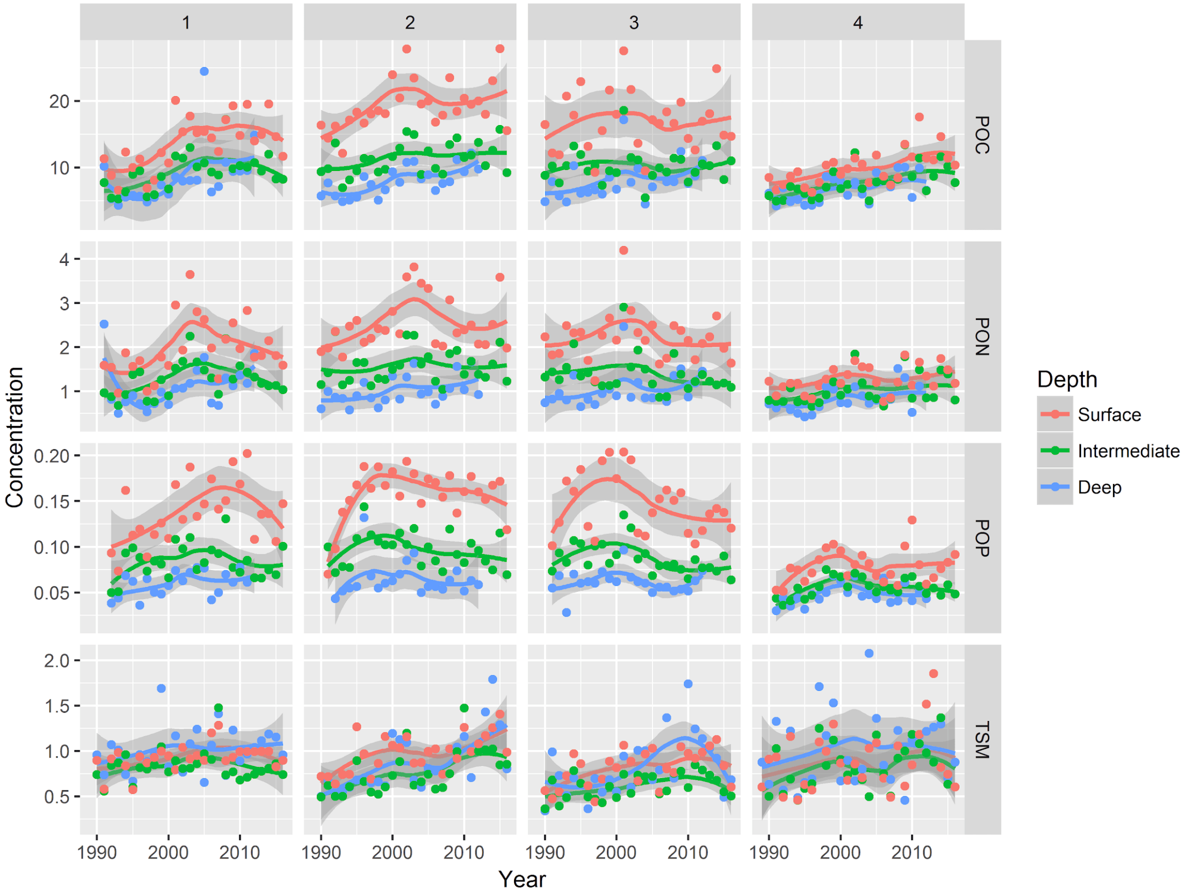


Plot A7. Seasonal transports of TotN and TotP (tons) for major rivers draining to Skagerrak

