Recent oxygen depletion and benthic faunal change in shallow areas of Sannäs Fjord, Swedish west coast

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A B S T R A C T

Sannäs Fjord is a shallow fjord (<32 m w.d.) with a sill depth of 8 m, located at the Swedish west coast of the Skagerrak (North Sea). The anthropogenic impact on the fjord represents combination of sewage from the local village of Sannäs and land run-off from agricultural areas. Sewage impact has been reduced since 1991 and today the fjord is included into several nature conservation programs administrated by the European Union. Yet, observations during the summers of 2008–2011 show that the shallow inner fjord inlet experiences severe oxygen depletion at 5–12 m water depth. To explore if the oxygen depletion is only a recent phenomenon and to evaluate the potential of fjord sediments to archive such environmental changes, in 2008 and 2009 seven sediment cores were taken along a transect oriented lengthwise in the fjord. The cores were analysed for organic carbon, C/N, benthic foraminifera and lead pollution records (as relative age marker). Carbon content increases in most of the cores since the ~1970–80s, while C/N ratio decreases from the core base upward since ~1995. Foraminiferal assemblages in most core stratigraphies are dominated by agglutinated species. Calcareous species (mainly elphidiids) have become dominant in the upper part of the records since the ~late 1990s or 2000 (the inner fjord and the deepest basin) and since the ~1950–70s (the outer fjord). In the inner Sannäs Fjord, an increase of agglutinated foraminiferal species (e.g. Eggerelloides scaber) and organic inner linings occurred since the ~1970s, suggesting an intensification of taphonomic processes affecting postmortem calcareous shell preservation. A study of living vs. dead foraminiferal assemblages undertaken during June–August 2013 demonstrates that in the shallow inner fjord, strong carbonate dissolution occurs within 1–3 months following the foraminiferal growth. The dissolution is linked to corrosive conditions present within the sediment–bottom water interface, and is likely caused by the organic matter decay, resulting in severe hypoxia to anoxia. Oxygen depletion at ~10 m w.d. develops fast due to the small water volume and limited bottom water exchange caused by a close proximity of pycnocline to the fjord bottom. Sediment cores from the deep fjord basin and the outer fjord are, on the contrary, characterized by good to excellent preservation of foraminiferal shells, higher sediment accumulation rates, and the greatest potential for high-resolution paleoenvironmental studies. Increased frequencies of low-oxygen tolerant species (e.g. Stainforthia fusiformis) in the outer fjord after ~the 1970s suggests that increased primary productivity and seasonal oxygen deficiency have existed in the area over the last century. Recent milder winters, absent sediment reworking by freezing and grounding of sea-ice, increased nutrient load due to higher precipitation and land run-off, and the luxuriant growth of filamentous green algae followed by the organic matter decay are discussed among the mechanisms driving formation of recent oxygen deficiency in the shallow fjord inlets.

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1. Introduction

Fjords are semi-enclosed basins, which act as natural sediment traps receiving large amounts of biogenic material generated in situ and sediments originating both from the catchment area and the adjacent continental margins and shelves (Howe et al., 2010; Smith et al., 2015). Due to the presence of shallow sills, long bottom water residence time, high oxygen consumption and a slow ongoing isostatic sill shoaling, fjords often naturally develop stagnant conditions in their deeper basins (Syvitski et al., 1987; Gustafsson and Nordberg, 2002; Stigebrandt, 2012). Such conditions are a necessary prerequisite for low activity of burrowing benthic macrofauna and, hence, a low degree of sediment disturbance (e.g. Gooday et al., 2009). Therefore, fjord sediments provide at annual to decadal resolution continuous high-
resolution temporal records of changes in local primary productivity and biogeochemical processes (e.g. Knies et al., 2003; Harland et al., 2013a, 2013b; Kjønnbakken, 2013), atmosphere-land-ocean interactions (e.g. Filipsson and Nordberg, 2010; Polovodova Asteman et al., 2013) and regional variations of climate and hydrography (e.g. Nordberg et al., 2000; Filipsson and Nordberg, 2004; Harland et al., 2004, 2006; Pützel and Dale, 2010; Faust et al., 2014). Located within coastal zones, which are often characterized by increased urbanization, industry and tourism, fjords and their sediments also record detailed history of human-induced environmental modifications and are thus increasingly used as environmental archives (e.g. Filipsson et al., 2005; Dolven et al., 2013; Polovodova Asteman et al., 2015).

Over the past 30 years, many fjords along the Swedish west coast have experienced periodic low-oxygen conditions in their deep basins (e.g. Nordberg et al., 2000; Gustafsson and Nordberg, 2000). In the summer 2008, severe low-oxygen conditions and laminated sediments were also recorded in Sannäs Fjord, where unlike other localities severe oxygen depletion persisted in the shallow areas (5–12 m w.d.) and not in the deepest basin (Nordberg et al., 2012).

This paper investigates the potential of the Sannäs Fjord sediments to archive at high-resolution such environmental changes back in time. To do so, we present, geochemical and benthiic foraminiferal data from 7 short sediment cores representing the last 1–3 centuries and discuss causes driving environmental and benthiic changes in the area.

2. Study area

2.1. Geographical and geological background

Sannäs Fjord is one of Sweden’s few silled fjords located along a fault line in the Precambrian bedrock, which was carved out by the Scandinavian Ice Sheet during the Pleistocene and was later, during the Late Weichselian and the Holocene, partially filled with sediments. The fjord is located on the Swedish west coast, approximately 25 km south of Strömstad (Fig. 1). It extends in a NW–NSE direction and is approximatively 7.5 km long and 100–800 m wide. The bathymetry in the fjord steepens gradually from 1 to 6 m water depth in the shallow inner part towards the Saltpannan deep basin (Fig. 1) where the water depth reaches 32 m. The fjord has an 8-m deep sill, located in its narrowest part. Outside the sill, water depths increase and reach 36 m in the outermost part forming the Västbacken basin (Fig. 1). The outermost part of Sannäs Fjord is partially sheltered by skerries and faces the adjacent Skagerrak Sea.

The coastal area in the outer Sannäs Fjord mainly consists of rocky shores with steep cliffs of Bohus granite. In the inner fjord, the shores are partly covered by vegetation, and rubble, gravel and sandy pocket beaches often alternate with steep cliffs. In turn, the sheltered shallow bays are characterized by fine-grained organic-rich muddy and silty sediments, which in the north-eastern part of the fjord are overgrown by eelgrass meadows marked by Zostera marina and Ruppia spp. (Appelqvist and Frömark, 2000).

In the deeper areas of the fjord on the inner slope of the sill, gravel, sand and silt prevail. The Saltpannan Basin sediments are mainly characterized by fine and organic-rich gyttja clay. Strong water exchanges and cascading inflow events, which take place across the sill, often have a high energy, which causes erosion of bottom sediments. As a result, a coarser sediment fraction is transported from the sill and the sill slope and may eventually be deposited in the deeper basin (Olsson, 2007; Johansson, 2010; Robijn, 2012).

