


# Spatial and temporal organic carbon burial along a fjord to coast transect: A case study from Western Norway

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## Abstract

We investigated spatial and temporal changes in accumulation rate and source of organic carbon on a gradient along the Lysefjord and the more coastal Høgsfjord, Western Norway. This was achieved through analysis of total organic carbon and nitrogen content of sediment cores, which were radiometrically dated to the early 19th and 20th centuries for the Høgsfjord and Lysefjord, respectively. Benthic foraminifera (protists) were utilized to determine changes in organic carbon supply and Ecological Quality Status (EcoQS) by their accumulation rate (benthic foraminiferal accumulation rate (BFAR)), assemblage composition, species diversity, individual species responses and the composition of stable carbon isotopes of the tests (shells) of *Cassidulina laevigata*, *Hyalinea balthica* and *Melonis barleeanus*. Organic carbon accumulation rates were greatest closest to the river Lyse at the head of the Lysefjord (83–171 g C m<sup>-2</sup> yr<sup>-1</sup>). The organic carbon at the head of the fjord is mainly terrestrial in origin, and this terrestrial influence becomes progressively less seaward. The  $\delta^{13}\text{C}$  in *H. balthica* tests as well as the benthic foraminiferal assemblage composition also showed a clear fjord to coast gradient. Organic carbon accumulation rates were lower and less variable at the seaward study sites (13–61 g C m<sup>-2</sup> yr<sup>-1</sup>). We observe no temporal trend in organic carbon, carbon isotopes, EcoQS or foraminiferal assemblage composition in the Lysefjord. In contrast, in the Høgsfjord, there seems to have been an increase in organic carbon accumulation rates during the 1940s. Subsequent accumulation rates are stable. The foraminiferal assemblages in the surface sediments reflect a recent transition from good/moderate to moderate/bad EcoQS.

## Keywords

benthic foraminifera, carbon storage, Ecological Quality Status, late-Holocene, Norway, organic carbon accumulation rates, stable isotopes, terrestrial influence

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## Introduction

A substantial part of the increased food production needed during the coming decades will have to occur in marine coastal areas (Food and Agriculture Organization of the United Nations, 2014). One way to achieve this is to explore the coastal ‘ecosystem services’ and increase food production through enhanced primary production by forced upwelling of nutrient-rich deep water. Such an experiment is currently being undertaken in the Lysefjord, western Norway (Aure et al., 2007; Strohmeier et al., 2015). The higher rate of primary production will result in an increase in the flux of organic matter to the sea floor. This elevated flux may, potentially, increase the carbon storage in fjord sediments, but may also impact the benthos through increased oxygen consumption. Changes in benthic ecosystems, probably because of eutrophication, have been shown to occur in the Skagerrak (e.g. Rosenberg et al., 1987) and fjords have been ranked as one of the ocean’s major ‘hotspots’ for organic carbon burial (Smith et al., 2015). Still, little is known about temporal organic carbon fluxes to, and burial rates in, Norwegian fjord sediments and their possible impact on the benthic ecosystems. Benthic foraminifera (protists) are particularly useful in the current context because changes in organic carbon supply can be reflected in (1) their abundance and rate of accumulation in the sediments (benthic foraminiferal accumulation rate (BFAR); Herguera, 1992; Herguera and Berger, 1991), (2) the assemblage composition (see references in Murray,

2006) and (3) the <sup>13</sup>C concentration in their carbonate shells (for a review see, for example, Rohling and Cooke, 1999). Finally, recent studies have shown the potential of benthic foraminifera in environmental monitoring, using the same quantitative approaches as in conventional monitoring based on macro-invertebrates. The fossilizable nature of the foraminiferal tests means they can be used not only in monitoring over space (Bouchet et al., 2012) but also time (Dolven et al., 2013).

Our primary objective is therefore to quantify both spatial and temporal patterns in organic carbon accumulation rates and storage in fjord sediments which have occurred over the last century. We also determine the sources of the organic carbon along a fjord

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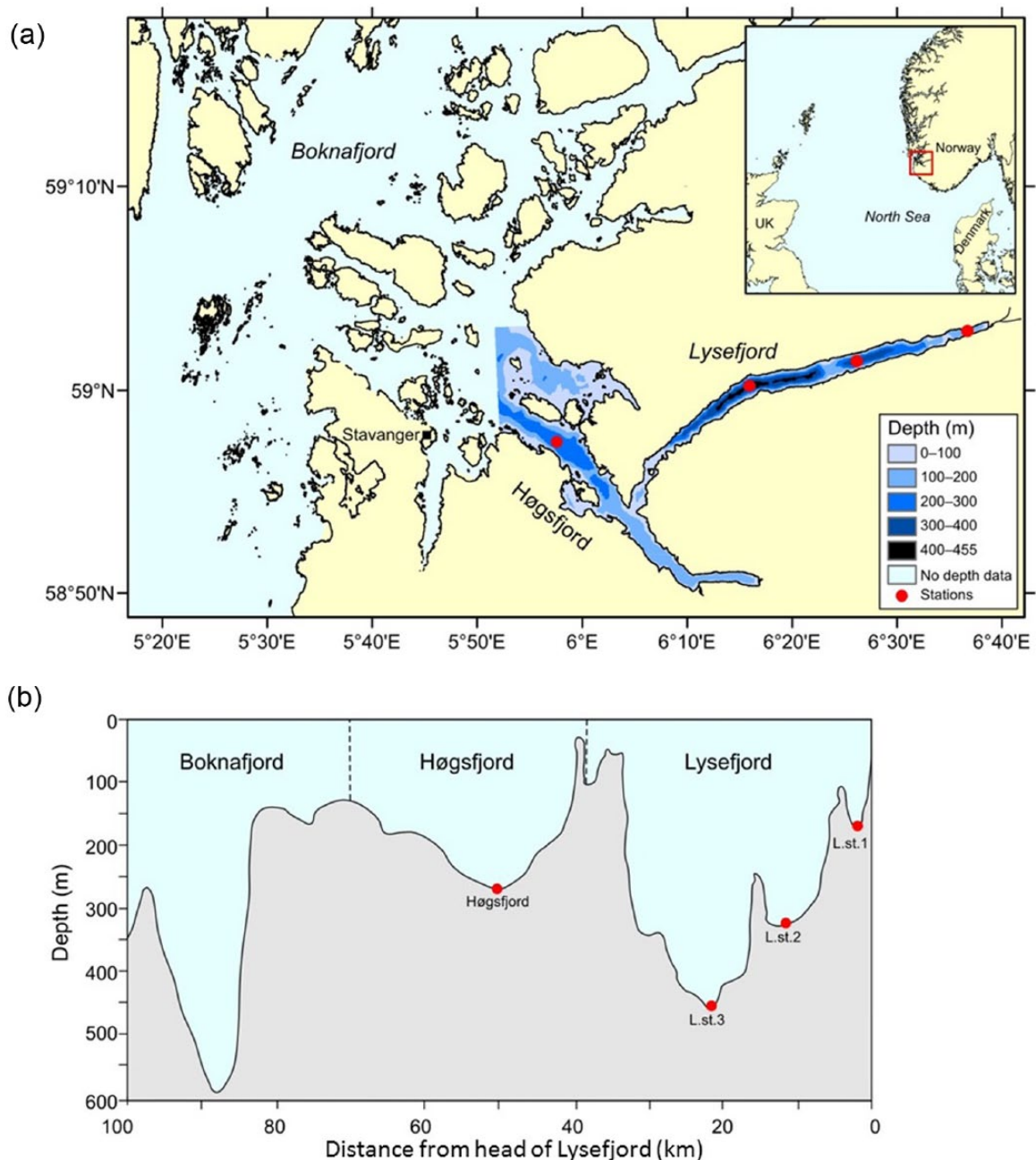
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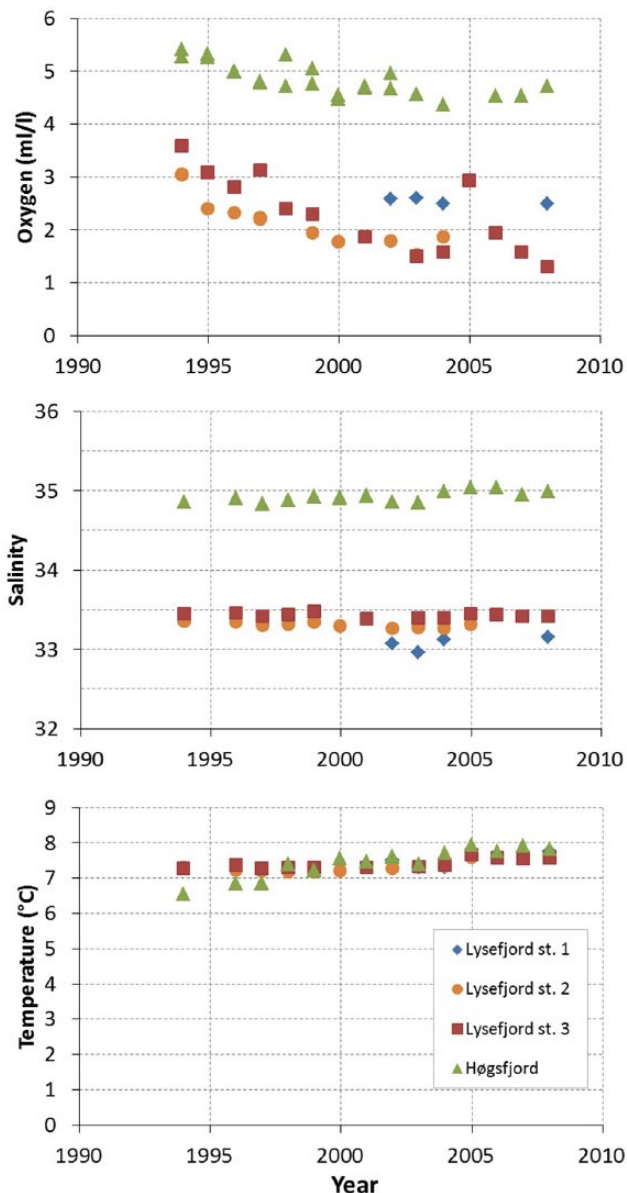
**Figure 1.** (a) Bathymetric map and (b) profile of the study area with sampling stations shown as red circles.

to coast transect in western Norway. In addition, we aim to investigate how ecological status changes along the transect, as reflected by benthic foraminifera.