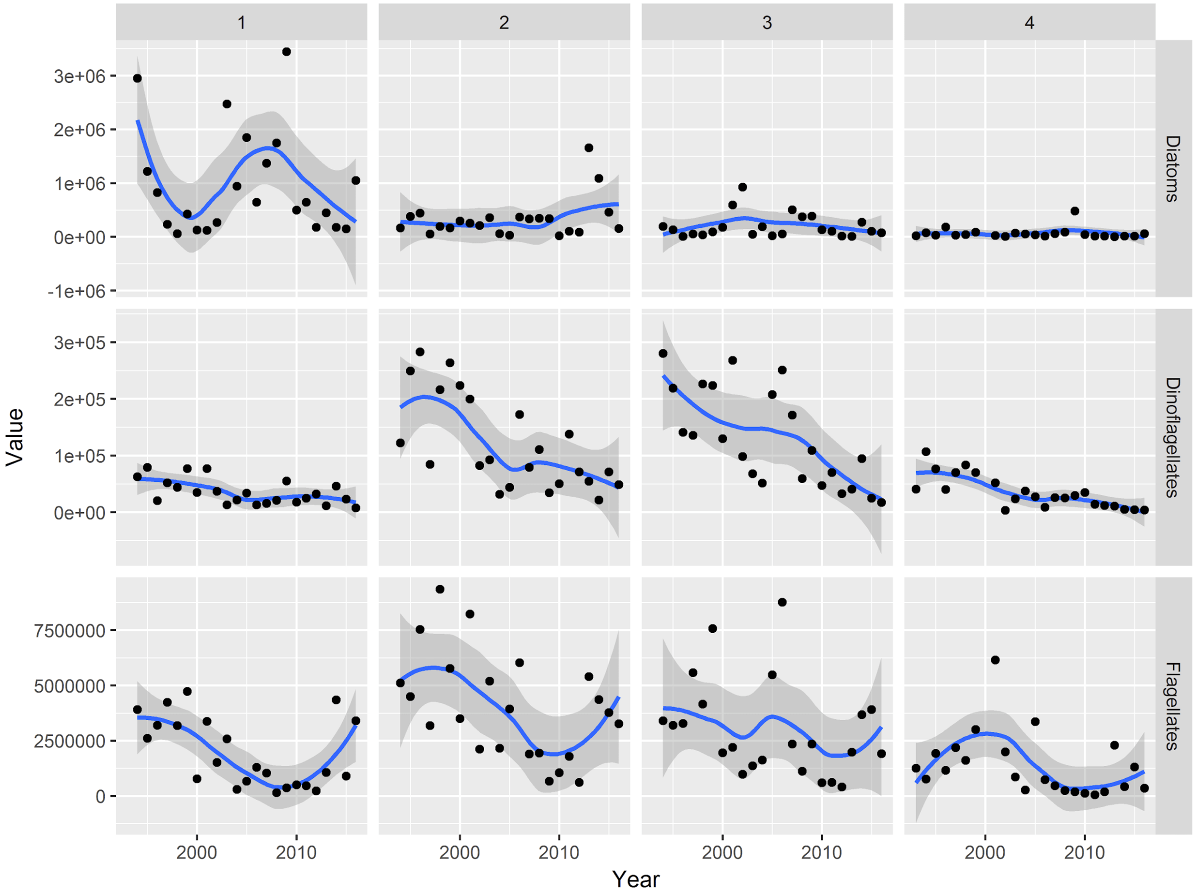
A8. Seasonal temperature, salinity and oxygen

