Benthic foraminifera as bio-indicators of chemical and physical stressors in Hammerfest harbor (Northern Norway)

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Highlights

- Physical, chemical and organic pollution are distinguished as dominant stressors
- Sediment contaminant concentrations reflect chronic to acute ecosystem impacts
- Two benthic foraminiferal assemblages were distinguished reflecting main stressors
- Organic pollution resulted in no living and low number fossilized tests
- The assemblage from an un-impacted reference site shows natural harsh conditions

Abstract

We investigated benthic foraminiferal assemblages in contaminated sediments in a subarctic harbor of northern Norway to assess their utility as indicators of anthropogenic impacts. Sediments in the harbor are repositories for POPs and heavy metals supplied through discharges from industry and shipping activities. Sediment contaminant concentrations are at moderate to poor ecological quality status (EcoQS) levels. The EcoQS based on benthic foraminiferal diversity reflects a similar trend to the EcoQS based on contaminant concentrations. Foraminiferal density and diversity is low throughout the harbor with distinct assemblages reflecting influence of physical disturbances or chemical stressors. Assemblages impacted by physical disturbance are dominated by *L.lobatula* and *E.excavatum,* while assemblages impacted by chemical stressors are dominated by opportunistic species *S.fusiformis, S.biformis, B.spathulata* and *E.excavatum*. The foraminiferal assemblage from an un-impacted nearby fjord consists mainly of agglutinated taxa. These assemblages provides a valuable baseline of the ecological impacts of industrialization in northern coastal communities.

1. Introduction

Urbanization and industrialization lead to the contamination of coastal marine waters, altering the ecological quality of the environment. As a result, faunal assemblages in these water bodies often deviate from those present under natural, undisturbed conditions. With increasing environmental pressure on the marine Arctic, there is a need for accurate, quick and cost effective tools to monitor and assess their ecological quality status (EcoQS). Assessment of EcoQS is based on the extent of deviation of the macro-benthic community to reference conditions, following the EU legislation of the Water Framework Directive (WFD, 2000). Reference conditions, or environmental baselines, are site- specific due to the broad diversity range of ecological regions within Europe. As macro-benthic fauna leaves an incomplete fossil record, reconstruction of in-situ reference conditions at already impacted sites is often not possible. In recent years, progress has been made to test the use of other biological groups, which better fossilize in the sedimentary record (e.g. Alve, 1991b; Andersen et al., 2004; Borja et al., 2008). Among those groups, benthic foraminifera have proved as effective indicators of environmental impact (Alve et al., 2009; Dolven et al., 2013).

Benthic foraminifera are considered as meiofauna and live in the upper layers of the seafloor. They are one of the most diverse and widely distributed groups of unicellular organisms in the oceans (Murray, 2006; Sen Gupta, 1999). They play a key role in the functioning of the benthic environment, actively contributing to bioturbation, ventilation of the sea floor and fate of organic matter (Gross, 2002). Foraminifera are sensitive indicators of environmental conditions, including both natural and anthropogenic alterations (Murray, 2006). In pristine environments, foraminifera are affected by parameters including temperature, salinity, nutrient availability, bottom substrate and dissolved oxygen (Murray, 2006). Anthropogenic stressors include amongst others heavy metals and polycyclic aromatic hydrocarbons (PAH) and organic matter enrichment. Foraminiferal reproductive cycles are short, and therefore their response to environmental change is fast (Kramer and Botterweg, 1991).

As benthic foraminiferal assemblages respond to geographical location and characteristics of the physical environment, site specific impact studies are a critical precursor to the use of foraminifera as a bio-monitoring tool. Benthic foraminifera have proven to accurately reflect the impact of pollution in several harbors located in the Mediterranean region (e.g. Armynot du Châtelet et al., 2004; Coccioni et al., 2009; Frontalini and Coccioni, 2011). However, the impact of anthropogenic activities in harbors in the sub-arctic regions has not been extensively studied (Dabbous and Scott, 2012). The main objective of this paper is to examine the suitability of benthic foraminiferal assemblages as indicators of different environmental stressors active in a subarctic harbor. Additionally, we test the applicability of foraminiferal diversity as measure of EcoQS (Bouchet et al., 2012) in this high latitude environment.

The harbor of the town of Hammerfest, Northern Norway (Fig. 1a)is an example of a harbor were various local pollution sources have resulted in pollution levels requiring immediate action (Pedersen et al., 2015). By studying living and fossilized foraminiferal assemblages from this harbor, the foraminiferal method enables both quantification of present and past impact of environmental stressors active in the harbor. At the same sites, the physical environment was mapped by means of grain size, total organic carbon and measurement of a range of heavy metals and POPs. We additionally quantified the natural baseline in a nearby un-impacted fjord. This dataset provides a useful baseline for future investigations of the ecological impacts of industrialization in northern coastal communities.

2. Study area

We focus on the inner harbor of Hammerfest which includes the city center (east side) and the industrial area of Fugleneset (west side) (Fig. 1b). The inner harbor is a 600 meter wide embayment with water depths ranging from 2 to 40 m. A CTD profile of the water column was measured during core collection in June 2015. The average salinity and temperature was 33.7 psu and 6.3 ^{o}C respectively (Suppl.Fig. 1). Bottom current speeds in the inner part of the harbor are <5cm/s, occasionally exceeding 10cm/s (Akvaplan-niva, 2013). The harbor receives freshwater from Lake Storvatn via the River Storelva which enters the harbor from the east.

Urban activities connected to Hammerfest harbor include ship traffic associated with the petroleum industry and service-related industries. These activities include various contaminant sources (Pedersen et al., 2015) the main ones being: petrol stations located at the harbor; (former) shipyards; discharges of untreated wastewater and sewage; and inflow of freshwater from the POPs polluted lake Storvatn. Additionally pollution from land based sources enter the harbor basin by, for example, subsurface water, rainwater, and snow melt. Polluted harbor sediments may be redistributed through resuspension by ships and marine organisms.

These pollution sources have resulted in elevated levels of heavy metals and POPs in harbor sediments as illustrated by several environmental studies carried out since 1985 (e.g. Dahl-Hansen, 2005; Evenset et al., 2006; Jahren and Helland, 2009; Johnsen and Jørgesen, 2006; Pedersen et al., 2015; Skjegstad et al., 2003). Previous investigations revealed a complex mixture of sediment pollutants such as heavy metals, PAH, PCB and TBT at levels of risk for the harbor environment and human health (Norwegian Environment Agency, 2014).

We used the nearby Revsbotn fjord (Fig. 1c) as a reference site for this study. The inner part of Revsbotn has water depths ranging between 0 and 50 m. A CTD profile of the water column taken at the time of collection showed bottom water temperatures of 5.8^{o}C, and bottom water salinity of 33.6 psu (Suppl.Fig. 1). A layer of fresh water transported from the river Russelva occurs at the harbor surface. No industrial or harbor activities occur at proximity to this site.

3. Material and Methods

3.1 Sample processing

In this study, we perform a multi-proxy study on a sediment core (core 6; Fig. 1) from Hammerfest harbor to reconstruct the pollution history of the area. In addition, the same parameters are investigated on a reference core from the nearby Revsbotn fjord (core 7; Fig. 1) to reconstruct reference conditions.

The present day conditions in both the harbor and at the reference site were assessed by a set of surface samples (stations 1 to 7; Fig. 1) covering the 0-2 cm sediment interval (Table 1).

Sediments at sites 1-5, were collected close to potential land based pollution sources (Table 1) (Skjegstad et al., 2003). Sediments were retrieved with a Van Veen grab sampler in October 2010. The sediment surface (0-2 cm) was collected for foraminiferal assemblage studies, while the top 10 cm of the grab sample was collected for chemical analyses.

At site 6 sediments were retrieved with a multi-corer in June 2015. Two cores were retrieved simultaneously at each station: Core 6 A intended for foraminiferal assemblages, grain size analyses and TOC and core 6 B intended for heavy metal and POP concentrations. The cores were sub-sampled at 1 cm intervals to a depth of 20 cm.

At site 7, sediments were collected with a box corer due to the hard substrate. After retrieval, two plastic core liners were pushed into the sediments: core 7 A, intended for foraminiferal analyses and; core 7 B intended for grain size, TOC and heavy metal analyses. The cores were sub-sampled at 1 cm intervals to a depth of 5 cm.

In the following, we refer to surface samples covering the 0-2 cm sediment interval, as “station” 1-7. For site 6 and 7 the results of the 0-1 cm and 1-2 cm sample were combined. We refer to the down core results presented for sites 6 and 7 as “core” 6 and 7 respectively.

3.2 Foraminiferal assemblages

The dead foraminiferal assemblages were identified for all samples. The living assemblage was studied in the surface samples (0-2 cm). After sampling, a Rose Bengal ethanol mixture (1g/l ethanol 95%) was immediately added to the sediment to stain the cytoplasm of the living fauna (Walton, 1952). The volume of the added mixture was at least equal to the sample volume (Murray, 2006). Samples were gently shaken to facilitate staining of living foraminifera within the sediment. The samples were stored cool for a minimum of two weeks (Lutze and Altenbach, 1991). Only specimens with a bright pink color of Rose Bengal stain inside more than half of the chambers were considered to be living at the time of sampling (de Stigter et al., 1998; 1999). In addition, for agglutinated foraminifera, specimens were defined as living if stain was present in the aperture (Schönfeld et al., 2012).

Foraminifera were identified to species level (Supplementary data B) according to the generic classification of Loeblich and Tappan (1987). Nomenclature is according to the accepted species names published in the WoRMS database (Mees et al., 2015). See Supplementary data B for taxonomical notes.

Both living and dead fauna were studied in the 100 µm to 1 mm size fraction. A minimum of 300 specimens from a known split of the sediment were identified to precisely determine the relative abundance of species of the assemblage (Patterson and Fishbein, 1989). Some samples contained low amounts of living benthic foraminifera (Table 2), and therefore 300 living specimens were not always possible to identify (Table 2).