## Study area

The Lysefjord connects to the 260 m deep Høgsfjord (Figure 1a) via a narrow inlet and a shallow sill (14 m; Erga et al., 2012). The Høgsfjord, in turn, branches off via a 125 m sill from the Boknafjord which is connected to the coastal waters to the west by a sill of about 200 m (Erga, 1989). The Lysefjord is approximately 40 km long and 0.5–2 km wide, and has a maximum water depth of 460 m and a surface area of 44 km<sup>2</sup> (Aure et al., 2007). Within the Lysefjord, there are three basins, each with a sill; these basins become progressively deeper seaward (Figure 1b). The steep granite rocks that line the fjord mean that human impact is minimal; there are no large settlements, heavy industry or agriculture along the fjord. The main human impact on the fjord is freshwater discharges from two hydroelectric power plants located in the

innermost part of the fjord, emitting approximately 100 million cubic metres of freshwater per year (mean = 3.1 m<sup>3</sup> s<sup>-1</sup>, Aure et al., 1993). A third hydroelectric power plant, located 15 km from the head of the fjord, has a mean discharge of 4.7 m<sup>3</sup> s<sup>-1</sup>. These freshwater contributions are minimal compared with the river Lyse, located at the head of the fjord. The discharge of the river Lyse varies between 40 and 90 m<sup>3</sup> s<sup>-1</sup>, with peak discharges occurring in May (Aure et al., 2007). In the Lysefjord, the estimated mean thickness of the brackish layer during summer is 3 m, and the mean transport of brackish water out of the fjord is 150 m<sup>3</sup> s<sup>-1</sup>, with a residence time of about 11 days during the summer (Johnsen et al., 2008). Salinity of the brackish layer is 20–24 (Aure et al., 2001; Johnsen et al., 2008). The inflow of coastal water under the brackish water is about 100 m<sup>3</sup> s<sup>-1</sup>, and the salinity of the intermediate water just below the brackish layer is 30 (Aure et al., 2001). The mean seawater transport between the brackish layer and 20 m depth is estimated to be 600 m<sup>3</sup> s<sup>-1</sup>, and the mean retention time of water between the surface and 20 m depth is estimated to be 11 days (Aure et al., 2001). Below



**Figure 2.** Bottom water oxygen, salinity and temperature at each of the four basins (Figure 1). Measurements taken 10–60 m from the sea floor, 1994–2008. From Institute of Marine Research (unpublished data).

approximately 50 m water depth, salinities range from 32.5 to 33.7 (Aure et al., 1993). From 1975 to 1993, the mean retention time of the basin water was 5.5 years, varying from 3.7 years at 30–100 m depth to about 7 years at 300–400 m depth (Aure et al., 1993). Since 1994, the Institute of Marine Research (IMR; unpublished data) has measured bottom water conditions (temperature, salinity and dissolved oxygen concentration) at the four study sites (Figure 1a and b) using a CTD/STD (model SD204, manufactured by SAIV A/S; Figure 2). Bottom water salinity and temperature in the basins of the Lysefjord have remained constant at 33 and 7.2–7.5°C, respectively. The bottom water in the two outermost basins shows a decrease in oxygen concentration, ranging from 3.6 to 1.3 mL L<sup>-1</sup> from 1994 to 2008 (Figure 2).

The Høgsfjord has a maximum water depth of 260 m (Figure 1b). The salinity during November/December from 1975 to 1993 was 30.9–32.7 at 10 m depth, and salinities below 125 m were typically 35 (i.e. Atlantic water; Aure et al., 1993). Based on the depth of the sill (125 m) between the Boknafjord and Høgsfjord, and oxygen data from 150 and 175 m water depth, the bottom water in the Høgsfjord appears to be well flushed and renewed

**Table 1.** Location and water depth of the four sampling stations.

Station name	Coordinates	Water depth (m)
Lysefjord st. 1	59°02'901"N, 06°36'352"E	163
Lysefjord st. 2	59°01'436"N, 06°26'178"E	326
Lysefjord st. 3	59°00'202"N, 06°15'949"E	446
Høgsfjord	58°57'446"N, 05°57'591"E	260

each year (Aure et al., 1993). We have no estimate for the surface retention time for this fjord. Temperatures in the bottom water of the Høgsfjord have risen from 6.5°C in 1994 to 7.8°C in 2008. Bottom water oxygen conditions have shown a decreasing trend during the mentioned time interval (Figure 2).

## Materials and methods

### Sample collection

Three sediment cores were collected from three different sub-basins of the Lysefjord and one from the adjacent Høgsfjord on 13 and 14 August 2013 (Figure 1b, Table 1). Sediment cores were sampled using a Niemistö corer (5.5 cm inner diameter; Niemistö, 1974). One core was collected at each site and immediately frozen within its liner after collection. Sediment cores were 26, 35.5, 20.5 and 30 cm in length for Lysefjord st. 1, 2, 3 and Høgsfjord, respectively. Three additional cores were collected at the Høgsfjord station and the top 0–1 cm and 1–2 cm were sliced off and a solution of 70% rose Bengal-stained ethanol added (1 g L<sup>-1</sup>; modified from Walton, 1952) for analysis of the live foraminiferal assemblage. Because of logistical problems, no core tops were obtained from the Lysefjord stations. After transportation to the Department of Geosciences, University of Oslo (UiO), the partly thawed cores were sectioned into 1-cm-thick slices down to 20 cm core depth and into 2-cm-thick slices from there on. When slicing the core from Lysefjord st. 1, a high number of plant fragments were observed between 20 and 24 cm. All samples were then freeze-dried and each gently homogenized before further analyses.

### Dating of sediment cores

For radiometric dating, based on the activity of <sup>210</sup>Pb, <sup>226</sup>Ra and <sup>137</sup>Cs, sub-samples of the four sediment cores (minimum dry weight, 5 g each) were analysed at the Gamma Dating Centre at the University of Copenhagen. The measurements were carried out on a Canberra ultra low-background Ge-detector. <sup>210</sup>Pb was measured via its gamma-peak at 46.5 keV, <sup>226</sup>Ra via the granddaughter <sup>214</sup>Pb (peaks at 295 and 352 keV) and <sup>137</sup>Cs via its peak at 661 keV. A modified constant rate of supply model (CRS; Appleby, 2001) was applied to calculate chronologies and sediment accumulation rates for the cores. The modification consists of calculation of the inventory in the lower part of the cores on the basis of a regression of unsupported activity versus accumulated mass depth. A cumulative mass-scale was chosen in order to take sediment compaction into account and enable direct calculation of accumulation rates.

### Organic carbon and nitrogen

For the analysis of total organic carbon (TOC) and nitrogen (N), sub-samples of approximately 1 g dry sediment were homogenized in an agate mortar and treated with 10% HCl to remove inorganic carbon, washed with distilled water and dried at room temperature. Analyses were performed using a Flash EA 1112 NC Analyser at the Department of Biosciences, UiO. Organic carbon accumulation rates were calculated by applying the TOC values to the sediment accumulation rates.

### Analysis of benthic foraminifera

For fossil foraminiferal analyses, approximately 2.5 g dry sediment was washed through a 63  $\mu\text{m}$  sieve and the  $>63 \mu\text{m}$  fraction was dried at 40°C. Lysefjord st. 2 was not considered because of unreliable dating in the lower part of the core (see 'Discussion'). Where possible, at least 250 foraminiferal tests were picked and determined to species level for faunal analyses. A taxonomic reference list is provided as Appendix A, available online. BFAR (in tests  $\text{cm}^{-2} \text{yr}^{-1}$ ) was calculated according to Herguera and Berger (1991). To express species diversity, and in accordance with the Norwegian classification of ecological status in water (Veileder 02:2013), the Shannon-Wiener index ( $H'_{\log_2}$ ) and Hurlbert's index ( $ES_{100}$ ) were calculated using PRIMER version 6.1.13 (Clarke and Gorley, 2006). PRIMER was also used to analyse community similarities through cluster analyses and non-metric multidimensional scaling (MDS) ordinations. For the latter analyses, the data were square root transformed to decrease the influence of dominant taxa on inter-sample similarities. The resemblance was based on the Bray–Curtis similarity (Bray and Curtis, 1957). Determination of Ecological Quality Status (EcoQS) based on  $H'_{\log_2}$  and  $ES_{100}$  follows the class boundaries defined by the Norwegian classification system for macro-invertebrates (Veileder 02:2013). During processing of the sediment for foraminiferal analysis, an approximation of sand content was made by weighing the fraction  $>63 \mu\text{m}$ .

To make the data from the rose Bengal-stained (living) samples comparable with the fossil assemblages, approximately 250 well-stained tests,  $>63 \mu\text{m}$  in size, were wet picked (Duffield and Alve, 2014) from the sample representing the sediment surface (0–1 cm). Subsequently, the sediment from which they were picked was dried and weighed to calculate individuals per gram. Sediment from 1–2 cm depth was only examined and no foraminifera were picked (see results).

### Stable isotope analysis

For stable isotope measurement well preserved, clean tests of three benthic foraminiferal species (*Cassidulina laevigata*, *Melolinis barleeanus* and *Hyalinea balthica*) were picked from the cores Lysefjord st. 1, st. 3 and Høgsfjord. Individual test sizes were measured to make sure that specimens of the same species used for analyses came from approximately the same size range (e.g. Filipsson et al., 2010; McCorkle et al., 2008; Schmiel et al., 2004; Schumacher et al., 2010). The size ranges were as follows: For *C. laevigata*, 245–350  $\mu\text{m}$ ; *H. balthica*, 430–570  $\mu\text{m}$ ; and *M. barleeanus*, 400–500  $\mu\text{m}$ . The number of tests picked per sample was 8–43, 5–27 and 4–17 for each species, respectively. These species were chosen as they had successfully been used in previous studies to assess variations in organic carbon in Scandinavian fjords and coasts (e.g. Brückner and Mackensen, 2008; Filipsson and Nordberg, 2010; Kjennbakken et al., 2011; Milzer et al., 2013; Sejrup et al., 2001).