A9. Seasonal DIN, PO_4 and Si

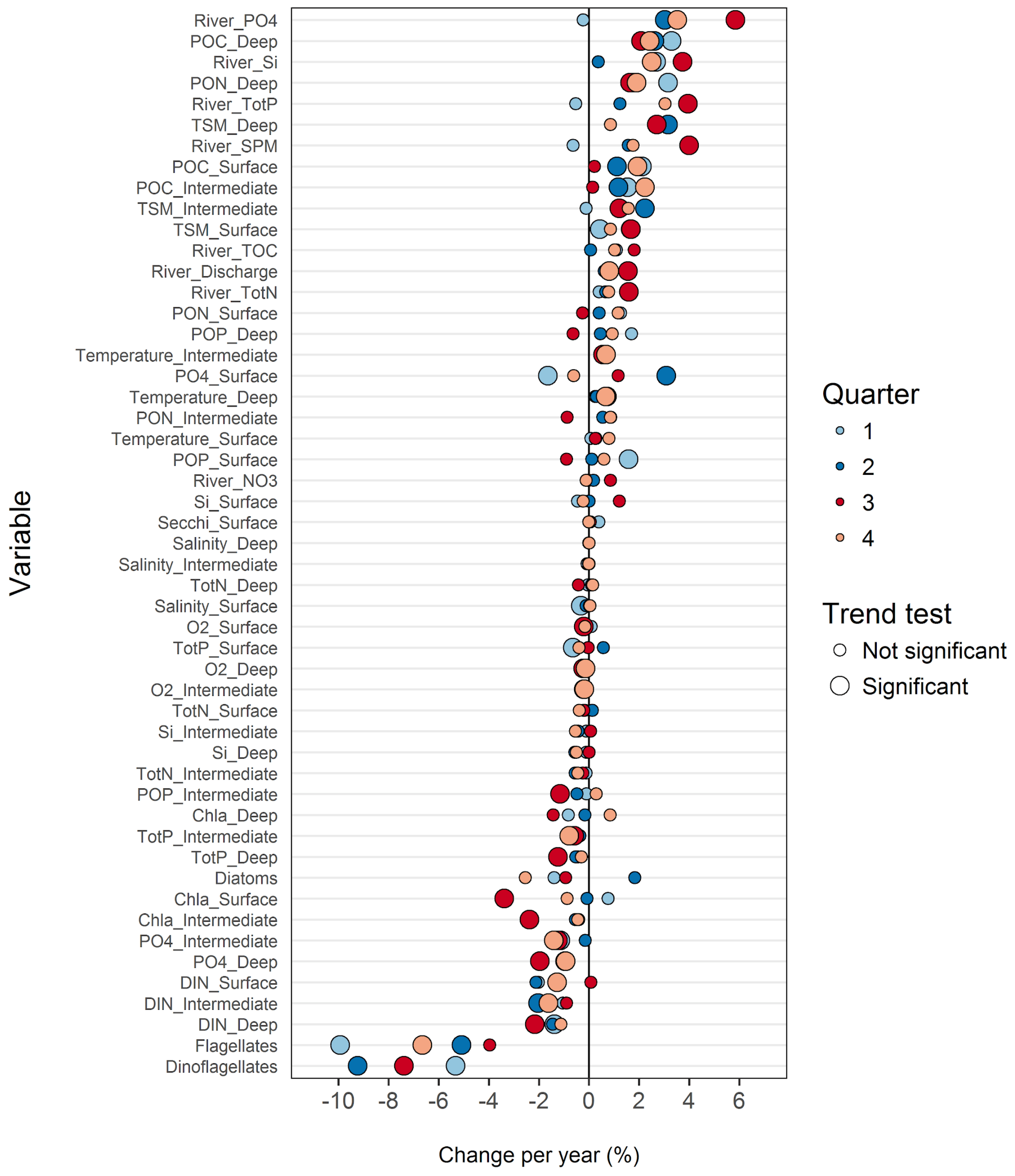
A10. Seasonal Chla, TotN, TotP and Secchi depth



A11. Seasonal POC, PON, POP and TSM.



A12. Seasonal phytoplankton



A13. Time trends of seasonally aggregated data for all variables in the hydrography, plankton and river datasets, as well as the lower growth limit (based on the MSMDI index) of the two hard-bottom stations. The trends (Theil-Sen slope) are given in percentage change in the mean quantity per year. Colors define season, while the size of dots indicate significant trends (Mann-Kendall trend test, $p < 0.05$). See Figure 13 for the corresponding figure based on annually aggregated data.

Appendix B. Additional tables

B1. Table of time trends of annually aggregated data for all variables in the hydrography, plankton and river datasets, as well as the lower growth limit (MSMDI) for macroalgae and (see Figure 13).

