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RESEARCH NOTE

# Can seabirds modify carbon burial in fjords?

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**Summary** Two high latitude fjords of Spitsbergen (Hornsund 77°N and Kongsfjorden 79°N) are regarded as being highly productive (70 g and 50 gC $m^{-2}$ $year^{-1}$) and having organic-rich sediments. Hornsund has more organic matter in its sediments (8%), nearly half of it of terrestrial origin, while most of that in Kongsfjorden (5%) comes from fresh, marine sources (microplankton). Analysis of the carbon sources in both fjords shows that a major difference is the much larger seabird population in Hornsund-dominated with over 100 thousands pairs of plankton feeding little auks in Hornsund versus 2 thousand pairs in Kongsfjorden, and marine food consumption estimated as 5573 tonnes of carbon in Hornsund, versus 3047 tonnes in Kongsfjorden during one month of chick feeding period. Seabird colonies supply rich ornithogenic tundra (595 tonnes of C, as against only 266 tonnes of C in the Kongsfjorden tundra). No much of the terrestrial carbon, flushed out or wind-blown to the fjord, is consumed on the seabed — a state of affairs that is reflected by the low metabolic activity of bacteria and benthos and the lower benthic biomass in Hornsund than in Kongsfjorden.


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## 1. Introduction

Carbon burial in Arctic fjords has recently become the focus of international research efforts, as these coastal areas have been recognized as being disproportionally (to their area) important as regards the carbon sink in the Arctic (Smith et al., 2015). General information on carbon in the Svalbard archipelago sediments was given by Winkelmann and Knies (2005). Coastal areas and fjords of the Svalbard archipelago are characterized by turbid waters derived from intense glacial discharge (Görlich et al., 1987). The Spitsbergen fjords Kongsfjorden and Hornsund are among the best studied Arctic areas (e.g. Hop et al., 2002; Svendsen et al., 2002), from where the most complete data sets are available for modelling and synthesis. Other well-studied Arctic fjords are Godhabsfjord and Young Sound on Greenland (Glud and Rysgaard, 2007), from which detailed information about carbon cycling is available. The data already published indicates that the organic carbon contents in Hornsund and Kongsfjorden differ markedly, since Hornsund is dominated by terrestrial carbon, whereas Kongsfjorden exhibits a higher proportion of fresh marine carbon (Koziorowska et al., 2016; Zaborska et al., 2016). Both fjords receive extensive glacial meltwater discharges estimated at between 0.4 and 1.5 $km^{-3}$ per year (Węsławski et al., 1995). Terrestrial carbon in marine sediments is regarded as a low-quality energy source and should first be transformed by heterotrophic bacteria before it can enter the food web (Glud et al., 1998). There have already been reports on the importance of refractory carbon in Svalbard sediments (Kim et al., 2011). There are several scenarios that may explain the extensive proportion of terrestrial organic matter (OM) in Arctic fjords: washout from melting permafrost (Anderson and Macdonald, 2015), local rocks with carbon ground by glaciers (Syvitski et al., 1987), terrestrial vegetation supplied by rivers (Anderson and Macdonald, 2015; Rysgaard and Sejr, 2007) and retreating glaciers that may release old organic deposits (vegetation). In this paper, we provide data on the terrestrial vegetation around two Spitsbergen fjords against the background of published and archival data on marine carbon sources in them. Our aim is to test the hypothesis that seabirds play an important role in modifying the carbon budget in Arctic fjords.

## 2. Material and methods

### 2.1. Marine biogeochemical sampling

Summer data from 2015 were used for calculating the organic carbon distribution in biota and sediments (stations as in Fig. 1). The three sampling stations in both fjords were carefully selected in order to: (1) represent the central fjord basin, (2) be comparable between and within the fjord, thus the flat, even, soft sediment seabed at 100 m depth was chosen and (3) create a replicate representative for the central fjord basin — the three selected stations were separated by less than 1 N m between each other. As routinely three replicates were collected for each type of sample on each of the three stations, finally at least nine samples of every type were taken from the fjord. All samples were collected during the same cruise in the period of one week in July 2015.

The top 2 cm of sediment was collected from 30 cm long Niemistö cores, and sediment slices were analyzed according to the procedure described in Zaborska et al. (2016). Meiofauna was collected from 10 cm × 10 cm Box Core samples, 2 cm diameter subsamples were collected and analyzed as described in Grzelak et al. (2016), and macrofauna was sampled using Van Veen grabs. All water column samples were collected from the same sites during the same sampling campaign, and details on the methodology are presented in specific works that are cited in Tables 2 and 3. The most important for this paper were carbon analyses, performed in a specialized analytical lab at IO PAN with the use of CHN analyser. The bacterial count in the water column and sediment is given in Ameryk et al. (2017). The pelagic organisms were assessed in Ormanczyk et al. (2017). For recalculating biomass to carbon where no specific data were available, we used, following Kleiber (1961) the relationship: 1 g organism wet weight = 0.25 g dry weight = 0.1 g C = 1 cal = 4.184 J. The carbon consumption by seabirds was recalculated from joules after Węsławski et al. (2006).