3.3 Contaminant analyses

At all sites, the following heavy metals were analysed: Arsenic (As), Cadmium (Cd), Copper (Cu), Chromium (Cr), Mercury (Hg), Nickel (Ni), Lead (Pb) and Zinc (Zn). In addition, in samples at sites 1-6, concentrations of persistent organic pollutants (POPs) were analysed and include: sum of 16 polycyclic aromatic hydrocarbons (PAH(16)EPA), sum of 7 polychlorinated biphenyls (7PCB) and tributyltin (TBT). Analyses at sites 1-6 were performed by Eurofins Environmental Testing Norway AS according to their certified methodology (Appendix A). Analyses of site 7 were performed by ALS Laboratory Group Norway AS according to their certified methodology (Appendix A). For heavy metals and POP concentrations of stations 1-5 we use data previously published in Pedersen et al. (2015). For sites 6 and 7 new pollutant data is presented.

3.4 Grain size analyses and TOC

The grain size distribution of stations 1-5 was determined by a combination of sieving (> 63 µm) and Sedigraph (< 63 µm). Sediments were wet sieved at size fractions of 63 µm, 100 µm and 1 mm. The silt (4-63 µm) and clay fractions (<4 µm) were quantified on the Micrometics SediGraph 5100 according to the technique described by Coakley and Syvitski (1991) (Table 1).

At sites 6 and 7, the grain size distribution was determined with a Beckman Coulter Laser particle sizer 13320 according to the method described by Xu (2000). Prior to analysis, the samples were chemically treated to remove organic material and $CaCO_3$, using H_2O_2 and HCl respectively. From each sample, 2 g of material and was placed in 20% HCl for 24 hours to remove the carbonates. After HCl treatment the samples were centrifuged and washed with distilled water two times to remove HCl. Hereafter, H_2O_2 was used to remove organic matter. To enhance the reaction the samples were placed into a warmth bath of 85 ^{o}C for two hours. The samples were washed with distilled water and centrifuged two times to remove all the H_2O_2 from the samples before they were left for drying in room temperature. After this, 0.5 g of sample material was mixed with 20 cl of water after which the samples were shaken for 24 hours. Just before analyzes a drop of Calgon solution was added to the samples after which they were placed in an ultrasound bath for 5 minutes to disintegrate flocculation of particles. Each sample was analyzed three times and the average grain-size values of the results were calculated.

The determination of TOC content of sites 1-5 was performed by Eurofins Environmental Testing Norway AS with infrared spectrometry (Norwegian Standard, 2001) and waspreviously published in Pedersen et al. (2015). The TOC content of sites 6 and 7 was performed at UiT - The Arctic University of Norway using a Leco CS-744 induction furnace (Table 1).

3.5 Data analyses

Assemblages and correspondence between core intervals of core 6 and 7 were determined with Q- and R-mode hierarchical clustering respectively, using Ward's method and Euclidean distance using the statistical program PAST version 3.06c (Hammer et al., 2001). Relative abundances of species within the dead assemblage were used as input. Only species that have a relative abundance of > 5 % in at least one sample were considered (Fishbein and Patterson, 1993). Before statistical analyses relative abundances were log transformed (log(1+X)) to increase the importance of less abundant species (Manly, 1997).

3.6 Ecological quality status

Ecological quality status (EcoQS), is used as a measure to quantitatively characterize the ecological quality of marine soft-bottom habitats, following the guidelines of the European Water Framework Directive (WFD, 2000). Assessment of EcoQS is based on the deviation from reference conditions as defined in the WFD, and is divided into five status categories, i.e. high, good, moderate, poor and bad. High EcoQS is considered as un-impacted reference or background conditions. Contaminant levels considered to be of good EcoQS if they have no ecosystem impact, while contaminant levels corresponding to moderate, good and bad EcoQS have chronic, acute and severe acute ecosystem impacts respectively (WFD, 2000) (Table 2).

Two different methodologies to define EcoQS are presented in the present study. The EcoQS of the sediments, hereafter referred to as “EcoQS(sed)”, is based on the classification scheme of sediment quality by Bakke et al., (Bakke et al., 2010). This classification scheme divides contaminant concentrations in classes based on their impact on macrofauna organisms.

Additionally, we derived EcoQS following the classification scheme proposed by Bouchet et al., (2012) based on benthic foraminiferal diversity, hereafter referred to as “EcoQS(bf)”, This classification scheme is based on changes in benthic foraminiferal diversity in response to different levels of environmental stressor. Diversity is expressed as the exponential of the bias corrected version of the Shannon-Wiener index, $\exp H'_{bc}$ (Chao and Shen, 2003). Dolven et al., (2013), showed that these EcoQS(bf) classes are applicable to fossil assemblages, enabling the reconstruction of past ecological status. The absolute abundances of all observed species was used to calculate $\exp H'_{bc}$, using the statistical language R (version 3.2.2; R Core Team, 2015), with the Entropy library (version 1.2.1; Hausser and Strimmer, 2009).

4. Results

4.1 Grain size distribution and total organic carbon

Grain sizes of the surface sediments from Hammerfest ranges from sandy silt on the east side (station 1 and 2) to sand on the west side and middle of the basin (station 3-6) (Fig. 2). The grain size distribution of core 6 is dominated by the sand fraction (Fig. 3). In this core we observed a distinct color change for sediment from dark brown to greenish grey at 7.5 cm core depth, corresponding to changes in physical properties (see below). For readability, we therefore refer to “core top” (0-7.5 cm) and “core bottom” (7.5-19.5 cm). An increase in the fine fraction is observed in the core top. In reference core 7, the grain size distribution of the sediments falls within the same range as core 6, with sand as the dominating grain size class (Suppl.Fig. 2).

The > 1 mm sediment fractions from stations 1, 2 and 6 contain lithogenic material, calcareous algae, shells and mollusks. The > 1 mm sediment fraction from stations 3, 4 and 5 consists mainly of organic material, kelp and some shells and mollusks. The > 1 mm fraction of core top 6 (Suppl.Fig. 2) mainly consists of lithogenic gravel, while core bottom 6 consists mainly of finer lithogenic material, calcareous algae, shell fragments, organic matter and wood particles.

At most stations, the TOC of surface samples varies between 0.3 and 3.2 % (Fig. 2). In station 4 the TOC concentration is significantly higher (9.7 %). At reference station 7 the TOC content is 0.7 %. The TOC content of core 6 varies between 0.3 and 2.9 %, shifting to lower values in the core top. The TOC content of reference core 7 is stable, i.e. 0.6 and 0.7%.

4.2 Contaminant levels

4.2.1 Surface samples

The distribution of metal and POP concentrations reflect the complexity of the pollution history and sources in the harbor (Fig. 2 and 3). High concentrations of PAH(16)EPA, 7PCB, Zn, As and Pb are generally found at the east side of the harbor (station 3-5), while high concentrations of TBT are observed in station 1 and 2 (west side). Additionally, station 4 (east side) holds the highest concentrations of heavy metals Cd, Cu and Hg. While station 6 generally has lower values of these pollutants, it contains the highest concentrations of Cr and Ni. At reference station 7, concentrations of all metals except Cr and Ni are lower than in station 1-6 from Hammerfest harbor (Fig. 2 & 3, Supplementary data A).

4.2.2 Cores

Considering the core 6 down-core contaminant profiles, there is a general trend of decreasing contaminant concentrations towards the core top, i.e. present day (Fig. 3; Supplementary data A). Exceptions are Ni and Cr, whose concentrations decrease towards 7.5 cm core depth (core bottom), but increase again in the core top. The down-core contaminant profiles of reference core 7 show a stable trend, with lower concentrations of all metals compared to core 6 (Fig. 3).

4.3 Benthic foraminiferal assemblages

4.3.1 Foraminiferal density

No living benthic foraminifera were observed at station 4. At other stations, the absolute abundances of the living fauna vary between 0.4 (station 2) and 9.2 (station 6) specimens per gram bulk dry sediment (#/g) (Table 2). The number of living foraminifera in control station 7 is 1.3 #/g.

The absolute abundance of dead fauna in surface samples varies between 4 (station 4) and 1667 (station 1) #/g. In core 6, the absolute abundance of dead fauna varies between 54 and 4141 #/g (Table 2). The core top and core bottom show a remarkable shift in absolute abundance, i.e. an average absolute abundance of 2545 #/g in the core bottom against 85 #/g in the core top (Table 2). In control core 7, the absolute abundance of the dead fauna varies between 36 and 138 #/g (Table 2).

In sediment samples from Hammerfest, an average of only 1% of the total assemblage consisted of agglutinated specimens while in control core 7 from Revsbotn, an average of 67% belonged to agglutinated specimens (Supplementary data B).

4.3.2 Foraminiferal diversity

In surface stations 1-6 from Hammerfest harbor, the living assemblage (October 2010) consisted of 8 agglutinated species and 32 living calcareous species. At reference station 7, the living assemblage (June 2015) consisted of 6 agglutinated and 12 calcareous species. The dead assemblage of the surface stations from Hammerfest, consisted of 8 agglutinated and 31 calcareous species, against 10 agglutinated and 26 calcareous species at reference station 7 (Supplementary data B). The dead assemblage of core 6 consisted of 7 agglutinated and 29 calcareous species; while the dead assemblage of reference core 6 consisted of 12 agglutinated species and 30 calcareous species.

The diversity measure exp H'_{bc} of the living assemblage from Hammerfest exhibit the lowest diversity in station 2 (7.4) and highest in the surface of core 6 (16.0) (Table 2; Fig. 4). The exp H'_{bc} for the living assemblage in Revsbotn was calculated to 15.9. The exp H'_{bc} of the dead assemblage of the surface samples from Hammerfest varies between 4.0 (station 1) and 12.4 (station 3), against 18.7 for reference station 7. The expH'_{bc} increases towards the top of core 6 (6.4 to 8.0) (Table 2; Fig. 4). The expH'_{bc} for reference core 7 varies between 18 and 20.