One hundred years ago, the fjord’s catchment area was deforested. Today it consists primarily of rocky granite hills with lean pines, mixed forests and agricultural land together with a single golf course and scattered small settlements (including the small village of Sannäs – Fig. 1). Though, the fresh water inflow to the fjord is generally minor, in the shallow inner part it is high enough to significantly reduce salinity of the upper water layer. The largest freshwater inflow occurs through the Skärboälven River, the largest stream in the area (Fig. 1), which has an average discharge of 0.5–1 m³/s (Olsson, 2007). The Skärboälven River has a catchment area of 42 km² and passes through a number of agricultural areas on its way to Sannäs Fjord (CAB, 2005; Johansson, 2010; Ödalen, 2012).

The anthropogenic impact on the fjord environment from the Sannäs village has been reduced since 1991 when all wastewater from households was routed to a water treatment facility in nearby small town of Grebbestad (Ödalen, 2012). The fjord is rich in marine life; there is a large stock of flat oysters (Ostrea edulis), and therefore has been included into the local nature management program “Tanums Coast III” and into the Nature Conservation Network “NATURA 2000” administrated by the European Union. Due to its environmental characteristics the fjord attracts hundreds of visitors for recreational boating and fishing. This results in a seasonal population boom in small settlements surrounding the fjord, i.e. population in the village of Sannäs reaches ~500 individuals during the summer months, as compared to its ~50 year-round residents.

2.2. Hydrography

The hydrography of Sannäs Fjord (Fig. 1) follows a complex fjord circulation pattern (Stigebrandt, 2012). The freshwater supplied by precipitation and run-off mixes with seawater to create the upper, ~1-m thick brackish water layer, which is separated by a halocline at 8–10 m depth from more saline (S > 25) water underneath. The halocline depth is generally controlled by the presence of 8-m deep sill. Wind mixing causes entrainment of the underlying seawater into the surface brackish layer and leads to a halocline deepening. This process creates an estuarine circulation when an outflow of the brackish surface water is caused by a difference in surface layer pressure inside and outside the fjord (Stigebrandt, 2012). At the same time there is an inflow of more saline water below the halocline. Water between the brackish surface water and the sill depth is often referred as intermediate water. Exchange of the intermediate water layer in Sannäs Fjord, and especially outside the Saltpannan Basin (Fig. 1), usually mirrors the density gradient between the fjord water and the coastal water of the adjacent Skagerrak. If changes in the coastal water density occur, the fjord responds by creating water stratification similar to that of the coastal water. This kind of adjustment causes strong inflows and outflows at different depths above the sill level (Pettersson, 1920) and is often referred to as intermediate circulation (Stigebrandt, 2012).

In addition to estuarine and intermediate circulation, variations of the local sea level (barotropic forcing) also play an important role for the water exchange across the sill in Sannäs Fjord (Johansson, 2010). When the sea level in the open sea exceeds that of the fjord, an inflow across the sill takes place and vice versa. Along the Swedish west coast, such mechanism of water exchange in the fjords is often dominated by tidal activity despite its relatively low amplitude (~20 cm) as compared to air pressure- and wind-driven variations of water level (Johansson, 2010). Tides in the study area are semi-diurnal, i.e. almost two cycles are completed in 24 h, which usually contributes more to the water exchange than the large-scale but long-term meteorological variations (Nordberg et al., 2012). According to Johansson (2010), the mean residence time of the fjord water above the sill is 6 days and the water exchanges due to tides, intermediate circulation and estuarine circulation constitute 5 m³/s, 7.5 m³/s and 7.5 m³/s, respectively.

The fjord water mass below the sill level is often referred to as deep water or basin water (Stigebrandt, 2012). According to the measurements performed during 2003–2006 (Olsson, 2007), deep-water exchange in Sannäs Fjord occurs ~5 times per year. The deep-water renewal in the fjord takes place when coastal water of high density and speed flows over the sill and replaces less dense deep water in the fjord. Such water exchange is often driven by prevailing northerly winds and co-occurs with upwelling, which at the Swedish
west coast mostly occurs during the winter and spring (Stigebrandt, 1980; Björk and Nordberg, 2003).

High-energy brackish water may also cascade over the sill and replace the basin water. This takes place rather regularly, mainly during the autumn (September–December) after a period of strong southerly winds (Johansson, 2010).

2.3. Nutrient load and oxygen consumption

According to the County Administrative Board of Västra Götaland, Sannäs Fjord annually receives 45 tons yr$^{-1}$ of nitrogen and 2 tons yr$^{-1}$ of phosphorus and about 50% of this nutrient supply is of anthropogenic origin (CAB, 2005, 2009, 2010; Ruist, 2008). One of the main nutrient sources to the fjord is associated with land run-off and with the Skärboälven River (Fig. 1). During rainy summers, a substantial amount of nitrogen and phosphorus from fertilizers is transported to the fjord (Ruist, 2008; Ruist and Lagergren, 2010). Such high nutrient transport into the fjord system provides the prerequisites for intermittent blooms of primary producers, especially during the growing season (Ruist, 2008; Ruist and Lagergren, 2010).

Decay of organic matter and biological respiration consume oxygen in the fjord waters, which together with regular periods of stagnation due to restricted water exchange may result in frequent bottom water hypoxia. In the fjord’s deepest basin, most of the stagnation periods, which result in hypoxic conditions, occur between January and September and may last for several months (Olsson, 2007). Measurements in late August of 2008 registered that dissolved oxygen concentrations fell from 5 to 0.2 ml l$^{-1}$ in the deep Saltpannan Basin water and such severe hypoxia lasted for about 2 months (Nordberg et al., 2012; Ödalen, 2012; Björk et al., subm.). At the same time a presence of a low-oxygen (<3 ml l$^{-1}$) water layer in shallow parts of the innermost Sannäs Fjord was observed. The layer had a thickness of 1–2 m and <1 ml l$^{-1}$ of dissolved oxygen was measured in proximity to the bottom. All oxygen measurements were performed 50 cm above the sea floor, which suggests even lower oxygen concentrations at the sediment-water interface. This interpretation is supported by the presence of abundant mats of H$_2$S- oxidizing bacteria *Beggiatoa* and black colour of sediment surface observed during the sampling in the innermost fjord in 2008–2009.

The oxygen depletion rate in the deep basin of Sannäs Fjord was estimated as 0.075 ml l$^{-1}$ day$^{-1}$ (Ödalen, 2012). This rate implies that within 2.5 months all oxygen in the fjord’s deep water will be consumed, given that its initial concentration was 6 ml l$^{-1}$, a typical value for surface water saturated with oxygen during the summer season (Nordberg et al., 2012). In the Saltpannan deep basin, similar low oxygen conditions were also occasionally observed near the bottom during the late summer and early autumn in 2010 and 2012 (Björk et al., subm.). A sediment core study from the deep basin suggests presence of low oxygen conditions several decades back in time, based on a high number of dinoflagellate cysts typical for eutrophic environments (Harland et al., 2013b).