Stable isotope compositions were measured at the Leibniz Laboratory, University of Kiel, using a Kiel IV preparation device connected to a MAT253 mass spectrometer. The analytical precision of carbon and oxygen isotope measurements was  $\pm 0.05\%$  and  $\pm 0.07 \%$ , respectively. The stable isotope ratios were calibrated to Vienna Pee Dee Belemnite (VPDB) using the international carbonate standard NBS-19 and lab-internal carbonate standards, previously calibrated using NBS-19 and NBS-20. Stable isotopic data are expressed relative to VPDB. Where enough tests were available, a duplicate analysis was made to determine the level of error. The error was calculated by taking the difference between two duplicates and then calculating the standard deviation of all the differences between duplicates. The standard deviation was divided by the square root of two (two duplicates) to give the error.

## Results

All raw data are available in Appendices. B–K available online.

### Sediment chronology and accumulation rates

Data for sediment chronology and accumulation rates are presented in Appendix B, available online. The core from Lysefjord st. 1 showed surface concentrations of unsupported  $^{210}\text{Pb}$  of around 120  $\text{Bq kg}^{-1}$  with a tendency for exponential decline with depth in the upper 17 cm (Figure 3b). The activity is at the detection limit or lower from a depth of about 17 cm. The concentration of supported  $^{210}\text{Pb}$  was relatively high, in the order of 50  $\text{Bq kg}^{-1}$ , which decreases the precision in calculation of the unsupported  $^{210}\text{Pb}$ . The calculated flux was 308  $\text{Bq m}^{-2} \text{yr}^{-1}$ . The core from Lysefjord st. 2 showed surface concentrations of unsupported  $^{210}\text{Pb}$  of around 500  $\text{Bq kg}^{-1}$  with a tendency for exponential decline with depth, but only in the upper 7 cm (Figure 3b). The activity is rather stable below this level. The calculated flux of unsupported  $^{210}\text{Pb}$  was 436  $\text{Bq m}^{-2} \text{yr}^{-1}$ .

At Lysefjord st. 3 and Høgsfjord, the cores showed surface concentrations of unsupported  $^{210}\text{Pb}$  of around 250  $\text{Bq kg}^{-1}$  and 165  $\text{Bq kg}^{-1}$ , respectively, with a clear tendency for exponential decline with depth throughout the cores (Figure 3b). For Lysefjord st. 3, the concentration of supported  $^{210}\text{Pb}$  is relatively high, in the order of 50  $\text{Bq kg}^{-1}$ , which decreases the precision in calculation of unsupported  $^{210}\text{Pb}$ . The calculated flux of unsupported  $^{210}\text{Pb}$  at Lysefjord st. 3 and Høgsfjord was 322 and 185  $\text{Bq m}^{-2} \text{yr}^{-1}$ , respectively.

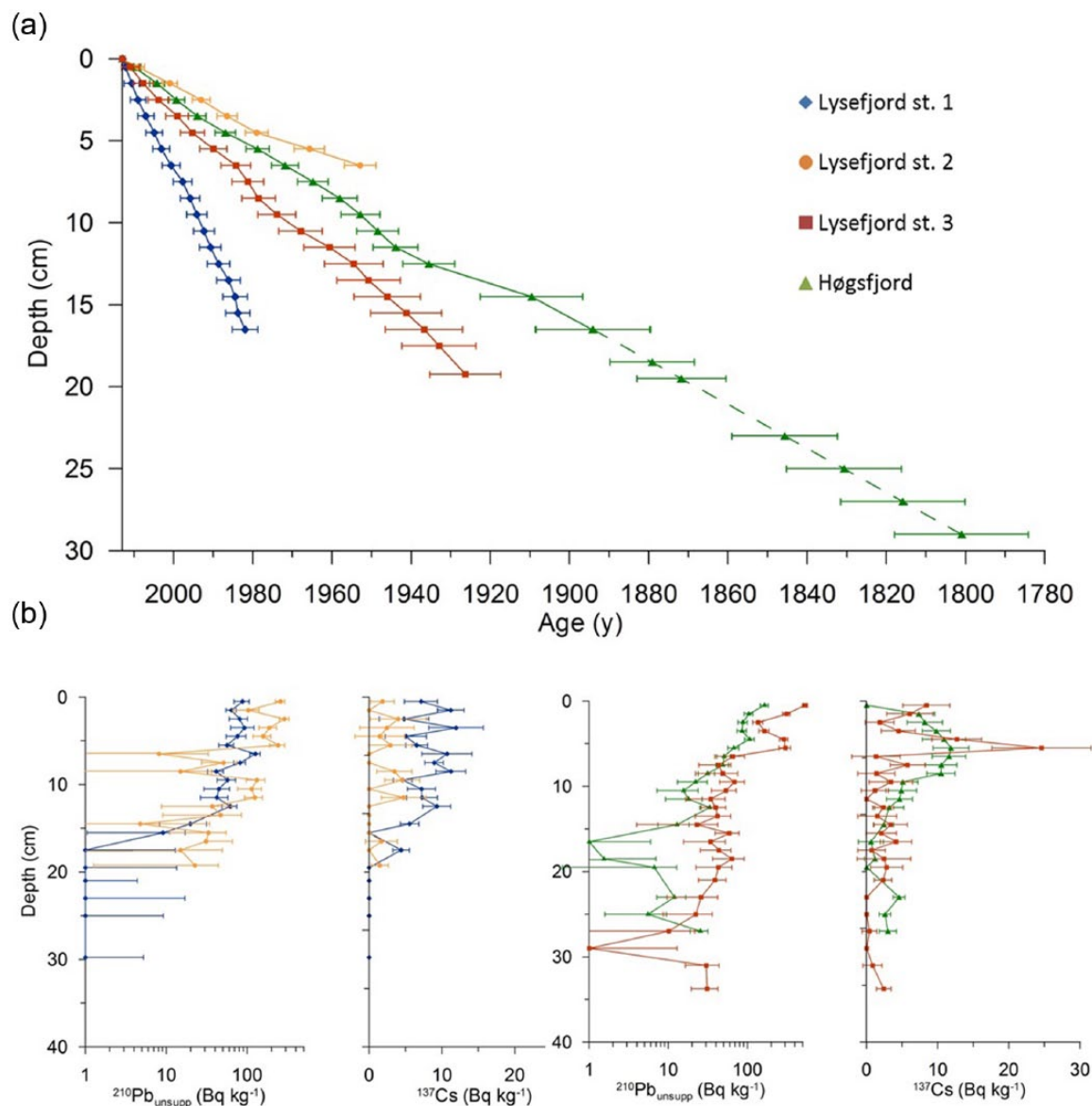
The concentration of  $^{137}\text{Cs}$  was generally low and decreased to below detection limits at depths deeper than 18 cm, 12 cm and 13 cm for Lysefjord st. 1, st. 3 and Høgsfjord, respectively (Figure 3b). At Lysefjord st. 2,  $^{137}\text{Cs}$  was generally low but showed a minor peak around 5.5 cm, and it was generally below detection limit at depths deeper than 8 cm. The chronology of the Høgsfjord core below 17 cm (1894) was extrapolated based on a constant flux, constant sedimentation rate model (CF-CS) using the accumulation rate calculated for the sediment above this level.

Sediment accumulation rates were highest at Lysefjord st. 1 (2.0–4.4  $\text{kg m}^{-2} \text{yr}^{-1}$ ), with an anomalously high value of 9.5  $\text{kg m}^{-2} \text{yr}^{-1}$  in the part of the core dated to 1984. Lysefjord st. 2, st.3 and Høgsfjord all have comparable sediment accumulation rates (0.42–1.41, 0.6–1.6 and 0.5–1.4  $\text{kg m}^{-2} \text{yr}^{-1}$ , respectively).

### Carbon/nitrogen ratio, organic carbon accumulation rates and sand content

Data for C/N ratios and organic carbon accumulation rates are presented as Appendix C, available online. Lysefjord st. 1 showed the overall highest C/N ratios with 13.3–16.7 (average = 15.1; Figure 4a) in the dated upper 17 cm of sediment and values up to 19.7 in the undated sediments at 17–22 cm depth (Appendix C, available online). St. 2 and st. 3 had lower, but mutually comparable, values (10.8–14.2, average = 12.5; and 10.8–14.4, average = 11.8, respectively). Within the dated intervals, there are peaks in C/N in all three Lysefjord cores during the mid-1980s. Høgsfjord had the lowest C/N ratio (8.6–9.7; average = 9.2).

Comparing the four sites, organic carbon accumulation rates were highest at Lysefjord st. 1, where values range from 83.0 to 170.9  $\text{g C m}^{-2} \text{yr}^{-1}$ , showing no overall trend with time (Figure 4b). However, an anomalously high organic carbon accumulation rate of 330.4  $\text{g C m}^{-2} \text{yr}^{-1}$  was seen in the sediments dated to 1984. High TOC values were recorded in the undated part of the core below 17 cm (4.2–6.8%; compared with values of  $<4\%$  in the dated part of the core; Appendix C, available online). The organic carbon accumulation rate at Lysefjord st. 2, st. 3 and Høgsfjord were all comparable, ranging from 14.2 to 30.1, 22.5 to 60.8 and



**Figure 3.** (a) Age model of the four sampling locations. Dashed line represents extrapolated ages. (b) Unsupported  $^{210}\text{Pb}$  and  $^{137}\text{Cs}$  profiles of the four cores.

13.0 to 40.9  $\text{g C m}^{-2} \text{yr}^{-1}$ , respectively (Figure 4b). There was a peak in organic carbon accumulation rate in the early 1980s at Lysefjord st. 3. The organic carbon accumulation rate increased in the Høgsfjord during the 1940s. Before 1940, the organic carbon accumulation rate ranged from 13.0–21.8  $\text{g C m}^{-2} \text{yr}^{-1}$  (average = 17.2  $\text{g C m}^{-2} \text{yr}^{-1}$ ) while after the organic carbon accumulation rate almost doubled, ranging from 23.1–40.9  $\text{g C m}^{-2} \text{yr}^{-1}$  (average = 31.9  $\text{g C m}^{-2} \text{yr}^{-1}$ ).

Sand content (Appendix D, available online) was highest at Lysefjord st. 1 and st. 2 (average 32% and 33%, respectively), followed by Lysefjord st. 3 (25%) and Høgsfjord (11%). Visual inspection showed that most of the  $>63\mu\text{m}$  fraction was composed of mineral sand. No consistent trends were seen up-core. There is a peak in sand content of 47.5% at 20–22 cm in the Lysefjord st. 1 core (Appendix D, available online).