4.3.3 Taxa in surface samples

In Hammerfest harbor, the dominant living taxa (> 10 % relative abundance) by station are as follows (Suppl.Fig. 3, Suppl.Data B): station 1 *Lobatula lobatula, Elphidium excavatum* and *Bulimina marginata*; station 2 *Cribristomoides* spp., *E. excavatum* and *L. lobatula*; station 3 *Stainforthia* spp., *Buccella* spp., and *E. excavatum;* station 4 contained no living benthic foraminifera; station 5 *Stainforthia* spp., *E. excavatum* and *Spiroplectammina biformis;* station 6 *Reophax* spp. and *Bulimina marginata*. For the control station 7, the dominant living taxa are *Adercotryma glomerata, Eggerella* spp., and *Reophax* spp.

In station 1, 2, 3, 5 and 6, the dead assemblage is dominated by *L. lobatula* and *E. excavatum*. In station 4, the dead assemblage is dominated by *Cribristomoides* spp., and *L. lobatula.* The dead assemblage of reference station 7 is dominated by *A. glomerata, S. biformis* and *Cribristomoides* spp. follows (Suppl.Fig. 3, Suppl.Data B).

4.3.4 Taxa in sediment cores

In Hammerfest harbor (core 6), 10 species had a relative abundance of >5% (Fig. 5; Suppl.Fig. 4), and are considered as “most frequent species.” The absolute abundances of most of the frequent species, show a sharp decrease above 7.5 cm core depth, corresponding with the change in physical properties. The species *L. lobatula* is in general the most abundant dead species together with *E. excavatum* and *Cassidulina reniforme* (Fig. 5). These three species have high absolute abundances in the core bottom (> 7.5 cm core depth). The species *L. lobatula* has an average relative abundance of 55% in the core bottom, decreasing to 9% in the core top (< 7.5 cm core depth). Consequently, the relative abundance of the other dominant species increases in the top part of the core, even though their absolute abundance decreases. Important accessory species are *Haynesina germanica, Stainforthia* spp. (Fig. 5), *Trifarina angulosa* and *Cassidulina laevigata* (Suppl.Fig. 4). Other abundant, species are *Elphidium hallendense, Elphidium asklundi* (Fig. 5) and *Nonionella labradorica* (Suppl.Fig. 4).

At the control site (core 7), 7 taxa reached > 5% relative abundance (Fig. 5; Suppl.Fig. 4). The species *A. glomerata* dominates in each interval (Fig. 5). Other frequent species are *Cribristomoides* spp., *Eggerella* spp. and *S. biformis*. Less frequent, yet abundant are *Buccella* spp., *B. marginata* and *Staintforthia* spp. (Fig. 5). The relative abundance of *A. glomerata, Eggerella* spp., *S. biformis* and *Buccella* spp. increases while the relative abundance of *Cribristomoides* spp., *B. marginata* and *Stainforthia* spp. decreases towards the top of the core (Suppl. Fig. 4). The absolute abundance of these species declines at 1.5 cm core depth. At this depth interval, the relative abundance of *Cribristomoides* spp. and *S. biformis* is elevated (Fig. 5).

Q-mode clustering of log transformed relative abundances of the >5% species resulted in three clusters (Fig. 6): A) all samples of core 7; B) core 6 depth 1.5 to 5.5 cm; C) core 6 depth 0.5 cm and 6.5-19.5 cm. R-mode clustering of the same parameter grouped: I) *C. reniforme, E. excavatum, L. lobatula;* II) *A. glomerata, Cribristomoides* spp., *Eggerella* spp., and *S. biformis;* III) *E. asklundi, E. hallandense* and *N. labradorica* and; IV) *B. marginata, Buccella* spp., *S. fusiformis, H. germanica, C. laevigata, T. angulosa.* (Fig. 6).

5. Discussion

5.1 Physical environment Hammerfest harbor

Input of contaminants into the harbor of Hammerfest over several decades has resulted in a significant accumulation of contaminants in harbor sediments (Fig. 2 and 3). In response measures were implemented in 2006 to control contaminant supplies by land based sources to the harbor (Johnsen and Jørgesen, 2006).

Skjegstad et al. (2003) measured sediment contaminant concentrations in 1998, at sites close by our stations from 2010 (Suppl. Fig. 5). Comparison shows that contaminant concentrations have decreased in the sediment surface collected in 2010 in comparison to those collected in 1998 (Suppl. Fig. 5; Suppl.

Data A). Additionally, station 6 (collected 2015) shows lower contaminant concentrations for almost all contaminants. This is in correspondence with the decreasing trend of almost all contaminant concentrations towards the top of core 6 (Fig. 3). Exceptions are Ni and Cr, with elevated concentrations for station 6 in comparison to the surface samples from 2010 (see below) and elevated concentrations in the core top. The concentration profiles of Ni and Cr show a trend similar to the fine fraction (Fig. 3). The affinity of metals to finer particles is well known and is attributed to the absorptive properties of clay minerals as well as the larger specific surfaces of fine grained sediment (Contu et al., 1984; Horowitz, 1991). Hence, the increase in Ni and Cr, might be explained by increased clay content of the sediments in the core top, rather than an increased input to the harbor of these elements.

The outcome of our study shows that the first measures to reduce input of contaminants from land based sources into the harbor basin have been effective. Yet contaminant concentrations are still elevated compared to contaminant concentrations at reference site 7.

A large abrupt shift in TOC content and > 1 mm particles is observed at 7.5 cm core depth. The change in contaminant concentrations is however more gradual (Fig. 3). A similar change is observed in the foraminiferal assemblages at 6.5 cm core depth (Fig. 5). The 1-cm offset between foraminiferal assemblage and abiotic properties is explained by the fact that the parameters were measured on two different multi-corers (see Material and Methods). A possible explanation for the change in sediment properties might be the result of a different source of sediments to the core site 6, while the same mechanisms transport contaminants to the core site, i.e. through the water column. Shipping routes within the harbor have been changed to prevent disturbance of polluted sediments on the east side of the harbor (Skjegstad et al., 2003). A change in shipping routes may have increased the reworking by ship propellers of the coarse sediments at the west side towards the deeper part of the harbor, where core 6 was retrieved.

5.2 Ecological quality status

We calculated EcoQS based on two different input parameters, i.e. sediment contaminant concentrations (EcoQS(sed)) and foraminiferal diversity (EcoQS(bf)).

Concentrations of heavy metals in surface samples from station 1-6 are within EcoQS(sed) classes high to poor. The concentrations of POPs reflect moderate to bad EcoQS(sed) (Fig. 2). This indicates that sediment contaminant concentrations have chronic to severe acute ecosystem impacts (Bakke et al., 2010; WFD, 2000). EcoQS(bf) based on the living assemblage varies between moderate to bad (station 1-5), while the EcoQS(bf) of station 6 corresponds to good conditions (Fig. 4). The diversity of the dead assemblages of stations 1 to 6 reflect moderate to bad EcoQS(bf) conditions. Hence, both the living and dead assemblages of station 1 to 5 (collected in 2010) consistently indicate a contaminated environment. The living assemblage of station 6 (collected in 2015) however appears to be un-impacted, corresponding to the generally lower contaminant levels at this station compared to stations 1-5.

The concentrations of all heavy metals at reference station 7 reflect high EcoQS(sed) (Fig. 3), indicating that metal concentrations in station 7 represent un-impacted reference conditions (Bakke et al., 2010). The living assemblage of reference station 7 on the other hand reflects moderate EcoQS(bf), while the diversity corresponds to good EcoQS(bf) conditions (Fig. 4).

Due to the decrease in metal concentrations in core 6 towards present-day, concentrations of most metals correspond to high and good EcoQS(sed) in the core top. Only Cu shows moderate EcoQS(sed) in the lower part of the core top. Concentrations of PAH(16)EPA and TBT on the other hand correspond to moderate to bad EcoQS(sed) classes in both the core top and bottom, while 7 PCB concentrations decrease from moderate to high EcoQS(sed) values (Fig. 3). This indicates that POP concentrations in harbor sediments are still at levels harmful to the ecosystem, while metal concentrations are considered to be of no ecosystem impact. This is only poorly supported by the diversity based EcoQS(bf), reflecting a poor status for the entire core 6 (Fig. 4).

In reference core 7, all heavy metal concentrations correspond to high EcoQS(sed) (Fig. 3), while EcoQS(bf) correspond to good status (Fig. 4). The latter suggests that the benthic foraminiferal assemblage of Revsbotn reflects an un-impacted benthic foraminiferal assemblage and can be used as reference to reconstruct the pre-impacted conditions for the Hammerfest harbor (see discussion below).

Our results show that EcoQS(sed) reflects better conditions than the EcoQS(bf). The discrepancy between different EcoQS is partly explained by the fact that multiple stressors influence benthic foraminiferal assemblages and the individual contribution of each stressor is not always possible to distinguish. From our dataset it is also not possible to reconstruct which contaminant has had a larger influence on the ecosystem. Additionally, EcoQS(bf) is based on the response of benthic foraminifera to oxygen depletion in Southern Norway (Bouchet et al., 2012), which might be different from the response of benthic foraminifera to chemical pollution prevailing in the Hammerfest harbor. Furthermore, the natural diversity of the South Norwegian coast, on which the EcoQS(bf) classes are based, is different from the benthic foraminiferal assemblage in Northern Norway. Hence the boundaries between the different EcoQS(bf) classes might not be directly applicable to our area.