**Fig. 1.** Map showing location of Sannäs Fjord on the Swedish west coast within the North Sea and the Skagerrak-Kattegat area. Stars indicate core sites mentioned in the text while circles show stations where surface sediment samples for living foraminifera were taken. Dashed line indicates fjord sill, which divides the fjord in the inner and outer parts; while Saltpannan Basin shows the fjord’s deepest area. Numbers along the fjord lengths indicated changes in fjord bathymetry (m).
3. Materials and methods

Sediment cores were collected at seven stations along a lengthwise transect in Sannäs fjord stretching from the innermost fjord inlet to the open sea beyond the sill (Fig. 1). Sampling was performed aboard the R/V Skagerok in September of 2008, 2009 and 2010. Sediment cores SSK08-1B, SSK09-2.5, SSK08-3B, SSK08-4D were retrieved from the inner fjord, core SSK09-4.5A (SSK10-4.5A) was taken in the deep Saltpannan Basin, while cores SSK09-5.5A and SSK08-6.5F were located outside the sill (Fig. 1; Table 1). A multiple corer MARK III-400 (Barnett et al., 1984, modified by P. Barnett in 1990) was used to collect cores taken during cruise 2008 (stations labelled as SSK08-X), whereas a Gemini corer (Niemistö, 1974) was used for sampling in 2009 and 2010 (stations labelled as SSK09-10-X). An additional core (SSK02-5A), collected in 2002 with a Gemini corer, corresponds to location of the station 4.5 and is used in this study in order to obtain a longer foraminiferal record. Also for station 4.5, heavy metal data from a gravity core SSK10-4.5 were used to obtain a more reliable age model. Multiple corer MARK III-400 retrieves sediment cores with a diameter of 10 cm and a maximal length of 50 cm, whereas by means of a Gemini corer longer but slender cores (length 80 cm, diameter 8.2 cm) can be obtained for longer but slender cores (length 80 cm, diameter 8.2 cm) can be obtained. Before being sliced into 1–2 cm sections, the cores were x-rayed using a portable X-ray device Andræx BV (155,140 kV/10 mA) for a core quality control and to locate laminated sediments. The control measure is necessary in order to confirm an absence of any heavy disturbances within the sediment column due to bioturbation or other mechanical damage, such as anchoring, the presence of drop stones or large mollusc shells. Upon return to the laboratory at the University of Gothenburg, all samples were freeze-dried. All samples were weighed before and after freeze-drying in order to approximate the water content, an additional measure to estimate the quality of the sediment cores.

For foraminiferal analysis approximately 10 g of sediment was weighed and washed over 1-mm and 63-μm sieves. When necessary, tetrasodium pyrophosphate (Na4P2O7) was used as a disaggregating agent during washing. Samples were then dried at 50 °C, and the dried >63 μm fraction was weighed in order to estimate the sand content. At least 300 individual foraminiferal tests of total fauna were then picked and identified to the species level where possible. Both absolute (ind./g) and relative abundances (%) were determined. The uppermost two samples from each core, comprising the top 2 cm, were averaged to study changes in total (living plus dead) foraminiferal fauna along the fjord’s transect. A stratigraphic record was produced for stations 1, 2.5, 3, 4, 4.5, 5.5 and 6.5. To complement the core SSS5-02A, which has a foraminiferal record extending only to 2002, we used the uppermost 10 cm of the core SSK09-4.5 in order to obtain the foraminiferal data for the period 2002–2009. Present benthic foraminiferal species were classified as dominant or accessory depending on their contribution to the assemblage (>10% or 1–10%, respectively). Rare species with relative abundances <1% were lumped together as others. The number of inner organic linings (IOL) was counted separately and is presented in absolute abundances as IOL/g dry sediment (when counting total faunas) or IOL/cm3 (for living and dead faunas). The taxonomic identification (see Appendix 3 for reference list) is based on Höglund (1947), Feyling-Hanssen (1964) and Murray (1971). The original description and synonyms of the species have been extracted from the World Modern Foraminifera Database (Hayward et al., 2016).

To study living faunas and to document taphonomical processes, which are crucial for understanding the formation of fossil assemblages, we also performed a seasonal study at two inner fjord stations (2.5 and 3) proximal to the village of Sannäs (Fig. 1). During foraminiferal growth season from June to August 2013 (Gustafsson and Nordberg, 1999, 2000, 2001), two to three replicates of the uppermost 0–3 cm sediment were collected every month at each station, preserved in alcohol and stained by Rose Bengal following a standard protocol suggested by Schönfeld et al. (2012). In the lab, stained samples were washed over 1-mm and 63-μm sieves and counted wet by using a wet-picking tray of Duffield and Alve (2014). The datasets with all foraminiferal absolute abundance data are available as Appendices 1 and 2.

To determine the total organic carbon (Corg) and the total nitrogen (TN) content, the freeze-dried sediment was pulverized in an agate mortar and then weighed into small silver capsules using a Cahn microbalance. Silver capsules with sediment were placed into an exsiccator and treated with exhalates of hydrochloric acid (HCl) for 48 h to dissolve the sediment carbonate content. Upon completion of the carbonate dissolution, the samples where dried for 1 h at 55 °C to dry off any excess HCl. Each silver capsule was then placed in a tin capsule, which was tightly closed and flattened in order to fit into the measuring cell of the analyser. The TOC and TN measurements were performed then by using Carlo Erba Nitrogen Analyzer NA1500 (Department of Earth Sciences, University of Gothenburg) and the results were used to calculate a C/N ratio.

To calculate the accumulation rates, the sediment cores were analysed for lead pollution and 206Pb/207Pb isotopic ratio. The analyses were performed according to Swedish Standard (SS 028183), which is an accepted and common methodology for environmental quality assessment and monitoring programs performed in the coastal zone of Sweden (SEPA, 2000). According to the method, 1 g of homogenised sediment was subject to leaching in 20 ml of 7 M nitric acid (HNO3) for 30 min. The leaching was performed in tightly closed polytetrafluoroethylene (PTFE) vials placed either in microwave oven (CEM MDS-81D Microwave Digestion System; ALS Laboratory Group, Luleå) or into autoclave at 120 °C (Department of Earth Sciences, University of Gothenburg). The liquid phase was then separated in a centrifuge and diluted for further analysis. All samples labelled as SSSK08-XY were analysed in ALS Laboratory Group (Luleå) by Inductively Coupled Plasma Quadro Mass Spectrometry ICP–QMS (VG Plasma Quad 2), whereas heavy metal content in SSSK09-XY and SSK10-XY samples was determined at University of Gothenburg by using Agilent 7500 ICP-MS. All 206Pb/207Pb isotope ratios were measured at the University of Gothenburg laboratory.