#### Foraminiferal diversity, EcoQS and BFARs

For the down core study, a total of 26 samples were analysed across the three cores in which 93 benthic foraminiferal species were identified (\*\*\*\*Appendix E and F, available online).

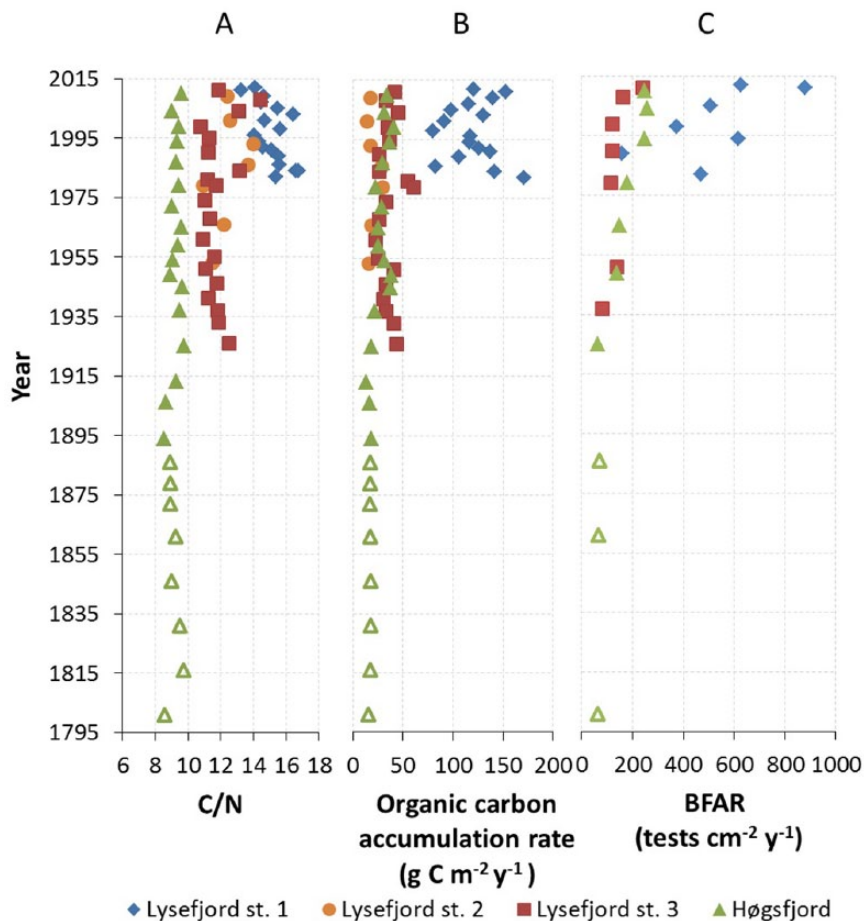
For the three replicates representing the living (stained) assemblages from the Høgsfjord site (Appendix G, available

online), both  $H'_{\log 2}$  and  $ES_{100}$  indicated that one replicate represented 'moderate' and two represented 'bad' EcoQS (Figure 5). In the fossil assemblage, both  $H'_{\log 2}$  and  $ES_{100}$  indicated a 'good' EcoQS throughout the cores from Lysefjord st. 1 and st. 3 (Figure 5; Appendix H and I, available online). In the Høgsfjord core, there was also no significant temporal change in diversity, with EcoQS of the fossil assemblages indicating 'good' to 'moderate' conditions throughout the investigation period.

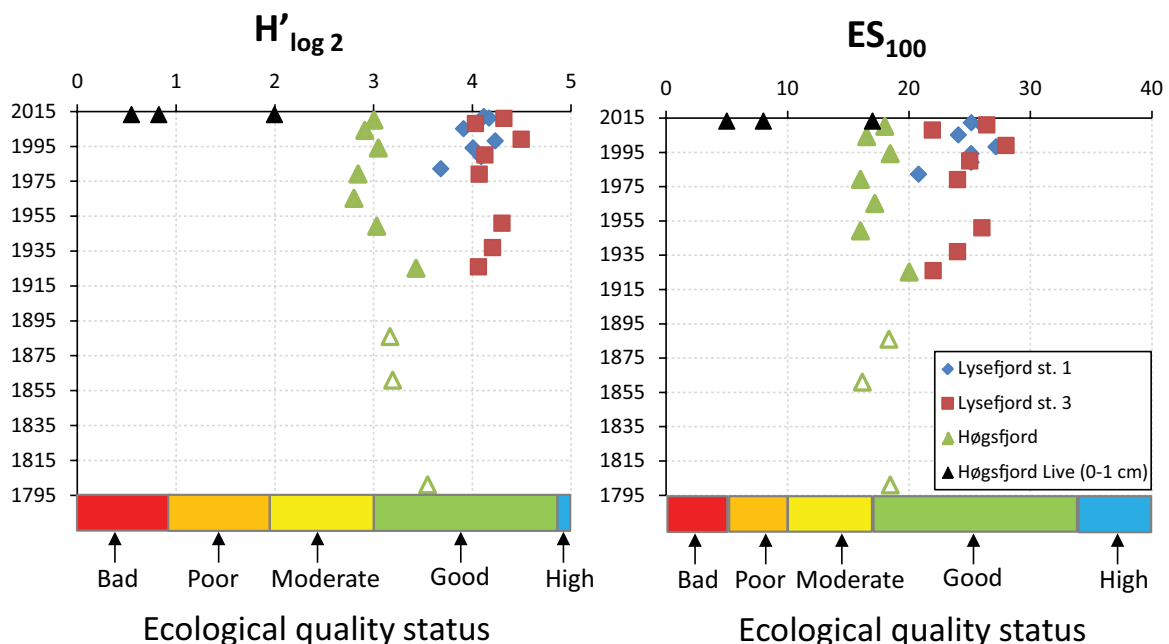
BFAR (Appendix J, available online) was greatest at Lysefjord st. 1 (159–881 tests  $\text{cm}^{-2} \text{yr}^{-1}$ ) and comparable at Lysefjord st. 3 and Høgsfjord (62–240 and 62–247 tests  $\text{cm}^{-2} \text{yr}^{-1}$ , respectively; Figure 4). At Lysefjord st. 1, BFAR showed an erratic temporal pattern with no overall trend with time (Figure 4). There was an increase in BFAR after 2000 at Lysefjord 3 and after about 1940 in the Høgsfjord core (Figure 4).

#### Live and fossil foraminiferal assemblages

From the three replicate, rose Bengal-stained sediment surface samples collected at Høgsfjord, 248–363 stained individuals were picked, equal to 1434–3012 individuals per  $\text{cm}^3$  of sediment (Appendix G, available online). The live assemblages contained 11–24 species and were dominated by *Stainforthia fusiformis*



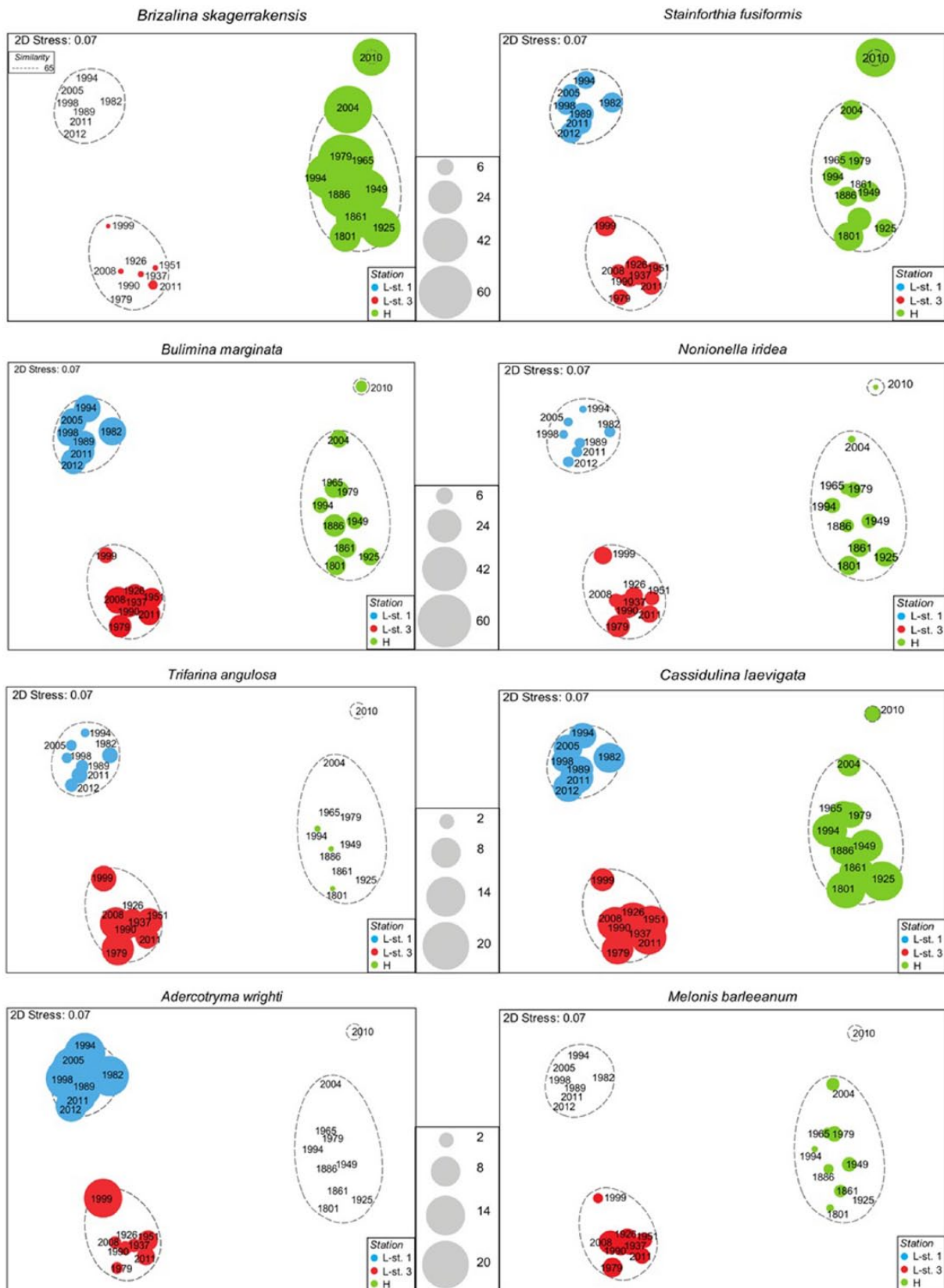
**Figure 4.** (a) Organic carbon/nitrogen ratios, (b) organic carbon accumulation rates and (c) benthic foraminiferal accumulation rate (BFAR) over time. Unfilled data points are based on extrapolated ages. Note that no foraminiferal analysis was carried out at Lysefjord st. 2.