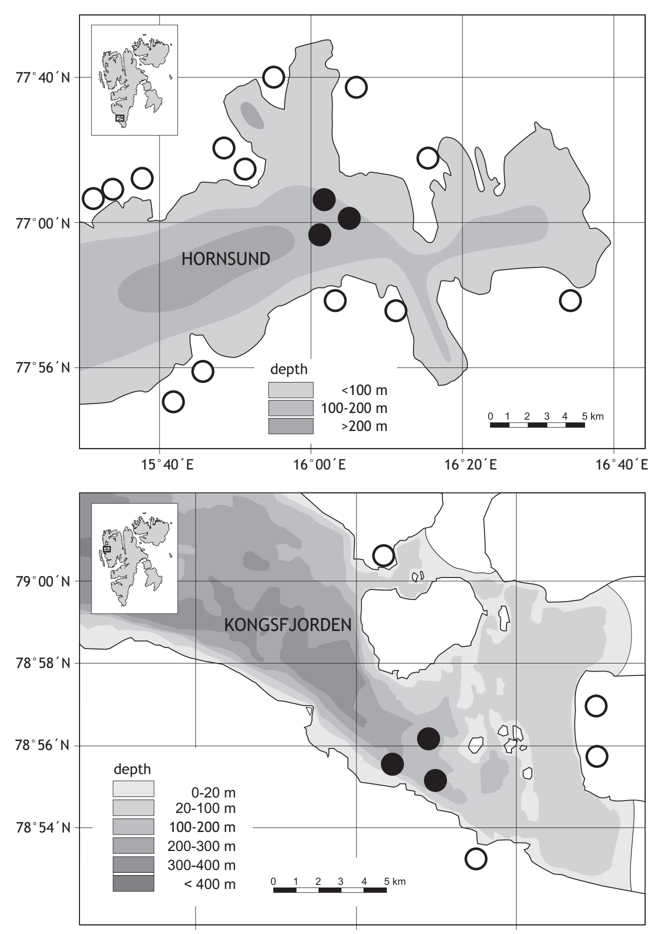


**Figure 1** Study area: black dots — sampling stations of marine biota and sediments in 2013—2014; open circles denote major seabird colonies.

## 2.2. Study area

Two west Spitsbergen fjords of similar size — Hornsund (77°N) 300 km$^2$ and Kongsfjorden (79°N) 210 km$^2$ — have been extensively studied in recent years (see reviews in Drewnik et al., 2016; Görlich et al., 1987; Hop et al., 2002; Svendsen et al., 2002; Węsławski et al., 2017). In many respects the two sites are similar: the occurrence of rapidly melting tidal glaciers, a thick layer of glaciomarine sediments, the absence of a sill in the outer fjord, the ice cover limited to the innermost basins. In general, the shallower Hornsund is more exposed to coastal and cold local waters of Atlantic/Arctic origin, whereas the deeper Kongsfjorden has a good connection with the outer shelf through a deep renna (furrow), which directs warm Atlantic waters into the fjord. Hornsund is dominated by large colonies of little auks, accompanied by kittiwakes and Brünnich's guillemots, whereas much smaller and less dense colonies are present in Kongsfjorden (Węsławski et al., 2006). The seabird colonies in the two fjords have been studied with regard to bird density, foraging, guano production and its influence on ornithogenic tundra plant and animal communities by many authors (Hop et al., 2002; Isaksen and Bakken, 1995; Jakubas et al., 2008; Skrzypek et al., 2015; Stempniewicz et al., 2007; Stempniewicz, 1990; Wojczulanis-Jakubas et al., 2008; Zmudczyńska et al., 2012; Zmudczyńska-Skarbek et al., 2015; Zwolicki et al., 2013).

## 2.3. GIS methodology

The Digital Elevation Model of the Svalbard archipelago with a spatial resolution of 20 m was used to delineate the Hornsund and Kongsfjorden watershed areas. The model is the result of an ongoing project of the Norwegian Polar Institute: it is generated mainly from stereo models and partly from elevation contours, lakes and coastlines. For our project, we used the model updated on 14.01.2015 (Norwegian Polar Institute, 2014). Landsat 8 is the latest satellite in the Landsat Project and has been operational since June 2014; its image quality and geometric accuracy is superior to its predecessors. Cloudless images of the area of interest were acquired from GloVis Viewer (available from the U.S. Geological Survey) to cover the entire watershed areas in summer. For Hornsund the images were taken on 31 July 2015 and for an additional small part of this fjord on 6 July 2015. For Kongsfjorden the image was taken on 7 August 2015. In addition, the vegetation cover on four homogeneous areas by Hornsund was recorded photographically on 1 August 2015. The borders of the polygons with a mean area of 0.3 ha were determined using GPS.