The accumulation rates are calculated using the peak of lead concentration due to widespread pollution throughout most of the 20th century (Renberg et al., 2001; Robijn, 2012). Lead had been added to gasoline as anti-knocking agent causing emissions into the atmosphere, biosphere and hydrosphere, which are well documented within the sediment records (Komárek et al., 2008; Bindler, 2011). Furthermore, the isotopic ratio of 206Pb and 207Pb is affected by the source of lead released into the environment. The natural background in 206Pb/207Pb ratio along the west coast of Sweden is about 1.3 whereas the lead used in gasoline origins from Australia and has a ratio of 1.04 (Renberg et al., 2001). The clear increase of lead pollution combined with the drop in 206Pb/207Pb ratio in the sediment cores of Sannäs fjord is attributed to the

<table>
<thead>
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<th>Station</th>
<th>Sampling date</th>
<th>Latitude N</th>
<th>Longitude E</th>
<th>Depth (m)</th>
<th>Core</th>
<th>EAR (mm/yr)</th>
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<td>58°43.487'</td>
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<td>58°44.227'</td>
<td>11°14.651'</td>
<td>8.5</td>
<td>SSK09-2.5A</td>
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<td>11°14.566'</td>
<td>9</td>
<td>SSK08-3B</td>
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<td>11°13.192'</td>
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<td>SSS25-02A</td>
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<tr>
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<td>58°45.340'</td>
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<td>11°12.214'</td>
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</table>
introduction of leaded gasoline in 1925. The concentrations are highest during the 1970s and decrease rapidly after 1995, when leaded gasoline was ultimately banned in Sweden.

4. Results

4.1. Relative dating

Lead concentrations and $^{206}$Pb/$^{207}$Pb isotopic ratio in Fig. 2 show the relative age correlation between the sediment cores. Based on the relative dating described in the methods the tentative sediment accumulation rates were calculated for each core (Table 1). The results show that the highest accumulation rates characterize sediment cores recovered in the deep fjord basin (station 4.5, see Salthanpann Basin – Fig. 1), which provides an environmental sediment archive with a nearly annual temporal resolution.

4.2. Sediment content of carbon and nitrogen

TOC in the sediments ranges between 3 and 6% for the majority of the cores and shows an increase for the upper part of the records (Figs. 3–9). Cores SSK09-4.5B (Fig. 7) and SSK09-5.5A (Fig. 8) differ in that they exhibit a wider range of $C_{org}$ (3–9%) and have a distinctly higher TOC values in the lower part. C/N ratio in all cores varies between 8 and 12 with lower values characterizing the upper core parts (since ~2000s) and increasing towards the core base (Figs. 3–9).

4.3. Benthic foraminifera

4.3.1. Total fauna in core tops (0–2 cm) along the fjord

The species composition for the total (living plus dead) foraminiferal fauna in the core tops (0–2 cm) is summarized at Fig. 10. The bulk of the assemblage at the innermost three stations (1, 2.5 and 3) is composed of typical shallow water species, *Elphidium excavatum* (~60%) and *E. excavatum* (~25%), which dominate the assemblages of the inner Sannäs Fjord. *Eggerelloides scaber* and *Ammonia* spp. (Plate 1, Figs. a–d) are present in the inner fjord as accessory species (~5% and ~8%, respectively). All of the innermost stations show the lowest species richness along the fjord transect.

*Elphidium excavatum* and *E. incertum* decrease in direction towards the deep basin of the fjord (Fig. 10) and are replaced by species such as *E. scaber*, *E. excavatum*, and *E. incertum* as co-dominant species. Species *Ammonia* and *Ammodiscus*, *Buliminella elegantiissima*, *C. pisum*, *E. gerthi*, *E. scaber*, *Scaphammina fusiformis*, *Stainforthia fusiformis*, and *Ammoscalaria runiana*, *Nonionella stella* and *Allogromia* sp. The agglutinated *E. scaber* (Plate 1, Fig. f), is an accessory species at station 3 during June and July and becomes a dominant component of living fauna in August (Fig. 11). The population density of living faunas at station 3 was remarkably lower (2–11 ind./cm$^3$) than that at station 2.5 but showed a similar declining trend from June to August (Fig. 13). The living assemblage is calcareous-dominated, with calcareous species comprising 86, 82 and 79% of the assemblage in June, July and August 2013, respectively.

The absolute abundances of empty foraminiferal shells at station 3 differ between replicates (Fig. 13: Appendix 1), but on average increase from June to August. The species composition of the dead fauna is clearly dominated by empty shells of *E. scaber* (>60%). Species *E. incertum* and *E. excavatum* are co-dominant species in June, but become accessory ones in July and August (Fig. 12). Other accessory species include *Ammonia* spp., *L. catella*, *Milliammina fusca*, *Textularia earlandi*, *Trocchammina* sp. and *R. dentaliformis*. The number of IOL/cm$^3$ at station 3 shows a consistent increase from June to August (Fig. 13). The dead assemblage has a high content of agglutinated shells, with calcareous species being only 29, 14 and 7% of the living assemblage in June, July and August 2013, respectively.

4.3.2. Living and dead assemblages in surface sediments (0–3 cm) from the inner Sannäs Fjord

In the uppermost 0–3 cm of station 2.5, living foraminiferal assemblages constitute 59%, 39% and 23% of the total (living plus dead) fauna in June, July and August 2013, respectively (Fig. 11). Species composition of the living faunas includes *Elphidium incertum*, *Elphidium excavatum* and *Allogromia* sp. as dominant species, whereas *Ammonia* spp., *Eggerelloides scaber*, *Crithionina pismum*, *Elphidium gerthi* and *Reophax dentaliformis* are present as accessory species (Fig. 11). *Elphidium incertum* (Plate 1; Fig. q) shows a clear decreasing trend from June to August, in contrast to *E. excavatum*, which increases in relative abundances over the same period. The population density of the living fauna ranges from 8 to 57 ind./cm$^2$ and, in general, decreases from June to August with a slight difference between replicate analyses (Fig. 13). Living assemblage at station 2.5 is calcareous-dominated, with calcareous species comprising 94, 90 and 70% of the assemblage in June, July and August, respectively.

The seasonal fluctuation of absolute abundances (ind./cm$^3$) of empty shells representing dead fauna shows a different behaviour in all three replicates (Fig. 13), but generally increases at station 2.5 from June to August 2013. Dead assemblage composition resembles that of the living fauna and is dominated by *E. incertum* and *E. excavatum* with an exception of *E. scaber*, which also becomes a dominant component in the thanatocoenosis (Fig. 12). The accessory species in the dead assemblage at station 2.5 include *Ammonia* spp., *E. gerthi*, *E. dentaliformis* and *Leptohalysis castella*. The number of inner organic linings (IOL: Plate 1, Figs. e–f) shows a consistent increasing trend among all replicates from June to July and decreases thereafter (Fig. 13). The dead assemblage is calcareous-dominated, with calcareous species comprising 69, 65 and 73% in June, July and August, respectively.