**Figure 5.** Changes in diversity indices  $ES_{100}$  and  $H'_{\log 2}$  in the three sediment cores analysed from which foraminifera were analysed. 'Høgsfjord live' based on rose Bengal-stained individuals from 0 to 1 cm sediment depth. Ecological quality status class intervals are for macrofauna from Veileder 02:2013. Unfilled data points are based on extrapolated ages.

which made up 71–94% of the assemblages. The remaining species all had abundances of  $\leq 3\%$  (except for *Brizalina skagerrakensis* which had a relative abundance of 7% in one replicate). In

the three replicates,  $ES_{100}$  was 5–17 and  $H'_{\log 2}$  was 0.5–2.0, representing an overall EcoQS of 'bad' to 'moderate'. Because of the strong dominance of *S. fusiformis* in the upper centimetre, no



**Figure 6.** MDS-ordination plot of benthic foraminifera assemblages from each sample (year). Based on relative abundance data.

quantitative work was carried out on the 1–2 cm samples; however, a cursory inspection revealed the same strong dominance of *S. fusiformis*.

The fossil Høgsfjord assemblage was distinctly different from Lysefjord st. 1 and st. 3 (Figure 6). Furthermore, Lysefjord st. 1 and st. 3 had their own distinct assemblages. There was a clear temporal pattern in the upper part of the Høgsfjord core; the two

samples from the top 2 cm of the Høgsfjord core (representing approximately the last 10 years) showed a pronounced dissimilarity compared with the samples below (Figure 6).

*B. skagerrakensis* was the only species to have high relative abundances in the Høgsfjord while being virtually absent from the Lysefjord (maximum abundance in Lysefjord <2%; Figure 6; Appendix F, available online). In the Høgsfjord, *B. skagerrakensis*

had its lowest BFAR and relative abundance at the base of the core in the early 1800s (13 tests  $\text{cm}^{-2} \text{yr}^{-1}$ ; 21%), its highest relative abundance was in 1965 (53%), whereas its greatest BFAR was in 2004 (124 tests  $\text{cm}^{-2} \text{yr}^{-1}$ ; Figure 7). In the top centimetre of the core, the BFAR dropped to 73 tests  $\text{cm}^{-2} \text{yr}^{-1}$  (30%). *Nonionella iridea* was present in the Lysefjord but showed a similar pattern in BFAR to *B. skagerrakensis* in the Høgsfjord (Figure 7); BFAR and relative abundance increased from 1965 (5 tests  $\text{cm}^{-2} \text{yr}^{-1}$ ; 6%) until 1994 (16 tests  $\text{cm}^{-2} \text{yr}^{-1}$ ; 7%) after which both BFAR and relative abundance decreased (2004: 4 tests  $\text{cm}^{-2} \text{yr}^{-1}$ , 2%; 2010: 2 tests  $\text{cm}^{-2} \text{yr}^{-1}$ , 1%). *S. fusiformis* also showed an increase in both accumulation rate and relative abundance from 1965 onward and dominated the assemblage in the top centimetre of the core (86 tests  $\text{cm}^{-2} \text{yr}^{-1}$ ; 35%; Figures 6 and 7). *H. balthica* showed an increase in BFAR in the Høgsfjord after 1979, reaching a maximum of 12 tests  $\text{cm}^{-2} \text{yr}^{-1}$  (5%) at the very top of the core. While virtually absent from Høgsfjord, both *Adercotryma wrighti* and *Trifarina angulosa* were common (max. 16% and 10%, respectively) in Lysefjord (Figure 6).

### Stable isotope analyses

Stable oxygen and carbon isotope values for *C. laevigata*, *H. balthica* and *M. barleeanus* were measured in Lysefjord st. 1, st. 3 and the Høgsfjord cores (Figure 8; Appendix K, available online). Based on duplicates, the error of a single measurement was calculated. For *H. balthica*, the error was  $\pm 0.174\text{‰}$  and  $\pm 0.089\text{‰}$  for  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$ , respectively (based on 21 pairs of duplicates), and for *M. barleeanus*,  $\pm 0.108\text{‰}$  and  $\pm 0.081\text{‰}$  for  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$ , respectively (based on five pairs of duplicates).

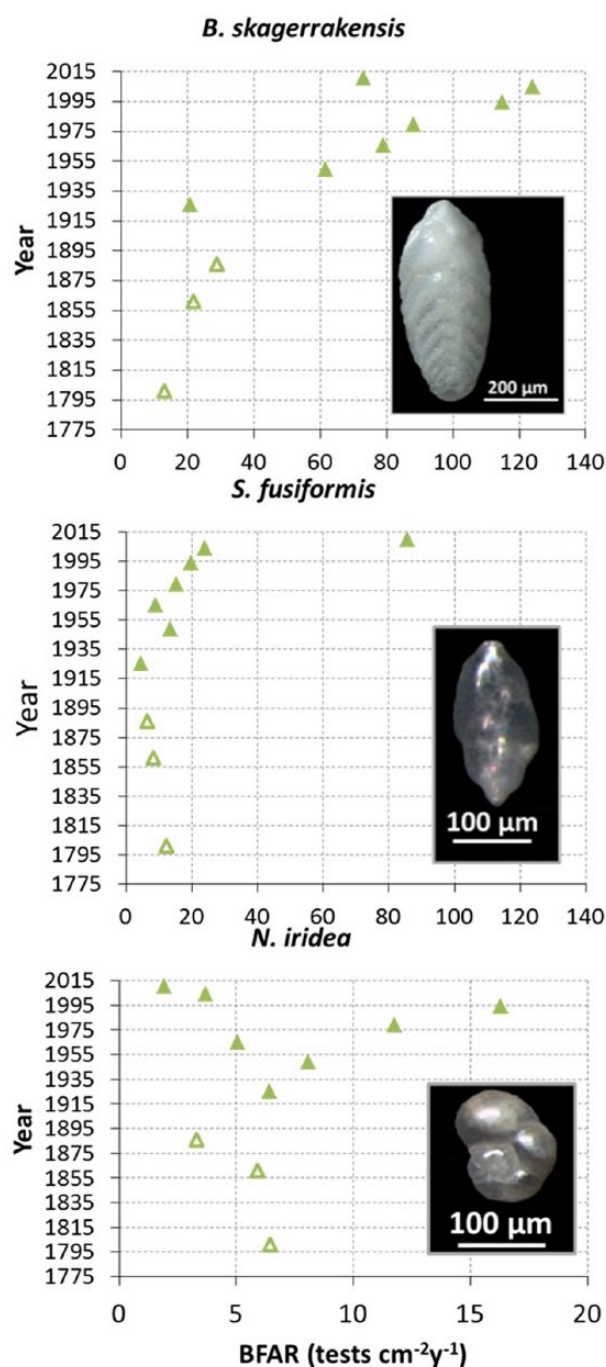
For Lysefjord st. 1, the  $\delta^{18}\text{O}$  values remained quite stable up-core with an average of 2.8‰ and 2.1‰ for *C. laevigata* and *H. balthica*, respectively (*M. barleeanus* was absent at Lysefjord st. 1). The  $\delta^{18}\text{O}$  values also showed little variability up-core at Lysefjord st. 3, with average values of 2.6‰ for *C. laevigata* and 2.1‰ for both *H. balthica* and *M. barleeanus*. In the Høgsfjord, the  $\delta^{18}\text{O}$  of *H. balthica* and *M. barleeanus* showed no change until the 1950s, after which there is an overall decreasing trend up-core; this is less clear from *C. laevigata*  $\delta^{18}\text{O}$  values (Figure 8).

In Lysefjord st. 1, the  $\delta^{13}\text{C}$  values for *C. laevigata* showed no overall trend and had an average of  $-0.7\text{‰}$  (Figure 8). Equally, the  $\delta^{13}\text{C}$  for *H. balthica* showed no trend and all were within error of one another, with an average of  $-2.2\text{‰}$ , excluding the uppermost centimetre of the core where the  $\delta^{13}\text{C}$  values for this species showed a negative shift to  $-2.8\text{‰}$ . There was also little trend in  $\delta^{13}\text{C}$  in Lysefjord st. 3. *C. laevigata* had an average  $\delta^{13}\text{C}$  of  $-0.58\text{‰}$ . The average  $\delta^{13}\text{C}$  of *H. balthica* was  $-1.5\text{‰}$ . There was also little change in the  $\delta^{13}\text{C}$  of *M. barleeanus*, with all points lying within error of one another, an average of  $-1.2\text{‰}$ . In the Høgsfjord, all three species showed constant  $\delta^{13}\text{C}$  in the lower part of the core, and for *C. laevigata* throughout (average  $-0.8\text{‰}$ ). After around 1955, the  $\delta^{13}\text{C}$  of both *H. balthica* and *M. barleeanus* showed a negative trend in the Høgsfjord, from a respective average of  $-1.31\text{‰}$  and  $-0.66\text{‰}$  to  $-1.71\text{‰}$  and  $-0.98\text{‰}$  (Figure 8). The  $\delta^{13}\text{C}$  of *H. balthica* was more negative at Lysefjord st. 1 (Figure 9) compared with the other two sites.