A similar discrepancy between EcoQS (sed) and EcoQS(bf) was observed by Dolven et al., (2013) who suggested to rather compare to temporal trends. The temporal pattern between EcoQS(bf) and EcoQS(sed) for core 6 is largely comparable, i.e. improving EcoQS towards the top of the core, and overall decreasing contaminant levels. This indicates that the reduction in contaminant concentrations, had a positive effect on foraminiferal diversity reflecting benthic recovery.

5.3 Foraminiferal assemblages and environmental stressors

The main focus of the benthic faunal studies in Hammerfest harbor (sites 1-6), was to test how the benthic foraminiferal assemblage in Hammerfest harbor reflects the ecosystem impact of the different environmental stressors active in the harbor. Site 7 in Revsbotn served as the reference site providing information on the potential non-impacted benthic foraminiferal assemblage. Care should be taken when interpreting living assemblages, as no replicate samples were analyzed in our study. Therefore our study does not take into consideration foraminiferal patchiness at the sampling site. Also since the surface stations 1-5 were taken with a grab corer, surface sediments might have been disturbed resulting in specimen loss together with some of the uppermost sediment (Riddle, 1989; Wigley, 1967). In addition, some samples contained low amounts of living benthic foraminifera (Table 2), which may introduce additional bias to our study. However, statistical studies based on a large number of paleo-ecological datasets, demonstrated that a sample size ranging between 25 to 60 specimens effectively produced the same multivariate result as data based on larger sample size (Forcino, 2012; Forcino et al., 2015). We therefore argue that, although care should be taken when interpreting samples with low number (60<n<300) of specimens, the living assemblages presented here are representative, as they rather precisely reflect the wide range of environmental stressors in the harbor (Suppl.Fig. 3). Nevertheless, data on living fauna has not been included in the statistical methods.

Estuaries and fjords are complex systems, with multiple factors other than pollution affecting benthic foraminiferal assemblages, i.e. grain size distribution, water mass properties and food availability. Our results show that both core 6 and 7 have a similar grain size distributions (Fig. 2 and 3) and were taken at similar water depths (40-41 m), with similar bottom water temperature and salinity (Suppl.Fig. 1). We therefore argue that the benthic foraminiferal assemblage from Revsbotn likely reflects the assemblage to be expected in Hammerfest harbor under non-impacted conditions.

Based on the physical properties and foraminiferal counts we identified four assemblages reflecting four different environmental stressors/settings. Q- and R- mode clustering was performed on the dead faunal counts to strengthen our observations (Fig. 6). Below we discuss the dominant stressors, with corresponding indicator species and contaminant sources (summarized in Table 3).

5.3.1 Physical disturbance

Samples from the west side of the harbor (station 1 and 2) are characterized by coarse grained sediments This is attributed to ship traffic as ship propellers may disturb and resuspend contaminated sediments and transport fine grained sediments away from the site. Additionally, the samples have high TBT concentrations. TBT has been used as a biocide in anti-fouling paint for ships until it was internationally banned in 2008 (Gipperth, 2009). The relatively high Pb and Hg concentrations might be attributed to spills of leaded gasoline, potentially from the gasoline station close by station 2 (Pedersen et al., 2015). The sediments of core top 6, resemble the grain size properties of the surface samples from the west side of the harbor (station 1 and 2). i.e. coarse grain sizes, generally lower heavy metal levels, but still elevated concentrations of POPs (Figs. 2 and 3). The increased amount of > 1mm sediment particles in core top 6 (Suppl. Fig. 2), confirms a more turbulent high energy environment.

The benthic foraminiferal assemblage prevailing in station 1, 2 and core top 6, reflects these physical properties. Correspondence clustering, based on dead assemblages of core 6 and 7, grouped samples of core top 6 (Fig. 6; Cluster B). The assemblage in this core interval is dominated by *E. excavatum*, *C. reniforme* and sub-dominance of *L. lobatula* (Fig. 6). Although *E. excavatum* frequently occurs in uncontaminated fjord settings (Husum and Hald, 2004; Jennings and Helgadottir, 1994; Mackensen et al., 1985), the species is reported to flourish in areas of physical and chemical stress, including high turbidity environments (Polyak et al., 2002) and heavy metal and POP contamination (e.g. Alve and Olsgard, 1999; Dabbous and Scott, 2012; Sharifi et al., 1991). Throughout the entire harbor, a relatively high amount of living specimens of *E. excavatum* was observed, reflecting the harsh conditions for benthic foraminifera in the harbor. *Cassidulina reniforme* often co-exists with *E. excavatum* (e.g. Husum and Hald, 2004; Jennings and Helgadottir, 1994; Mackensen et al., 1985) and has been reported as one of the first species to recolonize former barren areas when exposure to industrial effluents was reduced (Schafer et al., 1991). Other *Elphidium* species show additionally higher abundances in core top 6 (Suppl. Fig. 4 – see *E. asklundi). Elphidium* species are capable of adapting to harsh environments and are capable of quickly colonizing obliterated areas when environmental conditions improve (e.g. Alve, 1999; Corliss, 1985; Corliss and Van Weering, 1993; Linke and Lutze, 1993; Wollenburg and Mackensen, 1998). *Lobatula lobatula* is a clinging epifaunal species tolerant to relatively coarser grain sizes and high energy environments (Hald and Steinsund, 1992; Mackensen et al., 1985), which is consistent with the turbid, harsh physical environment prevailing in core top 6. Additionally, *L. lobatula* tolerates limited food availability (Mackensen et al., 1985; Nyholm, 1961), which is suggested by the low TOC content (Fig. 3). Hence, the assemblage reflects improved environmental conditions, in addition to the coarse grain sizes prevailing in core top 6.

Despite the lower contaminant levels and higher diversity in the core top 6 (Fig. 3 and 4), the total absolute abundance is one order of magnitude lower than the core bottom (Table 2). The low TOC concentrations in core top 6, might be indicative of a lower vertical export of organic matter, and hence decreased primary and secondary food sources for benthic foraminifera (Loubere and Fariduddin, 1999). The living fauna dominating in station 1 and 2, confirm that physical disturbances are the main stressors affecting the foraminiferal assemblage, with *E. excavatum and L. lobatula* as dominating species. The high abundance of *Cribristomoides* spp., reported to live attached and epifaunal (Murray, 2006), additionally supports the influence of the high energy environment on the foraminiferal assemblage.

5.3.2 Chemical stressors

Correspondence clustering grouped the 0-1 cm interval of core 6 with the core bottom 6 (Fig. 6). The core bottom 6 resembles grain size properties of the stations from the east side of the harbor (station 3 and 5), i.e. finer grain sizes and higher contaminant levels. The higher contaminant levels of station 3 and 5 are attributed to urban activities around the harbor, and partly are the result of input of contaminants by the outlet of the polluted lake Storvatn (Evenset et al., 2006; Pedersen et al., 2015). Similar contaminants have high concentrations in bottom core 6, suggesting a similar source.

The foraminiferal assemblage in core bottom 6 has a relatively lower diversity, and shows a strong dominance of *L. lobatula* with a sub-dominance of *E. excavatum* and *C. reniforme* (Fig. 6). This illustrates the harsh environmental conditions prevailing in Hammerfest harbor, for reasons explained above. The sand content in core bottom 6 partly explains the high abundance of *L. lobatula* in this interval of the core, however it does not explain why its abundance is elevated compared to the even coarse core top. *Lobatula lobatula* is easily reworked due to its low shell weight in comparison to shell size (Kontrovitz et al., 1978). We therefore argue that the high amounts of *L. lobatula* in this part of the core partly represents a reworked fauna.

An important difference separating the foraminiferal assemblage dominant in the core bottom from the assemblage in the core top, is the relatively higher abundance of opportunistic, stress tolerant, species, e.g. *H. germanica* and *B. marginata* (Fig. 5 and Suppl.Fig. 4). The pollution tolerant *H. germanica* is known to show positive responses to anthropogenic pollutants (Alve et al., 2009; Alve and Olsgard, 1999; Yanko et al., 1998). *Haynesina germanica* has been reported to be common and co-existing with *E. excavatum,* when contamination is highest (Sharifi et al., 1991). *Bulimina marginata* is considered to be an opportunistic species in anthropogenic stressed environments which thrives in nutrient rich muddy sediments (e.g. Jorissen et al., 1992; Langezaal et al., 2005; Mojtahid et al., 2006; Murray, 1991).

Opportunistic species also prevail in the living assemblage of station 3 and 5 i.e. *Stainforthia* spp., *E. excavatum, S. biformis*, *B. spathulata* and *B. marginata* (e.g. Alve, 1994, 1995, 2003; Gooday and Alve, 2001; Murray, 2006; Polovodova Asteman et al., 2015; Schafer et al., 1991; Scott et al., 2001).

Core bottom 6 contains a high density, yet low diversity, as a result of a high number of specimens belonging to a few opportunistic species, a trend that is more often observed in highly contaminated environments (e.g. Ellison et al., 1986; Murray, 2006; Pearson and Rosenberg, 1976). This, in addition to the relatively higher number of opportunists, makes us conclude that the benthic foraminiferal assemblage of the core bottom 6 (Fig. 6; Cluster B) and station 3 and 5 is mainly influenced by chemical stressors.

It should be noted that the low presence of agglutinated taxa (<1 %) in Hammerfest harbor stands in contrast to other studies from contaminated environments, where the opposite trend was reported, i.e. dominance of agglutinated opportunistic and stress-tolerant taxa when impact levels are highest (e.g.Alve, 1991a; Dabbous and Scott, 2012; Polovodova Asteman et al., 2015). Conversely, the total absence of agglutinated species has been reported in environments influenced by periodic discharges of oil and tar, resulting in either dissolution of agglutinated shells after deposition or unfavorable conditions for agglutinated taxa (Alve, 1995; Dermitzakis and Alafousou, 1987). Discharge of oil and tar in Hammerfest harbor is likely given the high ship traffic in the harbor and is supported by the high concentrations of PAHs, Pb and Hg in the sediments, and might therefore explain the absence of agglutinated taxa.