Station 3 is characterized by a lower living foraminifera number, which seasonally declines from 18% in June to 7% in August (Fig. 11). There is a strong dominance of *E. excavatum* (Plate 1, Fig. n) with *E. incertum* (Plate 1, Fig. q) as co-dominant species. Species *E. excavatum* decreases in relative abundances from June–July (63–65%) to August (28%), whereas *E. incertum* increases in abundance towards August. Accessory species include *Ammonia* spp., *Ammodiscus* sp., *Buliminella elegantissima*, *C. pisum*, *E. gerthi*, *E. magellanicum*, *Stainforthia fusiformis*, *Ammoscalaria runiana*, *Nonionella stella* and *Allogromia* sp. The agglutinated *E. scaber* (Plate 1, Fig. i), is an accessory species at station 3 during June and July and becomes a dominant component of living fauna in August (Fig. 11). The population density of living faunas at station 3 was remarkably lower (2–11 ind./cm$^3$) than that at station 2.5 but showed a similar declining trend from June to August (Fig. 13). The living assemblage is calcareous-dominated, with calcareous species comprising 86, 82 and 79% of the assemblage in June, July and August 2013, respectively.

The absolute abundances of empty foraminiferal shells at station 3 differ between replicates (Fig. 13; Appendix 1), but on average increase from June to August. The species composition of the dead fauna is clearly dominated by empty shells of *E. scaber* (>60%). Species *E. incertum* and *E. excavatum* are co-dominant species in June, but become accessory ones in July and August (Fig. 12). Other accessory species include *Ammonia* spp., *L. catella*, *Milliammina fusca*, *Textularia earlandi*, *Trocchammina* sp. and *R. dentaliformis*. The number of IOL/cm$^3$ at station 3 shows a consistent increase from June to August (Fig. 13). The dead assemblage has a high content of agglutinated shells, with calcareous species being only 29, 14 and 7% of the living assemblage in June, July and August 2013, respectively.

4.3.3. Stratigraphic distribution of benthic foraminifera

4.3.3.1. The inner fjord: cores SSK-08-1B, SSK-09-2.5 and SSK-08-3B. All 3 cores taken at the innermost stations (1, 2.5, and 3) have similar foraminiferal stratigraphy (Figs. 3–5). *Eggerelloides scaber* dominates (40–90%) the lower part of the cores but shows a sudden decline above 2–3 cm sediment depth (~1995) and a subsequent increase in absolute abundances towards the core tops. Other agglutinated species, such as *Ammoscalaria runiana* and *Ammobaculites balticwalli*, as well as calcareous *Ammonia* spp., appear between 20 and 2 cm (~1920–1995) in the innermost located core SSK-08-1B. Calcareous species show highest absolute and relative abundances in the uppermost 0–2 cm sediment (~1995–2008) in all three cores. Stations 2.5 and 3 exhibit the most dramatic increase in absolute foraminiferal abundances by factors of 15 and 30, respectively, in the uppermost part, due to an increase of shallow-water *Elphidium incertum*, *E. excavatum*, *E. magellanicum* and *Ammonia* spp. (Figs. 4–5). A considerable amount of the inner organic linings
(mainly of Ammonia and Elphidium spp.) is found throughout all 3 cores, which implies active taphonomical processes affecting post-mortem preservation of the calcareous foraminiferal shells at the innermost stations. Interestingly, there is a noteworthy decline of Ammonia spp. in all 3 cores, which is synchronous with an increase of inner organic linings at 9 cm (SSK-08-1B) and 10 cm (cores SSK-09-2.5 and SSK-08-3B) corresponding to ~1980s given that our age model is correct (Figs. 3–5).

4.3.3.2. The middle fjord: core SSK-08-4D. In general this core is characterized by somewhat better preservation of calcareous foraminiferal shells and by the highest absolute abundance of Eggerelloides scaber (1248 ind./g) observed in the fjord (Fig. 6). In the lower part of the core, at 15–35 cm (prior to 1970s) E. scaber shows a clear dominance (60–90%) together with Ammonia spp. (17%) and Ammoscalaria runiana, as accessory species (5–6%). From ~15 cm to 2 cm (~1950–1995) there is a clear increase in absolute and relative abundances of calcareous foraminiferal species Ammonia spp., E. incertum, E. excavatum and E. magellanicum (Fig. 6). In addition, Stainforthia fusiformis, absent or rare in the innermost fjord cores, appears in this core interval as dominant species (13–29%). In the top-most 2 cm (~1995–2008) there is a similar significant (6-fold) increase in absolute foraminiferal abundances.

4.3.3.3. The Saltpannan Basin: cores SSK-09-4.5A and S25-2A. The foraminiferal stratigraphy for station 4.5 was constructed by using the upper
0–10 cm of the core SSK-08-4.5A and the entire stratigraphy of the core S25-02A. Given an estimated sedimentation rate for this location of ~11 mm/yr (Table 1), the upper 10 cm of SSK-08-4.5A correspond to ~1999–2009, which provides some overlap with S25-02A stratigraphy extending up to 2002 (Fig. 7).

The agglutinated *E. scaber* remains dominant species (>20%) throughout the record together with calcareous *S. fusiformis* (10–20%), which also becomes a major component of the foraminiferal fauna in the upper part of S25-02A. In addition, *Bulimina marginata*, absent or rare in the inner Sannäs Fjord, is present as a dominant taxon in the upper part of the record. Both *B. marginata* and *S. fusiformis* become dominant in the upper part of SSK-08-4.5A at 0–10 cm (~1999–2009), with a concurrent decrease of *E. scaber* (Fig. 7). Accessory species are *Ammonia* spp., *Elphidium* spp., and *Cibicides lobatulus* (presently accepted and further referred to as *Lobatula lobatula*, following Gross, 2004), all present in abundances >10%. Most of the elphidiids decrease between 10 and 31 cm (~1980–1999), while *E. scaber*, *Ammonia* spp., *S. fusiformis* and *B. marginata* increase during the same time. Based on

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**Fig. 4.** Foraminiferal stratigraphy for the innermost station SSK-08-2.5 shown together with organic carbon and C/N ratio. Relative (%) and absolute (ind./g) foraminiferal abundances are indicated as white and black circles, respectively. Note different X scale for *Ammonia* spp.

**Fig. 5.** Foraminiferal stratigraphy for the innermost station SSK-09-03 shown together with organic carbon and C/N ratio. Relative (%) and absolute (ind./g) foraminiferal abundances are indicated as white and black circles, respectively. Note different X scale for calcareous vs. agglutinated foraminifera.
foraminiferal stratigraphy compiled by both records, the stratigraphy of station 4.5 demonstrates a good to excellent preservation of foraminiferal shells. Absolute abundances of foraminiferal shells are high throughout the core (mean 397 ind./g dry sed.), varying between 133 and 1145 ind./g and increasing towards the core top.