ArcGIS software (ESRI, 2015) was the main data processing tool. The DEM model was preprocessed to match the glacier margins on the satellite images by clipping the land part of DEM by land polygons. The watershed areas were delineated using a standard spatial analysis procedure that uses a flow direction raster. Each band of Landsat scenes was first converted to TOA reflectance with correction for the Sun's angle according to the USGS Landsat 8 product instructions (USGS, 2015). Following this, an atmospheric correction using dark object subtraction (DOS) was carried out, assuming as 1% surface reflectance from dark objects (Chavez, 1988).

The intensity and density of green vegetation can be estimated using the remote-sensing Normalized Differential Vegetation Index (NDVI). This index is often used because it compensates for variable factors like illumination, slopes and aspects (Lillesand et al., 2004). Two bands are used to calculate this index: the red band (R), with a high absorption of chlorophyll, and the near-infrared band (NIR), which accounts for the relatively high reflectance of vegetation. The difference in reflectance of the two bands is divided by the sum of reflectances in the same two bands to normalize for differing illumination conditions (NDVI = (NIR − R)/(NIR + R)). Using the corrected reflectance for bands 4 and 5 of Landsat 8, the NDVI indexes were calculated for both watershed areas as raster layers with a spatial resolution of 30 m.

NDVI has been used by several researchers for modelling numerous biophysical properties of arctic tundra, including the above-ground phytomass. The quantitative phytomass sampling method was described by Walker et al. (2003) and then used by other researchers (Johansen and Tømmervik, 2013; Raynolds et al., 2006). They all used the regression model to find the relation between NDVI and phytomass. Several researchers discovered linear relationships between NDVI and phytomass, but for a larger range of NDVI the relationship takes a curved form (Raynolds et al., 2006). In our project we used the formula originally proposed by Walker et al. (2003) and modified by Raynolds et al. (2006) in the form Phytomass = 26.58 * EXP(6.9357 * NDVI). This formula gives similar results to the one used by Johansen and Tømmervik (2013) for Svalbard. However, the main limitation of their formula is the narrower range of NDVI values than those we obtained. As low phytomass values ($<$200 g m$^{-2}$) in Svalbard conditions indicate a partial cover of mainly lichen and moss with no peat layer, the contribution of such a vegetation subzone to the carbon flux as a result of surface run-off will be negligible. Consequently, only phytomass values $>$200 g m$^{-2}$ were summed for both watershed areas (Table 1). According to Walker et al. (2003) this method in similar conditions of Alaska gave a relative standard errors of about 15% of estimated values.

## 3. Results

The areas analyzed for terrestrial vegetation ranged from 1150 km$^2$ in Hornsund to 1449 km$^2$ in Kongsfjorden (Fig. 2). Four types of terrestrial vegetation were identified for the biomass calculations (Fig. 3a) (a) sparse, dry vegetation on stony and gravel substrata, (b) poor moss tundra on semi-dry land, (c) wet rich moss tundra and (d) rich ornithogenic vegetation with variable plants and a high biomass. Four categories of biomass were associated with the areas of particular vegetation types (Table 1). The overall calculation yields 595 tonnes of carbon in the terrestrial vegetation around Hornsund, compared to 266 tonnes in the Kongsfjorden area.

## 4. Discussion

How representative are presented data for the seasons, interannual variability and regional scale? The circulation models published for the Spitsbergen fjords (Ingvaldsen

**Table 1** Areas and land vegetation biomass (July–August 2015).

| Biomass class [wet weight g m$^{-2}$] | Hornsund [km$^{-2}$] | Hornsund estimated biomass (595 tonnes C) | Kongsfjord [km$^{-2}$] | Kongsfjord estimated biomass (266 tonnes C) |
|---|---|---|---|---|
| 0–100 | 115 | 42 | 168 | 47.12 |
| 100–250 | 14 | 156 | 22 | 147 |
| 250–500 | 5 | 345 | 2.8 | 323 |
| 500–1000 | 2.6 | 695 | 0.81 | 698 |
| 1000–2500 | 1.1 | 1421 | 0.33 | 1453 |
| 2500–more | 0.08 | 3135 | 0.027 | 2905 |