5.3.3 Organic pollution

In station 4, no living foraminifera were present. The observed black sediments in combination with a high percentage of TOC in station 4, indicates a hypoxic or anoxic environment. This station is close to a sewage outlet, and the input of high amounts of organic material for sewage effluents, has created conditions unfavorable for foraminifera. The high percentage of TOC might also have resulted in a low pH, and consequently dissolution of carbonate tests. This explains the low number of dead specimens in station 4 (Table 2). The dead assemblage is dominated by agglutinated species e.g. *Cribristomoides* spp. and *Reophax* spp. Dominance of agglutinated specimens over calcareous specimens additionally indicates post-mortem dissolution of calcareous tests. These conditions have not been observed in core 6, and suggest a large local impact from the sewage effluents.

5.3.4 Natural stressors

Contaminant concentrations of reference core 7 reflect high EcoQS, and correspondence clustering based on dead foraminiferal counts clusters all samples of core 7 (Fig. 6; Cluster A). Agglutinated taxa dominate both the dead and living fauna in Revsbotn (Suppl.Data B). The dead assemblages in reference core 7 is dominated by agglutinated species *A. glomerata,* with *Cribristomoides* spp., *Eggerella* spp., and *S. biformis* as sub-dominant species (Fig. 6). Similar species are frequently observed in the living fauna of station 7. This is comparable to observations in other north Norwegian fjords (Corner et al., 1996; Husum and Hald, 2004; Strand, 1979) and fjord settings in other northern regions (Jennings and Helgadottir, 1994; Murray, 2006). The species *A. glomerata* has been reported as part of transitional fauna in southern Scandinavian fjords and is indicative of changing environmental conditions at the onset of a pollution period (Polovodova Asteman et al., 2015). The high abundance of *A. glomerata* at our un-impacted reference site, highlights that species indicative of environmental pollution at more southern locations might reflect natural conditions at higher latitudes, and addresses the need for region specific impact studies and indicator species. *Bulimina marginata, Stainforthia* spp., and *Buccella* spp. are the most important part of the calcareous fauna in Revsbotn (Suppl.Fig. 4). *Bulimina marginata* is a frequently observed in inner fjords (Husum and Hald, 2004; Murray, 2006). Polyak et al., (2002) observed elevated abundances of *Buccella* spp. in river-proximal settings. Station 7 is located near the Russelva river (Fig. 1). In turn, *Stainforthia* species are opportunistic and thrive on pulses of high seasonal productivity (Alve, 1995; Gustafsson and Nordberg, 2001). This type of food availability in the area is supported by the high abundance of *A. glomerata* reported to respond to pulses of fresh phytoplankton (Ernst and van der Zwaan, 2004; Heinz, 2002). Hence, the foraminiferal assemblage in Revsbotn reflects normal inner fjord settings. However, the presence of opportunistic species in Revsbotn, show that the environment is naturally challenging.

Density of benthic foraminiferal assemblages is typically low in environments subjected to severe levels of contamination (Schafer, 1973; Yanko et al., 1994). Hence, the low number of living foraminifera per gram dry sediment (Table 2) in the surface samples and core top 6, confirm the impact of contaminant on the living assemblage in the harbor. It should however be noted, that living foraminiferal density in station 7 from Revsbotn shows equally low absolute abundances of living specimens. Several studies from nearby non-impacted inner fjord settings show similar low abundances of living foraminifera, i.e. 0.05-30 specimens/g dry sediment (Corner et al., 1996; Husum and Hald, 2004), attributed to higher sedimentation rates and harsh delta conditions creating naturally unfavorable conditions for the living fauna. Similar conditions prevail at reference site 7 located close to a river outlet. This is confirmed by the moderate EcoQS(bf) based on the diversity of the living fauna, even though EcoQS(sed) reflects background conditions. This can be explained by the fact that the EcoQS (bf) is based on the more diverse foraminiferal assemblagea from Southern Norway (see discussion in Chapter 5.2). Similar naturally challenging conditions for benthic foraminifera might prevail in Hammerfest harbor. For bio-monitoring purposes, it is therefore important to keep in mind that density and diversity in Hammerfest fjord might be naturally low, even when contaminant levels have decreased to low impact values. This naturally challenging environment, in addition to similar opportunistic species in both impacted and non-impacted environments, might impede bio-monitoring in this area based on benthic foraminifera only.

6. Conclusion

This study investigated the correlation between contaminants, grain size and benthic foraminiferal assemblages in the harbor of Hammerfest (N. Norway). The harbor is highly contaminated by persistent organic pollutants and heavy metals mainly due to discharges from local industries and shipping related activities. The foraminiferal assemblage at a non impacted site in the nearby Revsbotn fjord was investigated to reconstruct the natural baseline. Due to recent measures to decrease contaminant supplies into the harbor, contaminant levels have decreased compared to levels measured in 1998 (Skjegstad et al., 2003). However, sediment contaminant concentrations, especially for POPs, are still at moderate to poor EcoQS(sed) levels causing chronic to acute ecosystem impacts.

Foraminiferal density and diversity in the harbor is low in. The EcoQS(bf), based on a benthic foraminiferal diversity, reflects a similar spatial and temporal trend as the EcoQS(sed) based on contaminant concentrations. However, the EcoQS(bf) does not directly reflect the EcoQS(sed), most likely due to the high-latitude location of Hammerfest harbor, with a naturally lower diversity than the more southern location on which the current EcoQS(bf) is based. This addresses the need for an adjusted EcoQS(bf) scheme for more northern latitudes. Based on the living and dead foraminiferal assemblages, four different stressors with associated foraminiferal assemblages indicative of these environmental stressors have been defined:

- Physical stressors by ship traffic. Sediments are characterized by coarse grain sizes (> 1 mm), low TOC, lower metal concentrations and elevated TBT concentrations. Associated benthic foraminifera include *L. lobatula, E.excavatum* and *Cribristomoides* spp.

- Chemical stressors by urban activities. Sediments are characterized by high heavy metal and POP concentrations. Associated benthic foraminifera include opportunists *Stainforthia* spp., *S. biformis*, *B.marginata* and *E. excavatum*
- Organic stressors from sewage effluents. Sediments are anoxic and characterized by high metal and TOC concentrations. No living foraminifera and only few dead agglutinated species were observed.
- Natural stressors prevail at the reference station and are associated with dominance of the agglutinated species *A.glomerata, Cribristomoides* spp., *Eggerella* spp., and *S. biformis.*

The patterns identified through this investigation provide a valuable baseline for future investigations of the ecological impacts of industrialization in northern coastal environments.

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Table 1
Overview of sample sites and water depth, collected material with corresponding equipment and overview of performed analyses with corresponding methods and laboratories. Analyses were performed at UiT The Arctic University of Norway unless stated otherwise below. Abbreviations: vGC = Van Veen grab, MC = multi corer, BC = box corer, EF = Eurofins Environmental Testing Norway AS, ALS = ALS Laboratory Group Norway AS, IRS = infrared spectrometry, Leco = Leco CS-744 induction furnace, Sed.Gr = Micrometics SediGraph, LPS= Beckman Coulter Laser particle sizer 13320.

Sites (water depth)	sub-sample	Reference in text	sample equipment	depth interval	living forams	dead forams	heavy metals	POPs	TOC	GS
1 (13 m)	A	Station 1	vGC	0-2 cm	x	x				Sed.Gr
	B			0-10 cm			EF	EF	IRS	
2 (7 m)	A	Station 2	vGC	0-2 cm	x	x				Sed.Gr
	B			0-10 cm			EF	EF	IRS	
3 (16 m)	A	Station 3	vGC	0-2 cm	x	x				Sed.Gr
	B			0-10 cm			EF	EF	IRS	
4 (15 m)	A	Station 4	vGC	0-2 cm	x	x				Sed.Gr
	B			0-10 cm			EF	EF	IRS	
5 (12 m)	A	Station 5	vGC	0-2 cm	x	x				Sed.Gr
	B			0-10 cm			EF	EF	IRS	
6 (41 m)	surface A*	Station 6	MC	0-2 cm*	x	x				
	core A	Core 6 core top 6 (0-7.5 cm) 7.5-20 cm: core bottom 6		0-20 cm; 1 cm intervals		x				LPS
	core B			0-20 cm; 1 cm intervals			EF	EF	Leco	
7 (41 m)	surface A*	Station 7	BC	0-2 cm*	x	x				
	core A	(reference) Core 7		0-5 cm; 1 cm intervals		x				LPS
	core B			0-5 cm; 1 cm intervals			ALS		Leco	

*results of 0-1 cm and 1-2 cm have been combined

Table 2

Number of counted specimens (n), species (S), total standardized absolute abundance (#/g) and diversity index (expH'_{bc}) of the surface stations (A) and cores (B). Color shading corresponds to environmental quality status defined by Bouchet et al., (2012) (exp H'_{bc}) as indicated in table (C).