Variable	**Change per year**	**Percent change per year**	**P-value**
River_Discharge	**429.7**	**0.90**	0.011
River_NO3	33.63	0.25	0.53
River_PO4	**7.694**	**3.30**	0.0035
River_Si	**3347**	**2.16**	0.008
River_SPM	5849	2.00	0.1
River_TOC	**1881**	**1.04**	0.038
River_TotN	**199.7**	**0.90**	0.02
River_TotP	**9.103**	**1.74**	0.022
Hydro_Chla_Deep	-0.001048	-0.27	0.74
Hydro_Chla_Intermediate	-0.009473	-1.10	0.05
Hydro_Chla_Surface	-0.01144	-0.68	0.23
Hydro_DIN_Deep	**-0.08121**	**-1.41**	0.013
Hydro_DIN_Intermediate	**-0.0509**	**-1.10**	0.0027
Hydro_DIN_Surface	**-0.04959**	**-1.43**	0.0027

Hydro_O2_Deep	-0.004005	-0.07	0.13
Hydro_O2_Intermediate	-0.006723	-0.11	0.2
Hydro_O2_Surface	-0.004992	-0.07	0.21
Hydro_PO4_Deep	**-0.004692**	**-1.08**	<0.001
Hydro_PO4_Intermediate	**-0.00307**	**-1.04**	0.0031
Hydro_PO4_Surface	-0.00133	-0.60	0.058
Hydro_POC_Deep	**0.2299**	**2.94**	<0.001
Hydro_POC_Intermediate	**0.1067**	**1.13**	0.004
Hydro_POC_Surface	**0.196**	**1.25**	0.0031
Hydro_PON_Deep	**0.02417**	**2.47**	0.0051
Hydro_PON_Intermediate	0.005212	0.39	0.32
Hydro_PON_Surface	0.01479	0.77	0.12
Hydro_POP_Deep	0.0003246	0.56	0.28
Hydro_POP_Intermediate	-0.0003997	-0.49	0.4
Hydro_POP_Surface	0.0002597	0.19	0.72
Hydro_Salinity_Deep	-0.002855	-0.01	0.32
Hydro_Salinity_Intermediate	-0.01134	-0.03	0.12
Hydro_Salinity_Surface	**-0.03101**	**-0.11**	0.037
Hydro_Secchi_Surface	0.01003	0.13	0.85

Hydro_Si_Deep	-0.007894	-0.21	0.43
Hydro_Si_Intermediate	-0.002968	-0.10	0.68
Hydro_Si_Surface	0.002418	0.08	0.93
Hydro_Temperature_Deep	**0.03856**	**0.44**	0.0052
Hydro_Temperature_Intermediate	**0.03822**	**0.40**	0.017
Hydro_Temperature_Surface	0.0221	0.22	0.087
Hydro_TotN_Deep	-0.01429	-0.09	0.74
Hydro_TotN_Intermediate	-0.02893	-0.19	0.42
Hydro_TotN_Surface	-0.01162	-0.07	0.9
Hydro_TotP_Deep	**-0.003718**	**-0.57**	0.0072
Hydro_TotP_Intermediate	**-0.003199**	**-0.60**	0.0082
Hydro_TotP_Surface	-0.001271	-0.25	0.22
Hydro_TSM_Deep	**0.01893**	**2.10**	<0.001
Hydro_TSM_Intermediate	**0.01102**	**1.44**	<0.001
Hydro_TSM_Surface	**0.01581**	**1.74**	<0.001
Plankton_Diatoms	3198	0.95	0.75
Plankton_Dinoflagellates	**-5522**	**-7.79**	<0.001
Plankton_Flagellates	**-1.154e+05**	**-4.42**	0.015
Hardbottom_Lowergrowth_HR104	**-0.003846**	**-0.43**	0.0043

Hardbottom_Lowergrowth_HT113	**-0.002308**	**-0.25**	0.04
SoftBottom_NQI1_BT44	8.72e-09	0.006	0.9958
SoftBottom_NQI1_BR1	0.4043506	0.00075	0.10

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