4.3.3.4. The outer fjord: cores SSK-09-5.5A and SSK-08-6.5F. The sediment cores from the two outermost stations are studied in a low resolution (6–8 samples per core) in order to obtain a general overview of foraminiferal distribution with core depth. The results show that *Eggerelloides* scaber remains a dominant component of total faunas in both cores (on average 53% in SSK08-6.5F and 15% in SSK-09-5.5A). There is an increase in calcareous foraminiferal species *E. incertum*, *E. excavatum*, *E. magellanicum* and *S. fusiformis* in the uppermost 15 cm (SSK08-6.5F) and 20 cm (SSK-09-5.5A), associated with a time period from 1920s to the present day (Figs. 8–9). Also the lowermost part of both cores is characterized by calcareous - dominated assemblages. Core SSK08-6.5F is characterized by the highest absolute abundance of foraminifera recorded in the fjord (6256 ind./g dry sed.: Fig. 9).

4.3.3.5. Sediment laminations. Laminated sediments were found at the sediment surface at station 2.5 in 2008. The only other laminations found within sediment cores were those from station 1, where they were present at ~20 and ~30 cm (~1920s and ~1850s). In those laminated sequences large amounts of eelgrass (*Zostera*) remains are preserved in the sediment and the benthic foraminiferal abundances decrease to 12.5 and 3.3 ind./g, respectively (Fig. 3).

5. Discussion

5.1. Carbonate shell loss – interplay between acidification and hypoxia?

The living assemblage study performed in the inner Sannäs Fjord during summer 2013 demonstrates that, despite calcareous species constituting a major part of the living fauna from July to August,
agglutinated species (mainly *E. scaber*) remain an important to

dominant component of dead assemblages. Cores stratigraphies from sta-
tions 1, 2.5 and 3 show a strong dominance of agglutinated species
throughout the majority of the cores with the exception of the core
tops, which all have a high content of calcareous shells. Possible expla-
nations for the downcore decline in calcareous component include
patchiness and different reproduction times of dominant species
(Murray and Alve, 1999) or challenged preservation of calcareous shells
(Murray et al., 2003). Station 3, in the inner part of Sannäs fjord, exhibits
a particularly striking difference in calcareous shell content between liv-
ing (82%) and dead assemblages (17%) during the summer of 2013. In
contrast, station 2.5, which is located even farther into the fjord, has
high amounts of calcareous shells in both living and dead assemblages
(85% and 69%, respectively).

In the modern world, assemblages dominated by agglutinated fora-
minifera occur in environments with waters under-saturated with re-
spect to calcium carbonate, such as high intertidal marshes, deep seas
below the calcium compensation depth, and deep continental shelves
(Bergsten et al., 1996; Murray, 2006; Murray and Alve, 2011 and refer-
ences therein). Agglutinated assemblages have also been recorded in
high latitude fjords influenced by Polar Water (Baffin Island: Schaefer
and Cole, 1988; Eastern Greenland: Jennings and Helgadottir, 1994)
and stratified fjords of Scotland and Scandinavia (Sandebukta,
Oslofjord: Alve and Nagy, 1986; Loch Etive: Murray et al., 2003;
Idefjord: Polovodova Asteman et al., 2015). In particular, assemblages
with dominant *Eggerelloides scaber* are known from the Skagerrak
coast of Norway (Alve and Nagy, 1986; Alve, 1995; Murray and Alve,
1999), southern Kattegat (Conradsen et al., 1994), Loch Etive (Murray
et al., 2003) and the SW Baltic Sea (Lutze et al., 1983) – all settings
with either hypoxic or CaCO₃ undersaturated bottom waters.

According to Murray and Alve (1999), the Skagerrak and its
coastal areas off southern Norway are known for an intense car-
bonate dissolution in foraminiferal assemblages likely due to both
CaCO₃ undersaturated bottom waters and severe oxygen deficiency.
caused by organic matter decay. It appears, however, that similar processes operate in the inner Sannäs Fjord rather intensely, if within 3 months nearly 70% of calcareous shells are gone (station 3). This appears to be consistent with findings of Ödalen (2012), showing that all oxygen in the fjords deep water can be consumed within 2.5 months, which would therefore cause corrosive bottom water conditions. Seasonal changes in bottom water carbonate saturation state were reported from another shallow fjord setting - Flensburg Fjord (SW Baltic) with the highest pCO2 concentrations (>1000–2000 ppm) reached in the near-bottom waters during summer-autumn (Haynert et al., 2012). In coastal zones, the carbonate system co-varies together with oxygen conditions on both diurnal (Burnett, 1997) and seasonal timescales (Melzner et al., 2013; Hagens et al., 2015). Hypoxia may thus amplify carbonate dissolution caused by ocean acidification due to an additional release of CO2 through respiration of benthic organisms and organic matter mineralization (Melzner et al., 2013; Hagens et al., 2015). In restricted basins, like fjords, such processes may further lower pH and carbonate saturation values (Feely et al., 2010). Such implications of hypoxia for carbonate saturation state were suggested by Murray et al. (2003) for the stratified Scottish Loch Etive and are well known for Flensburg Fjord (Nikulina and Dullo, 2009; Haynert et al., 2012), St. Lawrence Estuary (Mucci et al., 2011) and Puget Sound (Feely et al., 2010; Reum et al., 2014). Our study suggests that related processes may also operate in the inner Sannäs Fjord. To prove this, however, a seasonal survey of carbonate system parameters in the fjord is needed, which was unfortunately beyond the scope of the current study.

5.2. Causes behind shallow water hypoxia in Sannäs Fjord

The persistent seasonal coastal hypoxia was reported as a recent phenomenon developed since the 1970–80s in estuaries both on the eastern (e.g. Gustafsson and Nordberg, 1999, 2000, 2001; Nordberg et al., 2000; Conley et al., 2007; Nikulina and Dullo, 2009; Harland et al., 2013b; Björk et al., subm.) and the western North Atlantic coasts (e.g. Rabalais et al., 2002; Turner et al., 2005). In this respect, Sannäs Fjord has not been subject to numerous studies to date. One of the few completed studies reported a significant increase in cyst abundances of Lingulodinium polyedrum, “a dinoflagellate favoured by a rich availability of nutrients as a result of eutrophication” dated to the mid-1980s in a sediment core from the Saltpannan Basin (Harland et al., 2013b). Roughly at the same time, a remarkable change in the sediment facies along the Swedish NW coast (including Sannäs fjord) was documented by Cossellu and Nordberg (2010). These authors found in many shallow bays a shift from siliciclastic, coarse-grained deposits to organic-rich fine sediments promoting an extensive growth of green filamentous algae, instead of an expected coarsening upward trend due to the ongoing isostatic land uplift. Cossellu and Nordberg (2010) linked this to changed weather patterns related to variations in the NAO index, milder winters and absent sediment reworking by grounding and freezing of sea-ice, in combination with human-induced eutrophication and overfishing. Numerical model estimates (Björk et al., subm.) suggest that changes in water exchange rates or turbulent mixing are unlikely the main mechanisms behind formation of the recent shallow-water fjord hypoxia during 2008–2012. Instead, increased precipitation, land run-off and a high nutrient load with Skärboälven River have a strong
potential to generate present hypoxic conditions (Ödalen, 2012; Björk et al., subm.). It is quite intriguing that oxygen deficiency developed in the 2000s despite supposedly decreased nutrient load due to re-routed sewage; absence of fish farming in the fjord, and lack of dykes and dams on the river. According to Cossellu and Nordberg (2010), the hypoxia development in Sannäs Fjord may be amplified by the presence of recently accumulated muddy and organic-rich sediments, which stimulate extensive growth, subsequent advection and decay of filamentous algae in shallow bays of the fjord. The leakage of nutrients from the sediment nutrient pool into the bottom waters when conditions become anoxic following e.g. “phosphorus paradigm” of Stigebrandt et al. (2014) will further facilitate algal growth and oxygen consumption. These processes may be amplified by a significant contribution of the advected algal mats, which sink and accumulate at shallow bottoms during the summer time (Vahteri et al., 2000; Delgard et al., 2013). The fast decay and the resulting nutrient mineralization and release from both the algal mats and the anoxic sediment pool in combination with a thin bottom water layer, stagnation periods and low turbulence, make the shallow bottoms in Sannäs Fjord particularly sensitive to organic enrichment, which likely drives significant oxygen consumption and deficiency in the area (Ödalen, 2012; Björk et al., subm.).