## Discussion

### Sediment chronology

The steep slopes of the Lysefjord most likely have the effect that some sediment deposition takes place as subaqueous slides, resulting in episodic sedimentation of event-type deposits. The abrupt change in  $^{210}\text{Pb}$  and  $^{137}\text{Cs}$  at a depth of around 17 cm at Lysefjord st. 1 (dated 1982; Figure 3) indicates recent deposition on top of sediment which was deposited  $>100$  years ago. The relatively high sand content of the sediment at 20–22 cm suggests a

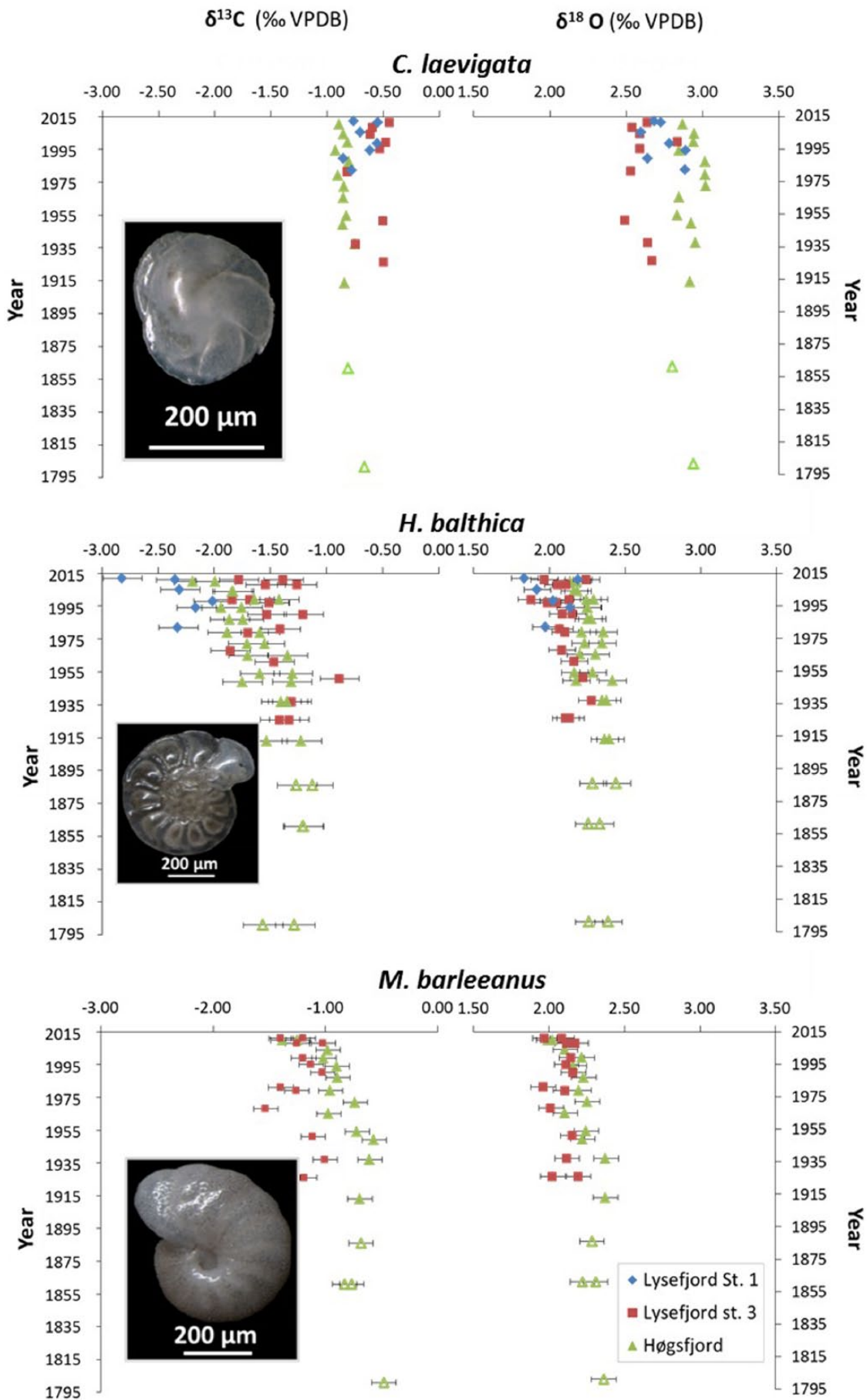


**Figure 7.** Benthic foraminifera accumulation rate (BFAR) of *Brizalina skagerrakensis*, *Stainforthia fusiformis* and *Nonionella iridea* in the Høgsfjord. Photographs are representative specimens of each species. Unfilled data points are based on extrapolated ages. Please note the different of scale on the x-axis for *N. iridea*.

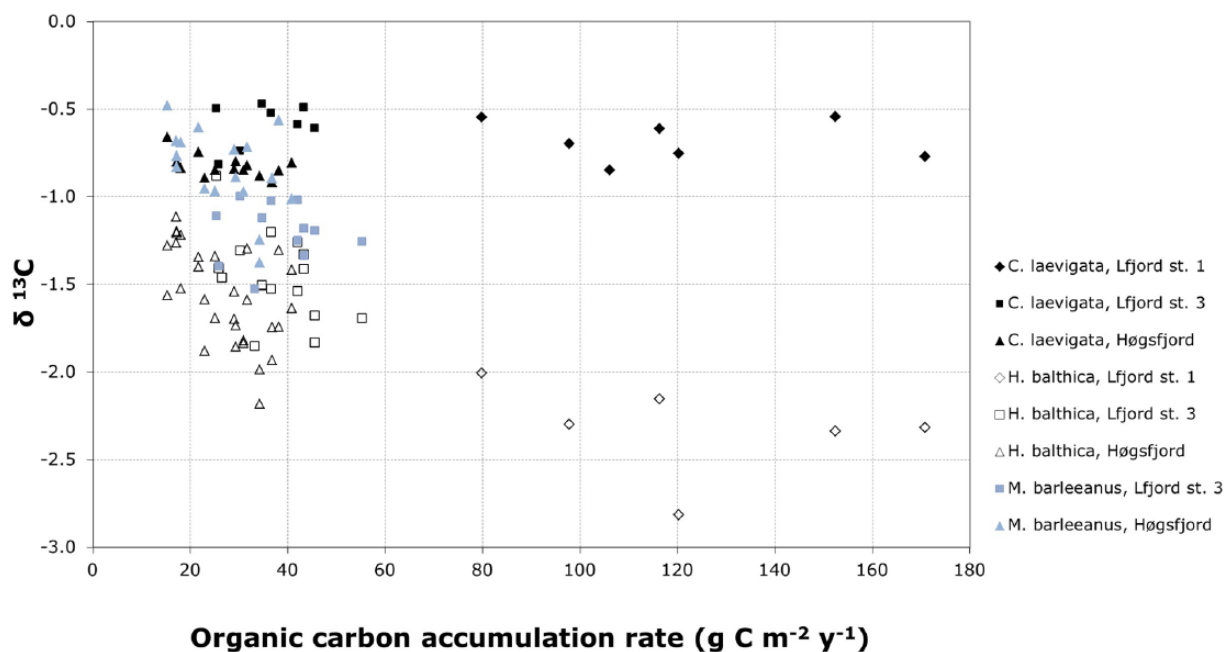
coarser texture which may be indicative of an event-type deposit, also indicated by the high TOC and C/N values seen below 17 cm (Appendix C and D, available online), as well as the high amount of terrestrial plant fragments observed at 20–24 cm. In the same way, the rather stable activity of  $^{137}\text{Cs}$  below 7 cm depth in the sediment core from Lysefjord st. 2 also indicates an event-type deposit. The sediments below 17 cm and 7 cm, in the two cores, respectively, are therefore not considered for further discussion as they most likely represent rapid sedimentation events and are difficult to date using the chosen radiometric methods.

For the deposits above these events, as well as for the cores Lysefjord st. 3 and Høgsfjord, the calculated chronologies (Figure 3a) are only valid if bioturbation and other sediment





**Figure 8.**  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values for the three foraminiferal species analysed: *Cassidulina laevigata*, *Hyalinea balthica* and *Melonis barleeanus*. Photographs are representative specimens of each species. Unfilled data points are based on extrapolated ages. Note that *M. barleeanus* was absent from Lysefjord st. 1. The displayed error bars represent average errors calculated on the basis of differences between duplicates from different samples ( $n = 21$  for *H. balthica* and  $n = 5$  for *M. barleeanus*). Because of limitation of material, no duplicates were analysed for *C. laevigata*.



**Figure 9.** Carbon isotopic composition for the three species analysed compared with organic carbon accumulation rate. In contrast to *Hyalinea balthica*, the carbon isotopic composition of *Cassidulina laevigata* is not affected by the accumulation rates of organic carbon. *Melonis barleeanus* was absent from Lysefjord st. 1; it remains unclear whether this species shows a relationship with organic carbon accumulation rate.

mixing were negligible. If this is not the case, the ages are underestimated and accumulation rates are overestimated. However, marking the fallout from the testing of nuclear weapons which ceased in 1963 (Delaune et al., 1978), the  $^{137}\text{Cs}$  peak from 5 to 6 cm at Lysefjord st. 2 was correctly dated to around 1963; this gives confidence in the chronology for that core. For Lysefjord st. 3 and Høgsfjord, some sediment mixing is indicated by smearing of the  $^{137}\text{Cs}$  profiles but the generally exponentially declining concentration of unsupported  $^{210}\text{Pb}$  indicates fairly continuous and stable sedimentation which supports the chronologies reported for these two cores. The upper 17 cm of Lysefjord st. 1 showed tendency of exponential decline with depth in unsupported  $^{210}\text{Pb}$  but an irregular profile of  $^{137}\text{Cs}$  indicating some disturbance of the stratigraphy.

#### Stable isotopes, vital effects and carbon accumulation rates

The stable carbon isotopes in benthic foraminiferal carbonates reflect a number of factors such as flux, origin and degradation of organic matter, together with microhabitat, test size and unknown vital offsets for different species (e.g. Brückner and Mackensen, 2008; Milzer et al., 2013). To decipher these effects is difficult in studies such as the one presented. To minimize the effect of test size, narrow size ranges for each species were sampled (see materials and methods). Hence, in the present data set, isotopic differences because of an ontogenetic effect were likely negligible.