(A)

dead fauna surface samples						living fauna surface samples					
station	interval	**n**	**S**	**#/g**	**exp H'_{bc}**	**station**	interval	**n**	**S**	**#/g**	**exp H'_{bc}**
1	0-2 cm	294	17	1667,2	4	1	0-2 cm	82	18	2,2	14,2
2	0-2 cm	290	18	975,8	4,2	2	0-2 cm	17	7	0,4	7,4
3	0-2 cm	300	24	98,4	12,4	3	0-2 cm	114	17	2,9	9,6
4	0-2 cm	60	15	4,3	10,7	4	0-2 cm	-	-	-	-
5	0-2 cm	297	19	1083,1	6,4	5	0-2 cm	242	20	8,3	8,6
6	0-2 cm	764	29	106,8	9	6	0-2 cm	213	30	9,2	16
7	0-2 cm	679	38	193,9	18,7	7	0-2 cm	91	18	1,3	14,4

(B)

	core 6 dead fauna						core 7 dead fauna				
	core depth	**n**	**S**	**#/g**	**exp H'bc**		**core depth**	**n**	**S**	**#/g**	**exp H'bc**
core	0,5	444	29	117,8	8,8	**core**	0,5	308	31	426,6	20
6	1,5	320	21	94,6	8,8	**7**	1,5	371	31	133,5	17,1
	2,5	297	21	54,2	8,3		2,5	301	27	356,1	17
	3,5	292	19	64,2	8,9		3,5	326	30	449,9	18,2
	4,5	299	14	57,5	7		4,5	311	28	391,2	18
	5,5	307	19	120,4	8,3						
	6,5	314	23	306,4	6,7						
	7,5	315	23	1985,6	6,5						
	8,5	300	19	2900,1	6,5						
	9,5	332	18	4141,2	5,7						
	10,5	303	21	3705,5	6,3						
	11,5	334	20	2380,4	5,3						
	12,5	312	23	2659,5	5,5						
	13,5	340	18	2378,4	5,4						
	14,5	363	20	1973,8	5,9						
	15,5	320	21	2047,8	6,7						
	16,5	319	16	2354,8	6,1						
	17,5	308	17	2275,2	6,7						
	18,5	311	21	1939,5	6,6						
	19,5	319	22	2347,9	6,4						

(C)

EcoQS class	**EcoQS range**	**Ecosystem impact**
High	**>20**	Reference conditions
Good	15-20	No impact
Moderate	10-15	Chronic impact
Poor	5-10	Accute impact
Bad	<5	Severe accute impact

(Bouchet et al., 2012)

Table 3

Overview of the defined stressors with sources and associated contaminants and foraminiferal species indicative for these stressors.

Main stressor	**Source + contaminants**	**Indicator species**	**Corresponding samples**
Physical disturbance	Shipping industry Mechanical reworking sediments TBT, Hg, Pb	High energy environment indicators including: *L. lobatula* *Cribristomoides* spp. *E. excavatum*	West site harbor (station 1, 2) Top core 6 (0-7.5 cm)
Chemicals	Urban industrial activities and inflow lake Storvatn heavy metals and POPs	Opportunistic species including: *Stainforthia* spp., *S.biformis*, *B. marginata*, *E. excavatum*	East site harbor (station 3, 5) Bottom core 6 (7.5-20 cm)
Organic pollution	Sewage effluents Organic matter, POPs, heavy metals	No living foraminifera Few dead foraminifera with dominance of agglutinated species	Station 4
Natural conditions	Pristine conditions	Agglutinated species including: *A. glomerata*, *Cribristomoides* spp., *Eggerella* spp., *S. biformis* Less frequent calcareous species include: *B. marginata*, *Stainforthia* spp.	Station 7 Core 7

Figure captions

Fig. 1. Location maps. Maps showing: Northern Norway and SW Barents Sea region (Andreassen et al., 2008). (a) The location of the town of Hammerfest and Revsbotn is indicated (top panel); (b) The inner harbor of the town of Hammerfest with the locations of site 1-6; (c) Location of site 7 in Revsbotn (bottom panel). Bathymetric contours are in meters (m).

Fig. 2. Element concentrations, grain size and TOC surface sediments. Concentrations of heavy metals and POPs measured in surface sediments Hammerfest and top of core 6 and 7. Corresponding EcoQS(sed) classes as defined by Bakke et al. (2010) are indicated by corresponding colors. Lower right panel shows grain size distributions expressed as weight percentage of the abundance of sand (> 63 µm), silt (4-63 µm) and clay (< 4µm) (left y-axis). The total organic carbon (TOC) of the surface sediments, indicated by red dot (right y-axis).

Fig. 3. Element concentrations, grain size and TOC cores. Down core concentrations of heavy metals and POPs measured in core 6 (black dots black line) and 7 (white dots dashed line). Corresponding EcoQS(sed) classes as defined by Bakke et al. (2010) are indicated by corresponding colors. Lower right panel shows the down core distribution in core 6 of sand (> 63 µm), silt (4-63 µm) and clay (< 4µm) content (upper x-axis) and down core distribution of TOC content, indicated by red line (lower x-axis). Grain size properties of core 7 can be found in supplementary figure 2.

Fig. 4. Diversity. Diversity expressed as exponential of bias corrected Shannon-Wiener index (exp H'_{bc}), for surface samples (upper panel) and sediment cores (lower panel). Black dots black line corresponds to core 6; white dots dashed line corresponds to core 7. EcoQS(bf) classes as defined by Bouchet et al. (2012) are indicated by corresponding colors.

Fig. 5. Foraminiferal assemblage core. Left panel shows dominating foraminiferal species in sediment cores 6 and 7. Shown are relative abundances (black line; upper x-axis) and standardized absolute abundances (grey shading; lower x-axis). Right panel show relative abundances of other relevant species.

Fig. 6. Q- and R-mode clustering. Dendrograms from Q- and R-mode clustering using Euclidean distance and Ward’s method based on log transformed relative abundances of both agglutinated and calcareous species from core 7, Revsbotn, and core 6, Hammerfest. Sample codes refer to code name and midpoint depth of sample interval. Grey shading indicates relative abundances of the species in sample interval (see legend).

Figure 1

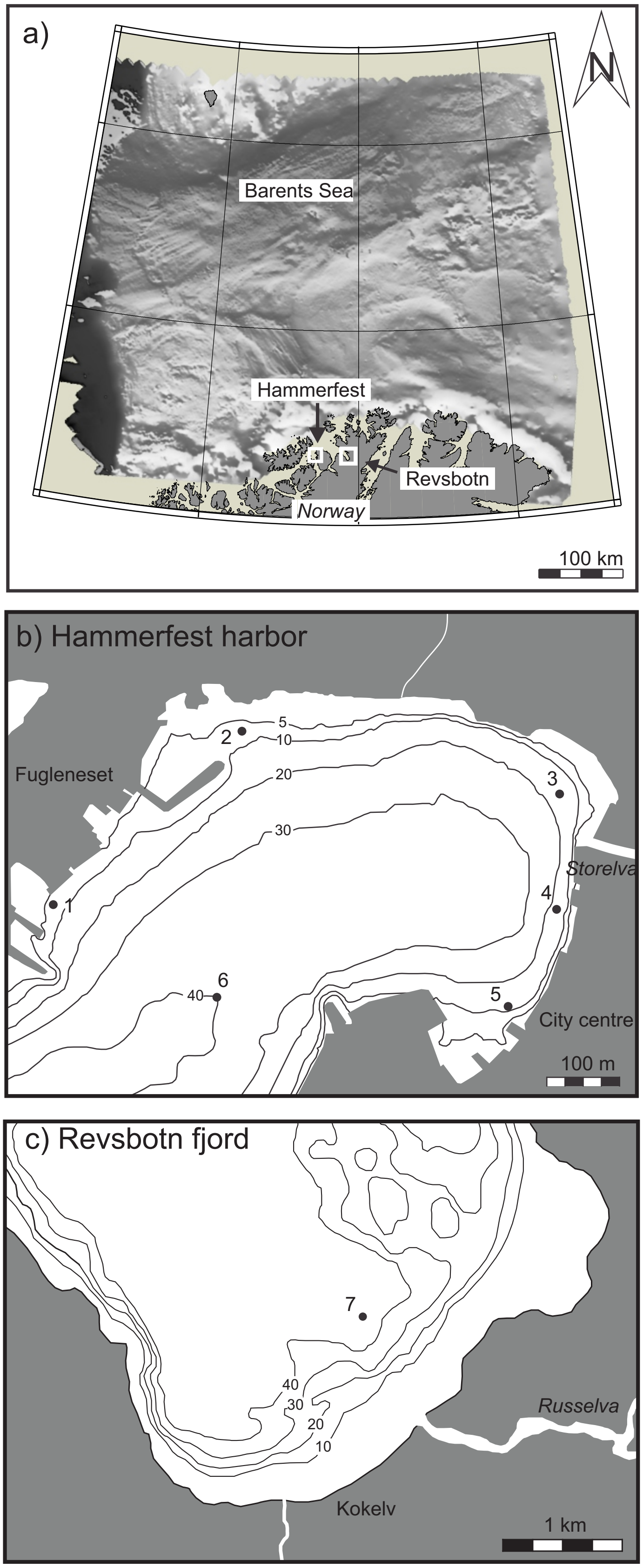

a)
N
Barents Sea
Hammerfest
Revsbotn
Norway
100 km
b) Hammerfest harbor
Fugleneset
2
5
10
20
30
3
Storelva
4
1
6
40
5
City centre
100 m
c) Revsbotn fjord
7
40
30
20
10
Russelva
Kokelv
1 km