5.3. The last 100 years of environmental history

5.3.1. Inner Sannäs Fjord

The deeper part of all inner fjord cores shows a striking dominance of the agglutinated foraminiferal species Eggerelloides scaber over the last century and until ~2000s. A decrease of this species in the upper part of the cores coincides with a distinct shift of C/N ratio towards more “marine” values (8–9) typical for primary producers (Figs. 3–5). Eggerelloides scaber is a typical estuarine and shelf species, which has omnivorous feeding strategy and responds by an opportunistic behaviour in the absence of competition and predation (Alve, 1995; Polovodova Asteman et al., 2015), therefore both the presence of E. scaber and changing C/N values suggest a shift in the quality of organic matter exported to benthic environment in the shallow inner Sannäs Fjord. Higher C/N values are typical for more rigid terrestrial plants (Meyers, 1994), and may thus indicate an increased land run-off in the area prior to ~2000s. Increased run-off would likely result in a stronger pycnocline, and also would favour foraminiferal species dwelling in proximity to the pycnocline, in areas with relatively thin saline bottom water layer, such as E. scaber (Conradsen et al., 1994), which requires S > 24 most of the year (Lutze et al., 1983). This interpretation is consistent with the findings of Björk et al. (subm.) – see discussion above.

It is notable that there is a decrease of Ammonia spp. in the inner fjord around ~1970s (core SSK 08-01B) and ~1980 (cores SSK08-2.5A and 3B) while the amount of their inner organic linings increases. Many studies reported “chitinoid” organic linings of Ammonia spp. as remarkably resistant to taphonomic processes and hence indicating carbonate dissolution (e.g. Banner et al., 1973; Polovodova and Schönfeld, 2008; Haynert et al., 2011; Flahicheart et al., 2013). This trend in Sannäs fjord suggests a gradual decrease of dissolved oxygen in the bottom waters caused, perhaps, by a halocline deepening in the inner fjord (see discussion above) starting ~30–40 years ago, which would lead to conditions more corrosive for preservation of calcareous foraminiferal shells. Ammonia spp. are found worldwide in shallow estuarine and marginal settings, tolerate wide salinity range (S = 10–50), highly variable TOC and mud contents (Murray, 2006) and low oxygen < 0.1 ml l−1 (Moodley and Hess, 1992).

Ammonia spp. also dominates the uppermost part of the inner fjord cores (SSK08-01B, 2.5A and 3B) together with E. incertum and E. excavatum indicating shallow water and conditions even more brackish than those indicated by E. scaber (Polovodova et al., 2009). In particular, Elphidium incertum is the major dominant species in the uppermost assemblies. The species is a brackish epifaunal to infaunal and is often found dwelling down to 3–6 cm sediment depth (Linke and Lutze, 1993) but migrates to the surface if sediments become severely depleted in oxygen (Wefer, 1976). Assemblages with dominant E. incertum were described in the muddy and organic-rich (Corg = 6–11%) sediments of the inner Flensburg Fjord (SW Baltic) characterized by regular bottom-water stagnation and salinities of 15–25 (Polovodova et al., 2009). On the Swedish west coast, E. incertum reproduced in response to spring blooms and was highly abundant at oxygen concentrations > 2 ml l−1 and sedimentary Corg values of 1–7% in a strongly stratified and stagnant Koljö Fjord (Gustafsson and Nordberg, 1999) but disappeared together with E. excavatum at dissolved oxygen < 0.2 ml l−1 in the periodically anoxic Byfjord (Olsson, 1975). Elphidium incertum is commonly reported as occurring in a narrow zone just below the halocline (Lutze, 1965, 1974; Gustafsson and Nordberg, 1999). This agrees with our results from the inner Sannäs Fjord where a summer halocline lies fairly close to the bottom (8 m depth) while the total inner fjord depth range is 5–10 m. The close proximity of halocline, a 1–2 m thick bottom water layer with dissolved O2 < 3 ml l−1 (O2 < 1 ml l−1 for the water mass closest to the bottom) and the recently increased amounts of filamentous algal mats during the summer (Björk et al., subm.), may explain increasingly higher abundances of E. incertum in the inner fjord core tops.

Haynert et al. (2012) monitored carbonate system parameters in a naturally CO2-rich Flensburg Fjord and found no traces of shell dissolution in E. incertum in contrast to Ammonia species, which had all stages of shell loss. They suggested that the former is more tolerant to waters undersaturated with respect to CaCO3. In our study, however, E. incertum becomes a minor component of dead assemblages at station 3, implying that its tests are likely also to undergo rapid postmortem dissolution processes, in particular at that location.

An intriguing observation noted during our inner fjord living foraminiferal survey during summer 2013, regards the appearance of invasive species Nonionella stella (Fig. 11: see SSK 3), previously not reported in the area. Polovodova Asteman and Schönfeld (2016) recorded this species in other settings on the Swedish west coast and in the Skagerrak-Kattegat during 2013–2014 and suggested its first introduction to the area during the 1980s, likely facilitated by ship ballast water and sediment and sustained by high organic matter abundance and bottom water hypoxia.