For most benthic foraminiferal species, the stable isotopes in their carbonate tests are not formed in equilibrium with bottom or pore waters (e.g. Fontanier et al., 2006). To compare isotope values from different species, their values need to be corrected for vital offsets. The shallow infaunal *C. laevigata* probably calcifies so that oxygen isotopes are in equilibrium with seawater (Kjennbakken et al. (2011), and references therein). In contrast, the shallow infaunal *H. balthica* needs a correction by +0.64‰ for the vital offset (Rosenthal et al., 2011). After this correction (not shown in Figure 8), both shallow infaunal species (*C. laevigata* and *H. balthica*) show on average identical oxygen isotope values within each core: Lysefjord st. 1 ( $+2.78 \pm 0.12\text{‰}$  and  $+2.66 \pm 0.13\text{‰}$ ), Lysefjord st. 3 ( $+2.62 \pm 0.10\text{‰}$  and  $+2.74 \pm 0.10\text{‰}$ ) and

Høgsfjord ( $+2.92 \pm 0.07\text{‰}$  vs  $+2.92 \pm 0.08\text{‰}$ ). The intermediate infaunal species *M. barleeanus* needs a correction of the oxygen isotope values by about +0.4‰ for vital offset (Jansen et al., 1989). However, on the basis of a larger data set (Hoogakker et al., 2010) and by using differences between different benthic foraminifera, a vital offset of +0.54‰ was estimated for *M. barleeanus*. After correction with this offset of Hoogakker et al. (2010), *M. barleeanus* displays on average nearly identical oxygen isotope values as the other two species: Lysefjord st. 3 ( $+2.64 \pm 0.08\text{‰}$ ) and Høgsfjord ( $+2.76 \pm 0.12\text{‰}$ ). Consequently, in the present study, there is no indication of a larger difference in oxygen isotopes between the shallow infaunal and intermediate infaunal species which reflects differences in pore water.

There is some indication that the vital offset for carbon isotopes in *H. balthica* is larger than those for *C. laevigata* and *M. barleeanus*:  $>1.3\text{‰}$ ,  $>0.7\text{‰}$  and  $>0.7\text{‰}$ , respectively (Brückner and Mackensen, 2008). With deeper microhabitat depths, lower carbon isotope values could be expected. This is because of  $\delta^{13}\text{C}$  in sediment pore water depleting with depth as a result of the decomposition of organic matter. The  $\delta^{13}\text{C}$  signal of the foraminiferal test reflects the surrounding pore water in which calcification takes place and hence the sediment depth at which the foraminifera preferentially occupy, creating a 'microhabitat effect' (e.g. Fontanier et al., 2006). In case microhabitat is the main driving force, the carbon isotopes from *M. barleeanus* should be lower compared with the two shallower dwelling species. However, this is not the case. The carbon isotopic composition from *C. laevigata* is not affected by the accumulation rate of organic carbon (Figure 9). It should be noted that Lysefjord st. 1 (where organic carbon accumulation is greatest) is strongly influenced by terrestrial organic carbon, and terrestrial plant material is more resistant to decay (see discussion below). A different response may have been observed if there was a high accumulation of labile, rapidly degrading organic matter. That said, carbon isotopic composition of *C. laevigata* does not respond to the increase in organic carbon in the algae-dominated Høgsfjord sediments, so it may be the case that the isotopic signal of *C. laevigata* is unaffected by the type of organic carbon as well as the accumulation rate of organic carbon. This could indicate that it reflects bottom water conditions rather than those in the sediment pore

water, as already discussed above. In contrast, the carbon isotope values from *H. balthica* were lower at Lysefjord st. 1 compared with Lysefjord st. 3 and Høgsfjord (Figure 9). Whether this was because of a higher accumulation rate or stronger influence of terrestrial organic material at Lysefjord st. 1 is not clear (Figure 9). Since no data are available for *M. barleeanus* from Lysefjord st. 1 with the highest organic carbon accumulation rate, it remains unclear whether this species would show a relationship with carbon accumulation rate (Figure 9) reflecting a fjord to coast gradient. However, in the Høgsfjord, there may be an indication that the carbon isotope signal of *M. barleeanus* shows the same trend as *H. balthica*, decreasing with an increasing rate of organic carbon accumulation (Figure 4b, Figure 8). This suggests that while *C. laevigata* may reflect bottom water conditions, *H. balthica* and *M. barleeanus* likely reflect sediment pore-water conditions affected by the level of decaying organic matter.

#### Fjord to coast transect – Environmental characteristics within Lysefjord

Within the Lysefjord, a clear seaward gradient can be observed in respect to the type and accumulation rate of organic carbon. The high C/N values at all three sites within the Lysefjord (>11; Figure 4a) reflect an influence from terrestrial organic matter (Lamb et al., 2006; Meyers, 1994). The highest C/N values, sediment- and organic carbon accumulation rates occur at the fjord head (Lysefjord st. 1), in close proximity to the river Lyse and the outlet of the two hydropower plants. The difference between Lysefjord st. 1 and st. 3 is further highlighted by their distinct foraminiferal assemblages (Figure 6). All three sites are subject to sediment focusing; the calculated flux of unsupported  $^{210}\text{Pb}$  at Lysefjord st. 1 and st. 3 was about twice the expected flux from atmospheric deposition (Appleby, 2001), while at Lysefjord st. 2, it was approximately three times the expected flux.

The nature and rates of accumulation of organic carbon in Lysefjord are largely controlled by freshwater supply and episodic depositional events. It is at the head of the fjord where there is greatest potential for rapid organic carbon accumulation. An example is the high C/N ratios and organic carbon accumulation rates in Lysefjord sediments during the mid-1980s (Figure 4a and b), indicating increased input of terrestrial organic carbon. The source of this material was likely associated with reported heavy rainfall and snowmelt which caused flooding in 1983 (reported by a local newspaper: Stavanger Aftenblad, 1983a, 1983b). The presence of plant fragments, the high sand content and the likely abrupt changes in sedimentation indicated by the radiometric data (see discussion above) give further evidence of occasional rapid depositional events of terrestrial origin.

In addition, terrestrial plant material has a greater potential for storage in the sediment than marine material because of terrestrial plant matter being composed of lingo-cellulosic tissue which is more stable and resistant to decay (Tyson, 1995). In comparison, the biogenic carbon generated by algae during spring and autumn blooms sink more or less as ungrazed aggregates to the benthos (Wassmann, 1997). Once it reaches the sediment, the labile matter is consumed rapidly, hence it is only found in the first few millimetres of the sediment (Carney (1989), and references therein). However, this is not always the case. First, there are numerous eutrophic environments where retention of organic matter in the surface waters can be substantial (Wassmann, 1997). In conditions where grazing by zooplankton does take place, the organic flux not only occurs as algal aggregates but also faecal pellets; however, not all of the organic matter will sink, some of the organic matter will remain in a microzooplankton/microbial loop (Wassmann et al., 1999). Second, the residence time of the brackish surface water of many silled fjords with an estuarine circulation pattern is short, for example, 1–4 days in Frierfjord (south Norway; Rygg et al.,

1987), 5–25 days in the inner Drammensfjord (south Norway; Magnusson and Næs, 1986) and about 11 days during the summer in Lysefjord (Johnsen et al., 2008). This brackish nature combined with short residence time probably hampers growth, subsistence (rapid transport out of the system) and, hence, sedimentation of marine algae in such river-influenced fjords. Additionally, Lysefjord is considered to be very poor in nutrients (Johnsen et al., 2008). The result is likely a fjord bottom limited in food available for benthic communities.

The residence time of the bottom water in Lysefjord has been about 8 years since 1975 but was about 11 years between 1992/1993 and 2004 during which time bottom water dissolved oxygen concentrations ranged between 4.0 and 1.5 mL L<sup>-1</sup> (Johnsen et al., 2008). Macrofauna investigations reflected 'good' to 'moderate' ecological status in 1992 and 'poor' to 'bad' status in 2007 (Johnsen et al., 2008). Johnsen et al. (2008) considered these to reflect natural conditions for the Lysefjord. The lack of temporal trends concerning organic carbon accumulation rates (Figure 4b) and fossil benthic foraminiferal assemblages (Figures 4–6) support this view. However, whereas the macrofauna show different status at different times, the foraminifera indicate 'good' status throughout the investigation period. One reason for this apparent discrepancy is probably the fact that whereas the macrofauna reflects the conditions at the time of sampling, the fossil foraminiferal assemblages are time-averaged. The latter means that the assemblage recorded in each sample represents the average of the conditions that occurred during the time represented by the analysed sediment, possibly including some physical/biological mixing with older (below) and younger (above) sediment layers. This time-averaged nature of the assemblage data reflects the main, overarching environmental conditions and dampens short-term variability and patchiness (see discussion in, for example, Martin, 1999; Schafer, 2000). Another reason may be that the terrestrially influenced, food-limited fjord bottom is less hospitable to marine macrofauna than to benthic foraminifera which may feed on decaying organic matter and associated microbes (e.g. Duffield et al., 2015). The erratic temporal pattern in BFAR at st. 1 is probably a combination of the latter and an artefact of the dynamic sedimentation within the fjord.

In concert, the results imply that little overall environmental or ecological change has occurred in the deeper parts of the inner Lysefjord basin since the 1980s (i.e. the oldest dated sediments at st. 1) and since the 1950s and 1930s in the middle (st. 2) and outer (st. 3) basins, respectively. The high sedimentation rates of fjords make them important carbon sinks (St-Onge and Hillaire-Marcel, 2001). This applies especially in areas such as the head of the Lysefjord, where there are rapid deposition events of sediments enriched in terrestrially derived organic carbon. Strong dominance of terrestrial organic matter also characterizes the inner parts of recently investigated Spitsbergen fjords (Koziorowska et al., 2016). Perhaps the principal factor that makes fjords important carbon sinks is the rapid sedimentation of terrestrial carbon, which is not easily degraded in the marine environment.