Figure 2

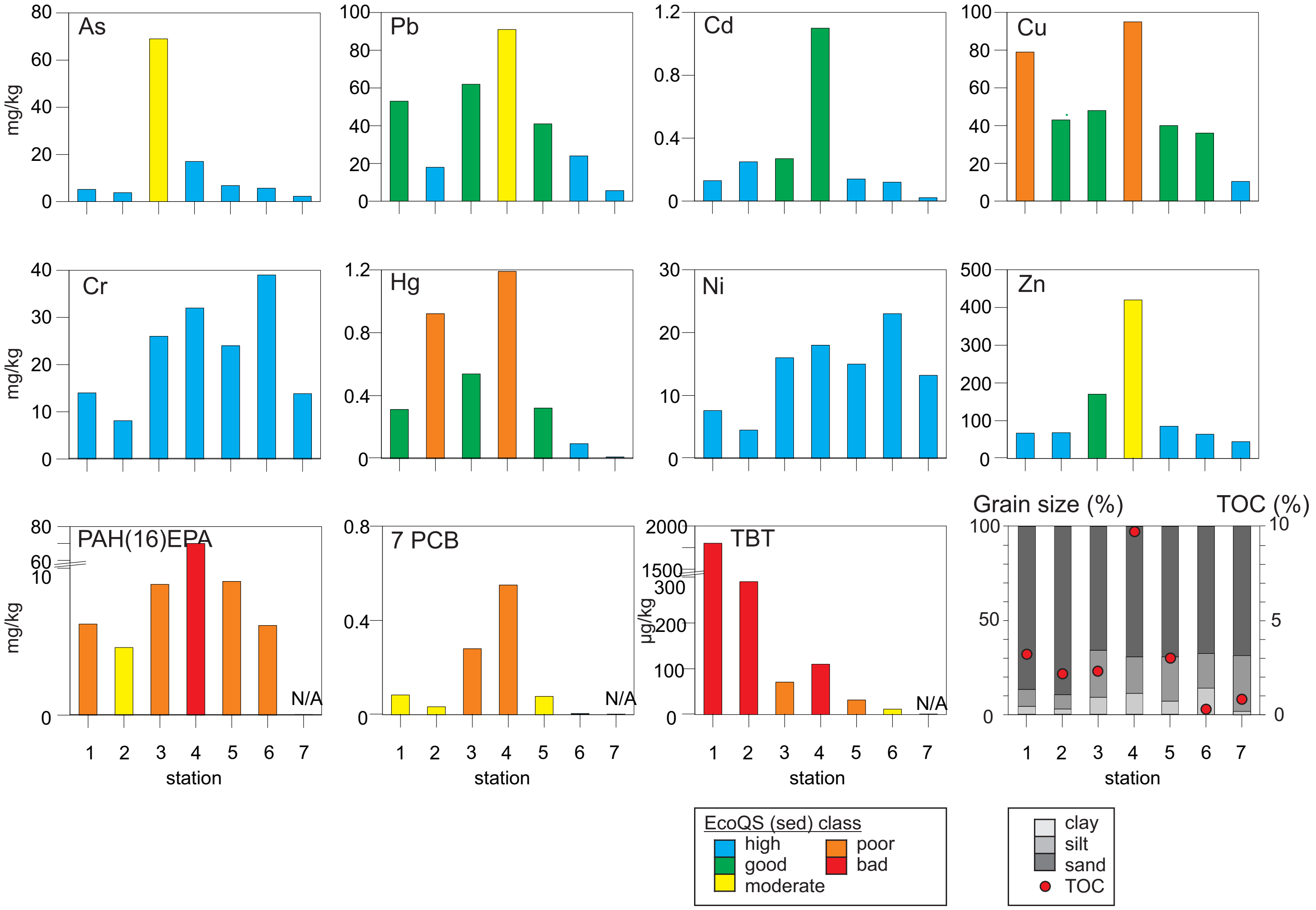

As
Pb
Cd
Cu
Cr
Hg
Ni
Zn
PAH(16)EPA
7 PCB
TBT
Grain size (%)
TOC (%)
mg/kg
µg/kg
station
1
2
3
4
5
6
7
N/A
0
20
40
60
80
100
0.4
0.8
1.2
10
30
200
300
400
500
1500
2000
50
5
EcoQS (sed) class
high
good
moderate
poor
bad
clay
silt
sand
TOC

Figure 3

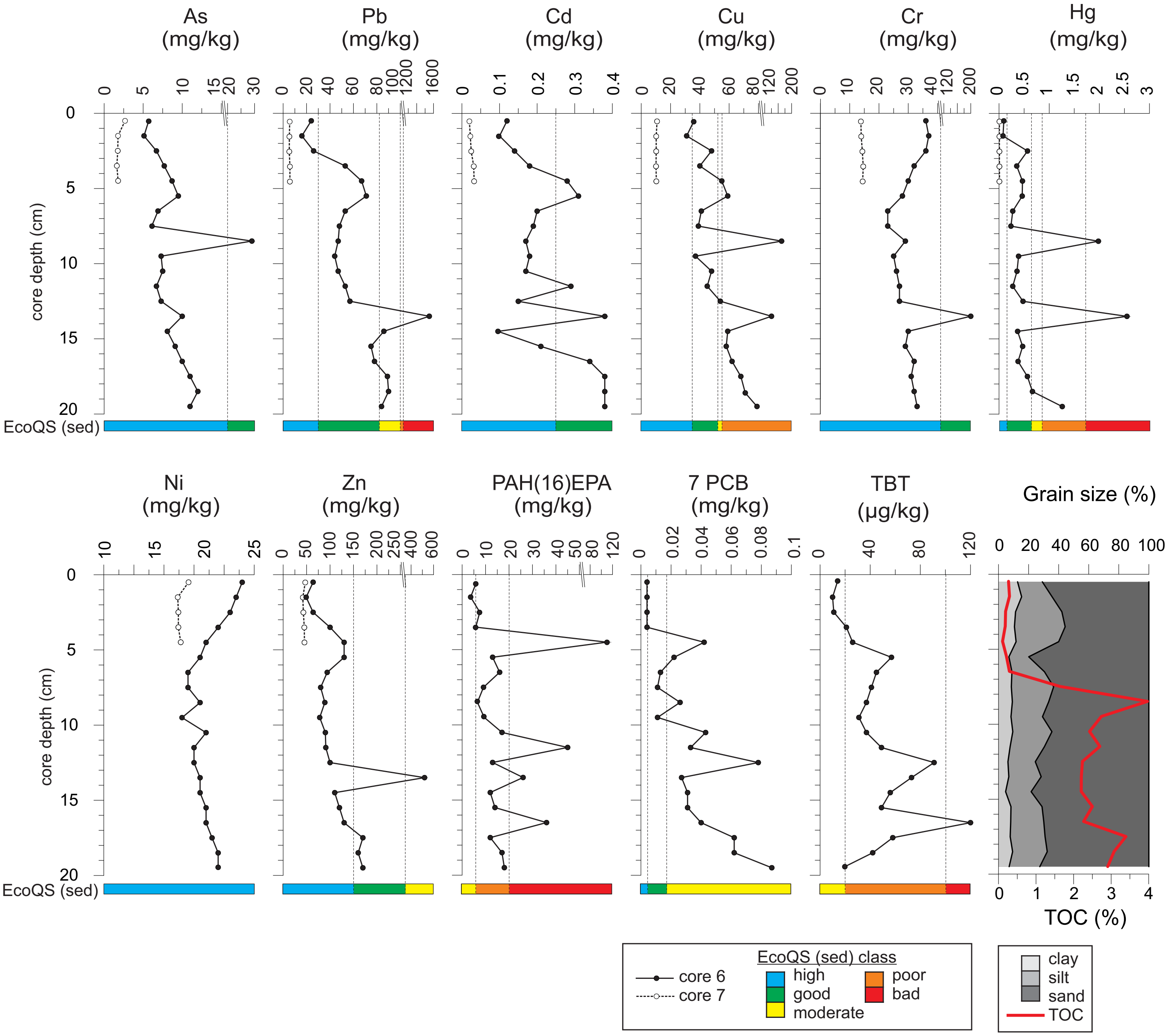

As (mg/kg)
0 5 10 15 20 30
Pb (mg/kg)
0 20 40 60 80 100 1200 1600
Cd (mg/kg)
0 0.1 0.2 0.3 0.4
Cu (mg/kg)
0 20 40 60 80 120 200
Cr (mg/kg)
0 10 20 30 40 120 200
Hg (mg/kg)
0 0.5 1 1.5 2 2.5 3
core depth (cm)
0 5 10 15 20
EcoQS (sed)
Ni (mg/kg)
10 15 20 25
Zn (mg/kg)
0 50 100 150 200 250 400 600
PAH(16)EPA (mg/kg)
0 10 20 30 40 50 80 120
7 PCB (mg/kg)
0 0.02 0.04 0.06 0.08 0.1
TBT (µg/kg)
0 40 80 120
Grain size (%)
0 20 40 60 80 100
TOC (%)
0 1 2 3 4
core 6
core 7
EcoQS (sed) class
high
good
moderate
poor
bad
clay
silt
sand
TOC