5.3.2. Outer Sannäs Fjord

Though Elphidium magellanicum (Plate 1; Fig. a) is present throughout the deepest basin core SSK09–4.5B (Fig. 7), in cores from both sides of the fjord sill it appears only after ~1925 (Figs. 6, 8). This appearance is likely explained by different sedimentation rates. The section of the core SSK09–4.5B presented herein does not extend further back in time than ~1950s and therefore does not capture the increase of E. magellanicum at ~1925 as it occurs in cores SSK08-4D and SSK09–5.5A. The shallow- and brackish-water species, E. magellanicum has been previously described in fjords at the Swedish west coast in connection with bottom water oxygen deficiency (Gustafsson and Nordberg, 1999, 2000). It has also been reported from high-water-energy areas such as sandy bays and channels (Atkinson, 1971; Dobson and Haynes, 1973). Several studies suggest the species’ affinity to sandy sediments, enhanced sediment erosion and increased bottom current energy. Dobson and Haynes (1973), in particular, report E. magellanicum among other foraminifera “finding shelter under epifaunal holdfasts such as hydroids”, as a likely
protective strategy to mechanical stress. This is consistent with our results, since areas proximal to the Sannäs Fjord sill every year experience multiple cascading water inflows likely causing sediment erosion and transport and, hence, favouring increased abundances of this species. The co-occurrence of *E. magellanicum* with *Lobatula lobatula* (Plate 1; Figs. p–r) in SSK-09 5.5A supports the hypothesis of a somewhat higher frequency of cascading water inflows beginning around ~1925. *Lobatula lobatula* is an epifaunal species often reported attached to algae, stones, mollusc shells, or sediment clasts in areas with strong bottom currents (Murray, 2006, as *Cibicides lobatulus*). Corner et al. (1996) found *L. lobatula* in a high-energy delta-plain habitat in Tana Fjord (Norway). Based on abraded test appearance authors suggested transport and re-sedimentation of *L. lobatula* while Freiwald [1995], demonstrated that test etching and abrasion in this species in aerobic and turbulent coarse-grained environments also could be induced by bacterial carbonate degradation and not necessary by transportation. In our study, however, *L. lobatula* tests were shiny and well preserved, which suggests that they either have been deposited in-situ just inside the shallow sill area (in the fine-grained basin sediments) or were subject to an instantaneous transport from the sill with cascading bottom water inflows without any significant damage to their tests.

Another observation, which is important for the outer fjord cores regards a decrease of *Eggerelloloides scaber* towards the upper core part, which occurs simultaneously with an increase of *Stainforthia fusiformis* after ~1925 (Figs. 6, 9). Agglutinated *E. scaber* requires salinities of >24 for the majority of the year (Lutze et al., 1983), while calcareous and thin-shelled *S. fusiformis* is found at salinities >29 (Gustafsson and Nordberg, 2000). Such faunal shift indicates a possible change in salinity, or a stronger stratification, which took place starting from ~1925, likely attributable to more frequent inflows of more saline water above the fjord sill. In SSK09-5.5A this change in faunas coincides with an increase of *L. lobatula*, which supports this hypothesis (see discussion above). *Stainforthia fusiformis* is also a well-known opportunist able to withstand long periods of severe oxygen deficiency and dwelling in sediments enriched with organic matter (e.g. Alve, 1994; Nordberg et al., 2000). Therefore abundance peak of *S. fusiformis* found in the uppermost sediments in most of the outer fjord cores suggests recent oxygen depletion and/or an increase in food availability, which probably developed time transgressively with the inner fjord.

Finally, core SSK09-5.5A shows an increase in species *Nonionella turgida* appearing in the record around ~1970s (Fig. 8). Though *N. turgida* is considered by some studies as an opportunist, preferring...
high food availability and tolerating hypoxia and even anoxia (e.g. Van der Zwaan and Jorissen, 1991; Moodley et al., 1998), it responded negatively to a short-term anoxic treatment by decreasing its abundances in a mesocosm experiment (Ernst et al., 2005) and was associated with high bottom-water oxygenation in a field study from the Adriatic Sea (Duijnstee et al., 2004). Furthermore, in an unfed experiment by Pucci et al. (2009), N. turgida migrated to the sediment surface in nitrogen flushed (and hence strongly hypoxic) sediment cores, in contrast to an air-bubbled set-up in which the species maintained its infaunal habitat. This behaviour has been interpreted as controlled by food particles available at the sediment surface at strongly hypoxic conditions in contrast to constantly oxygenated cores with a more oligotrophic sediment surface. Food control has been also suggested to be more important by Mojtahid et al. (2009) and Goineau et al. (2012), who found higher abundances of N. turgida at sites characterized by a higher input of marine organic carbon in Rhone Prodelta. Most recently, however, N. turgida has been placed in a group of species indifferent to organic enrichment and often found in low abundances over a broad range of organic matter concentrations (see: Group II in Alve et al., 2016). Given all the above-mentioned findings and their rather contradictory conclusions, at this point it is difficult to interpret the environmental changes, which caused the increase of N. turgida in one of our sediment cores.

6. Conclusions

- Sediment cores from the inner Sannäs Fjord suggest bottom water salinities of around 24 probably caused by higher precipitation and increased land run-off, based on a dominance of omnivorous E. scaber and higher C/N values prior to ~2000. The increased precipitation and land run-off, likely starting during the late 1970s, may have gradually increased nutrient and terrestrial organic matter load into the fjord system, enhanced water column stratification and caused severe bottom water hypoxia to anoxia characteristic of the inner Sannäs Fjord today. The uppermost sediments of the inner Sannäs Fjord contain great abundances of brackish and low-oxygen tolerant Elphidium species suggesting a further decrease in salinity in the inner fjord bottom waters from ~2000 towards 2008–2009.

- Study of both the living (stained) and the fossil assemblages in the inner fjord cores demonstrates a poor preservation of calcareous foraminiferal shells, suggesting active post-mortem dissolution processes. Dissolution processes likely have been amplified in the inner fjord over recent decades due to an increase of organic matter accumulation on the fjord bottoms and highly variable dissolved oxygen and carbon dioxide concentrations in the bottom waters, which likely enhance/trigger carbonate dissolution.

- Sannäs Fjord’s deepest basin contains the most complete sediment records characterized by good to excellent preservation of calcareous foraminiferal shells.

- In the outer fjord, increased abundances of E. magellanicum and L. lobatula since the 1920s suggest increased frequency/energy of cascading bottom water inflows of higher salinity (S > 29), which is also supported by a gradual decline of E. scaber and a concurrent increase of S. fusiformis. The abundance peak of S. fusiformis was found in the uppermost sediments, which may indicate most recent oxygen
depletion in the outer fjord likely being time-transgressive with similar processes operating on shallow bottoms in the inner fjord inlet.

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Fig. 13. Changes in absolute abundances of living and dead foraminiferal faunas and the number of inner organic linings (IOL) in the surface sediments (0–3 cm) during June–August 2013 at two innermost stations in the Sannäs Fjord. Each data point is based on 2–3 replicate samples (A, B, C) and the mean per station is calculated for each parameter. References:


Robijn, A., 2012. A 250 Years Sediment Record from the Sannäsford, Swedish West Coast, Environmental Changes Reflected by Benthic Foraminifera and Heavy Metal Concentrations. Department of Earth Sciences, University of Gothenburg, B702 (ISSN 1400–3821, 27 pp.).