#### Fjord to coast transect – Environmental characteristics of Lysefjord versus Høgsfjord

In contrast to the Lysefjord, the low C/N ratios in the Høgsfjord (approximately 9; Figure 4a) indicate that organic matter is mainly derived from algae (Figure 4a; Lamb et al., 2006; Meyers, 1994). Milzer et al. (2013) used stable carbon isotope values from *M. barleeanus* in the Trondheimsfjord to discuss changing input from terrestrial versus marine material, finding that  $\delta^{13}\text{C}$  values increase seaward, with the lowest values being closest to river inlets. This is explained by the dissolved inorganic carbon in rivers originating mainly from the degradation of  $^{12}\text{C}$  enriched organic matter from terrestrial soils, resulting in generally lower  $\delta^{13}\text{C}$  values relative to marine water. Since *M. barleeanus* does

not occur at our most terrestrial dominated site, Lysefjord st. 1, a potential similar behaviour in the carbon isotopes based on this species cannot be reliably tested on our data set. However, at Lysefjord st. 1, *H. balthica* shows the lowest carbon isotope values (Figure 8), which could indeed be explained by high terrestrial input. The lack of a similar pattern for *C. laevigata* may support the above-mentioned assumption that the stable carbon isotopes of this species reflect the conditions of the bottom water rather than the sediment pore water. As discussed above, a more important influence on carbon isotope values is probably organic carbon accumulation rates (Figure 9).

The fjord to coast gradient is further shown in the  $\delta^{18}\text{O}$  values. The slightly higher oxygen isotope values at Høgsfjord (Figure 8) likely reflect the more saline Atlantic bottom water which is too heavy to enter over the shallow sill (14 m) at the entrance to the Lysefjord (Figure 1b). Similarly, Mikalsen and Sejrup (2000) show a gradient in  $\delta^{18}\text{O}$  in the Sognefjord, Norway, with more positive values seaward.

The foraminiferal assemblage composition also reflects a distinct fjord to coast gradient in environmental conditions.

While *B. skagerrakensis* and *M. barleeanus* were hardly recorded in inner Lysefjord (sta. 1), they occurred in outer Lysefjord (sta. 3) and both were common in Høgsfjord where *B. skagerrakensis* even dominated the fossil assemblages (Figure 6). *B. skagerrakensis* is common in muddy sediments, mainly seems to feed on fresh organic matter (e.g. Alve et al., 2011; further discussed below) and is probably unable to sustain itself on the food associated with terrestrial organic matter of the Lysefjord. Additionally, limited supply of fresh organic matter because of poor nutrient conditions and restricted sedimentation of marine algae to the Lysefjord sediments (discussion above) probably restricts the abundance of *B. skagerrakensis*. This may also apply to *M. barleeanus*. Although previously reported from fjords, this is primarily a shelf and deep-sea species adapted to live in muddy, organic-rich sediments and the literature points in different directions concerning possible food preferences (see Murray (2013), and references therein). It is not clear whether the conditions linked to the somewhat higher sand content in Lysefjord compared with Høgsfjord impacts their distribution.

*T. angulosa* and *A. wrighti*, although not very abundant (max 10% and 16%, respectively), show a near opposite distributional pattern compared with *B. skagerrakensis* and *M. barleeanus* (Figure 6). *T. angulosa* is common in coarse sands/gravels along shelf edges subject to currents (Murray, 2013) and seems to occupy interstitial microhabitats in coarse-grained sediments where it may withstand water turbulence (see Schönfeld (2002), and references therein). *A. wrighti* is abundant in the muddy sands of the Celtic Sea (Murray and Alve, 2000). Consequently, their abundance in Lysefjord and their near absence in Høgsfjord may reflect the different characteristics of the sediments and associated hydrodynamic regimes in the two fjord systems. Other common species such as *C. laevigata*, *H. balthica*, *N. iridea* and *Bulimina marginata* occurred at all stations.

As opposed to the sediment focusing recorded in Lysefjord, the calculated flux of unsupported  $^{210}\text{Pb}$  in Høgsfjord was in the order of the expected flux from atmospheric deposition (Appleby, 2001). The Høgsfjord, therefore, does not show evidence of elevated, event-driven deposition of organic carbon accumulation, in contrast to Lysefjord where this is more pronounced.

#### Comparison of carbon sources and accumulation with other fjords

Our organic carbon accumulation rates ( $13\text{--}171\text{ g C m}^{-2}\text{ yr}^{-1}$ ) are comparable with those reported in other fjords. Based on data from Husum and Alve (2006), the total carbon accumulation rate (an over estimate of organic carbon flux) in fjords on the Skagerrak

coasts is  $8\text{--}185\text{ g C m}^{-2}\text{ yr}^{-1}$ . The data from the study of five localities in the inner Oslofjord by Dolven et al. (2013) show an organic carbon accumulation of  $14\text{--}60\text{ g C m}^{-2}\text{ yr}^{-1}$ . The C/N ratios for the study sites of Dolven et al. (2013) range from 9 to 12 (Alve, unpublished data) as there are no major rivers entering the inner Oslofjord. These C/N ratios and organic carbon accumulation rates from Norwegian waters are comparable with those in the Patagonia fjords, Chile ( $10\text{--}16, 0.7\text{--}82.5\text{ g C m}^{-2}\text{ yr}^{-1}$ ; Sepulveda et al., 2011). In the Idefjord/Ringdalsfjord system at the southern border between Norway and Sweden, the C/N values were in the range 15–20 before (i.e. reference conditions) and up to 30 during maximum discharges from local paper/pulp industry (Polovodova Asteman et al., 2015). No sediment accumulation rates were reported. Overall, our present knowledge of the origin of organic carbon and its accumulation rate in sediments from coasts and fjords is limited, and quantifying the extent of fjords as carbon sinks will require more research.

#### Temporal changes in Høgsfjord

The increase in BFAR (Figure 4) and decrease in  $\delta^{13}\text{C}$  of *H. balthica* and *M. barleeanus* (Figure 8; Figure 9) both support our other data, suggesting increased organic carbon accumulation rate in Høgsfjord from the 1940s onward (Figure 4b). The constant low C/N ratios (Figure 4a) indicate that if there has been an increase, it is from a marine source. The change in benthic foraminiferal assemblage composition (Figure 6) indicates that the increased carbon accumulation rate has affected the benthos, although this is not reflected in the diversity indices (Figure 5). The change in the foraminiferal composition is most pronounced in the top 2 cm of the core, representing approximately the last decade. Although the fossil assemblages do not show any temporal changes in EcoQS, the living foraminiferal assemblages in the surface sediments reflect a recent decline from 'good'/'moderate' to 'moderate'/'bad' EcoQS (Figure 5).

Increased supply of fresh organic carbon is likely the cause of the increase of *B. skagerrakensis*, *N. iridea* and *S. fusiformis* (Figure 7) and the eventual decline of the two former species. Duffield et al. (2015) suggest that these three species show a successive ability of tolerance to organic enrichment and subsequent oxygen depletion in the sediment pore water. Our data from the Høgsfjord provide support of this. *N. iridea* is an opportunistic species, and it has been suggested that its opportunism is in response to organic fluxes of phytodetritus (e.g. Duchemin et al., 2005; Gooday, 1986; Gooday and Hughes, 2002; Mackensen et al., 1990). However, *N. iridea* has also been observed to tolerate conditions where there is little or no organic flux (Alve, 2010; Duchemin et al., 2005). It even responded opportunistically in experimental conditions where there was no organic input (Duffield et al., 2014, 2015), probably sustaining itself on food sources (e.g. bacteria) associated with the hypoxic-suboxic boundary related to degrading organic material in the sediment (Duffield et al., 2015). *B. skagerrakensis*, however, has been suggested to be reliant on fresh organic matter (Alve et al., 2011). To complement its preference of feeding on fresh organic material, this species has an epifaunal or shallow infaunal habit. It has been shown to have a preference for occupying the top centimetre of sediment (Duffield et al., 2014, 2015), and the  $\delta^{13}\text{C}$  values of the test suggest it calcifies close to the sediment–water interface (Brückner and Mackensen, 2008). The recently increasing BFAR of these three species in Høgsfjord (Figure 7) may likely be the faunal response to increased organic carbon input. Initially, *B. skagerrakensis* and *N. iridea* could benefit from this organic input but could not tolerate the eventual resultant suboxic pore-water conditions, allowing the opportunistic *S. fusiformis* to dominate in the topmost centimetre of the core (Figure 7) as well as in all three replicate core tops analysed for the live assemblages. *S. fusiformis* has been shown to be an opportunistic species, able to increase its

population by a factor of 7 within a month following a spring phytoplankton bloom, and tolerant of even anoxic sediment pore-water conditions (e.g. Alve, 1994, 2003; Bernhard and Alve, 1996; Gustafsson and Nordberg, 2000, 2001; Filipsson and Nordberg, 2004; Risgaard-Petersen et al., 2006). The high dominance of *S. fusiformis* in the live assemblage suggests the increased organic carbon flux in the Høgsfjord has created suboxic sediment pore-water conditions. At the moment we cannot explain the causes behind the temporal development observed in Høgsfjord. Considering the persistent high oxygen concentration in the bottom water (Figure 2), the Høgsfjord appears to be well flushed with annual deep water renewals (Aure et al., 1993) and the macrofauna reflected 'good' ecological status in both 2008 and 2014 (Lode and Isaksen, 2014). Consequently, the development reflected by the foraminiferal data is likely a local effect, and further investigation is required.

## Conclusion

- We have successfully quantified organic carbon accumulation rates in both space and time in the Høgsfjord and at three sites along the length of the Lysefjord, Western Norway.
- Organic carbon accumulation rates were 14–171 g C m<sup>-2</sup> yr<sup>-1</sup> in the Lysefjord since the early 20th century and 13–41 g C m<sup>-2</sup> yr<sup>-1</sup> since the early 19th century in the Høgsfjord. Both ranges are comparable with the limited data from other fjords.
- The greatest potential for organic carbon accumulation in our study area is at the head of the fjord system, where, because of the influence of the river, sediment accumulation and organic carbon flux are highest.
- C/N ratios show that organic matter is predominantly from a terrestrial source in the innermost Lysefjord with a progressively more marine influence seaward. This fjord-to-coast gradient is also reflected by the δ<sup>13</sup>C in *H. balthica* tests and in the benthic foraminiferal assemblages which show a distinctly different composition from the inner Lysefjord to Høgsfjord.
- Carbon isotopic analyses of *C. laevigata* indicate that it reflects bottom water conditions rather than those in the sediment pore water.
- In the Lysefjord, we observe little overall temporal trend in either organic carbon or the benthic foraminiferal assemblages and the diversity reflects good EcoQS during the time span the cores represent (<100 years).
- Both the geochemical and faunal data from Høgsfjord point to a recent increase in organic carbon accumulation and development from good/moderate to moderate/bad EcoQS which probably is related to local rather than regional conditions.

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