Figure 4

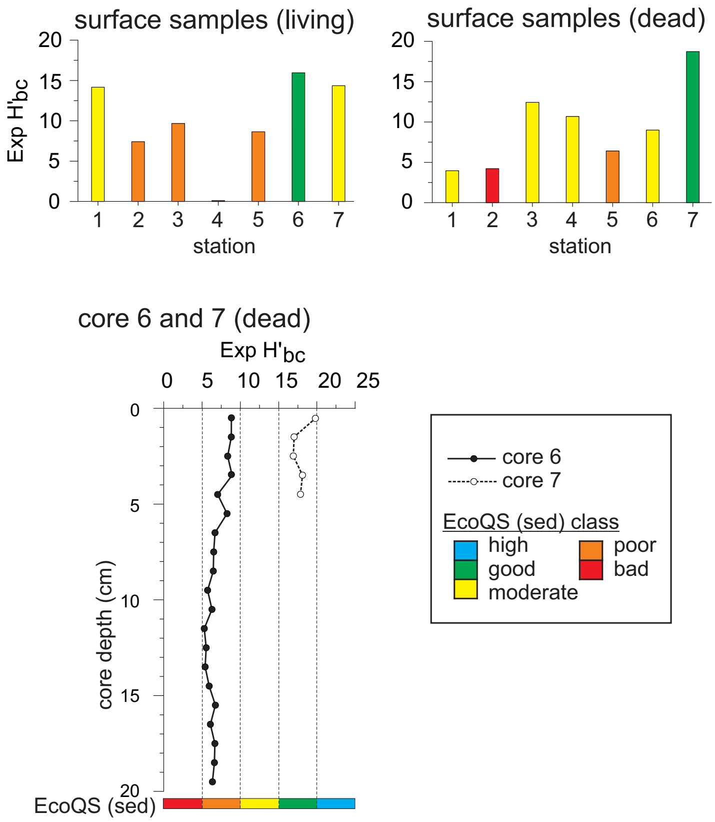
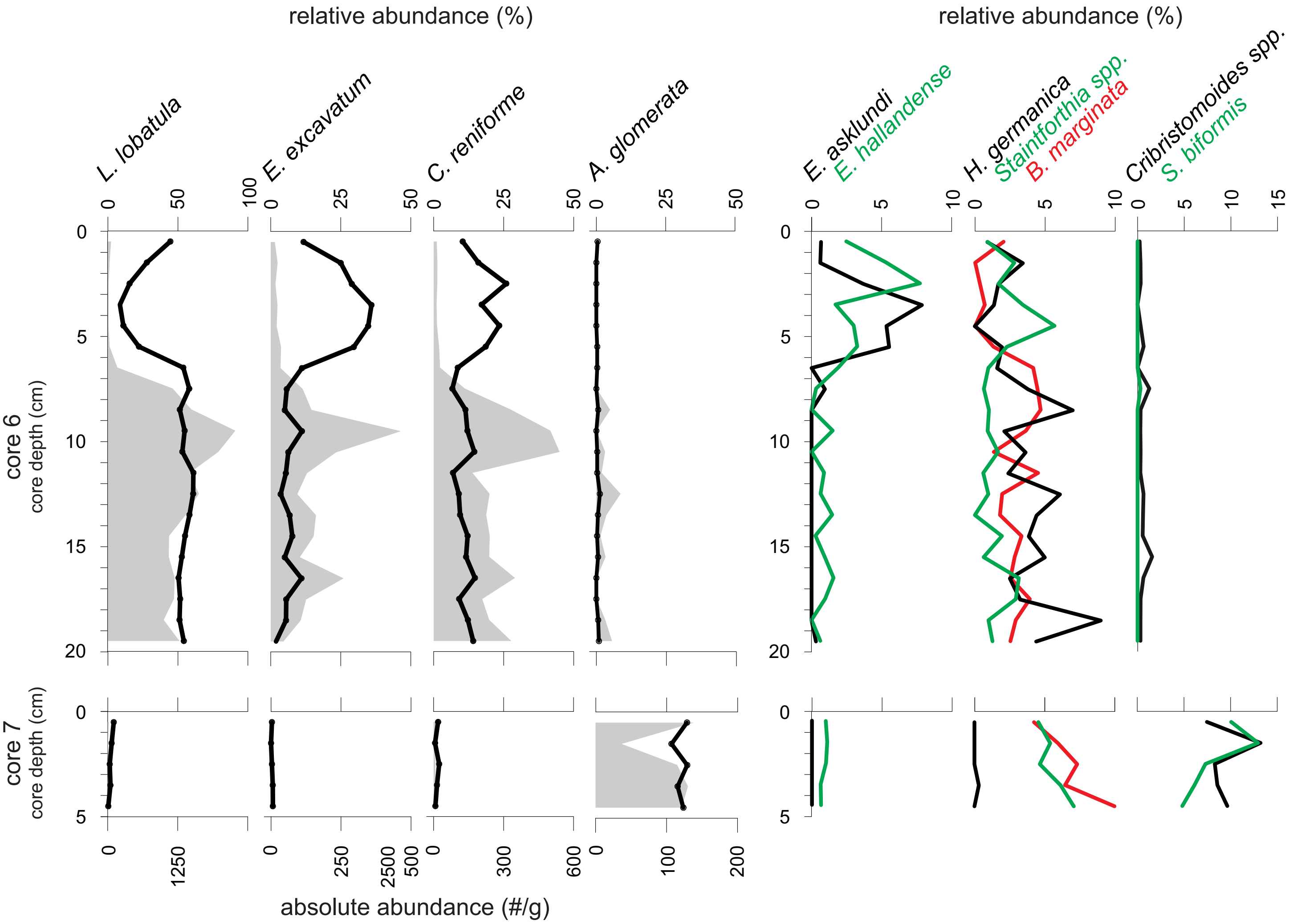
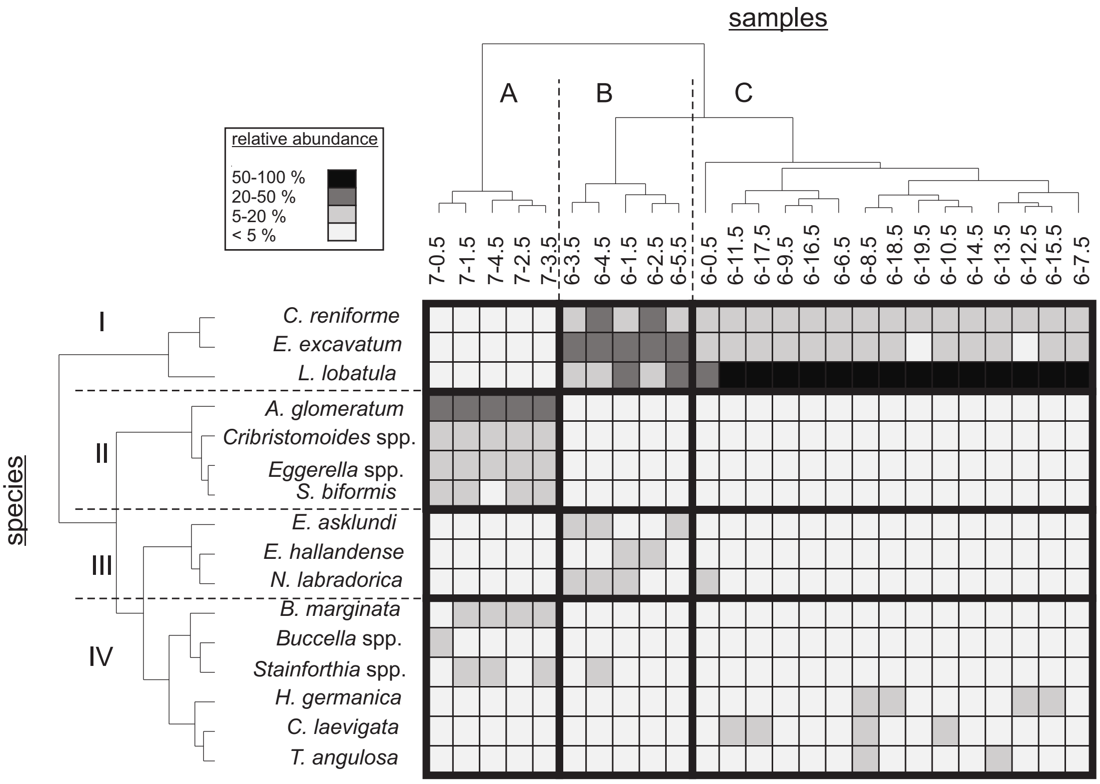

surface samples (living)
Exp H'bc
20
15
10
5
0
1 2 3 4 5 6 7
station
surface samples (dead)
20
15
10
5
0
1 2 3 4 5 6 7
station
core 6 and 7 (dead)
Exp H'bc
0 5 10 15 20 25
core depth (cm)
0
5
10
15
20
EcoQS (sed)
core 6
core 7
EcoQS (sed) class
high
good
moderate
poor
bad

Figure 5



relative abundance (%)
relative abundance (%)
L. lobatula
E. excavatum
C. reniforme
A. glomerata
E. asklundi
E. hallandense
H. germanica
Staintforthia spp.
B. marginata
Cribristomoides spp.
S. biformis
0
50
100
0
25
50
0
25
50
0
25
50
0
5
10
0
5
10
0
5
10
15
core 6
core depth (cm)
0
5
10
15
20
core 7
core depth (cm)
0
5
0
1250
0
250
2500
500
0
300
600
0
100
200
absolute abundance (#/g)

Figure 6



relative abundance

- ■ 50-100 %
- ▓ 20-50 %
- ▒ 5-20 %
- □ < 5 %

		7-0.5	7-1.5	7-4.5	7-2.5	7-3.5	6-3.5	6-4.5	6-1.5	6-2.5	6-5.5	6-0.5	6-11.5	6-17.5	6-9.5	6-16.5	6-6.5	6-8.5	6-18.5	6-19.5	6-10.5	6-14.5	6-13.5	6-12.5	6-15.5	6-7.5
I	*C. reniforme*	□	□	□	□	□	▒	▓	▒	▓	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒
	E. excavatum	□	□	□	□	□	▓	▓	▓	▓	▓	▒	▒	▒	▒	▒	▒	▒	▒	□	▒	▒	▒	□	▒	▒
	L. lobatula	□	□	□	□	□	▒	▒	▓	▒	▓	▓	■	■	■	■	■	■	■	■	■	■	■	■	■	■
II	*A. glomeratum*	▓	▓	▓	▓	▓	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
	Cribristomoides spp.	▒	▒	▒	▒	▒	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
	Eggerella spp.	▒	▒	▒	▒	▒	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
	S. biformis	▒	▒	□	▒	▒	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
III	*E. asklundi*	□	□	□	□	□	▒	▒	□	□	▒	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
	E. hallandense	□	□	□	□	□	□	□	▒	▒	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
	N. labradorica	□	□	□	□	□	▒	▒	▒	□	□	▒	□	□	□	□	□	□	□	□	□	□	□	□	□	□
IV	*B. marginata*	□	▒	▒	▒	▒	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
	Buccella spp.	▒	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
	Stainforthia spp.	□	▒	▒	□	▒	□	▒	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
	H. germanica	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	▒	▒	□	□	□	□	▒	▒	□
	C. laevigata	□	□	□	□	□	□	□	□	□	□	□	▒	▒	□	□	□	▒	□	□	▒	□	□	□	□	□
	T. angulosa	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	▒	□	□	□	□	▒	□	□	□