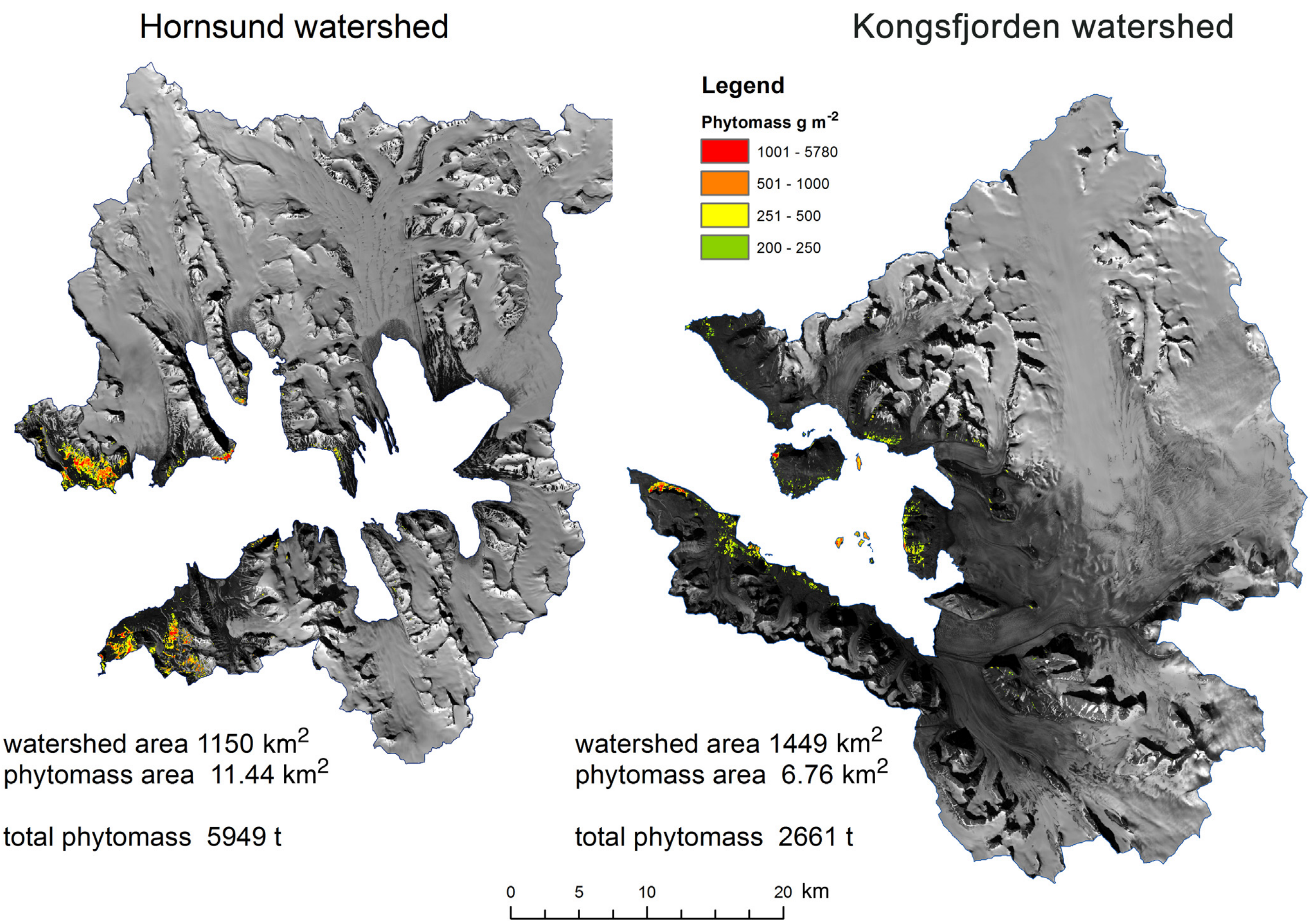


**Figure 2** Hornsund and Kongsfjorden water shed areas and terrestrial vegetation cover.

et al., 2001; Jakacki et al., 2017) show that our sampling sites were placed in the gyre that is formed in the central fjord part, and is separated hydrologically from both innermost fjord basins (where the water used to be more stagnant) and outer fjord part (with frequent water exchange with shelf). The seasonal aspect (samples were collected in the mid of summer) represents situation after the peak of vegetation period and settling the bloom in Spitsbergen fjords (Węsławski et al., 1988). As most of the benthos of Svalbard are long living (perennial) species, the seasonal difference in biomass and density is low (Berge et al., 2015), and summer sampling shows the peak of the annual growth, the general – annual situation. Carbon accumulation in the sediment is an integrated value of year-long processes and is not very changeable (Pawłowska et al., 2011), hence our data are comparable in two analyzed fjords and likely representative for the given spatial scale and time.

Seston (dead organic matter suspended in the water column) contributes 45% of the carbon in Hornsund and 33% in Kongsfjorden (Table 2). The carbon stored in living organisms (biomass) in the water column differs between fjords in some important aspects: there are more bacteria and microplankton in Hornsund, whereas macroplankton is more important in Kongsfjorden (Fig. 4).

The percentage of detritus in sedimentary organic carbon is even higher than in the water column, with values of 97%

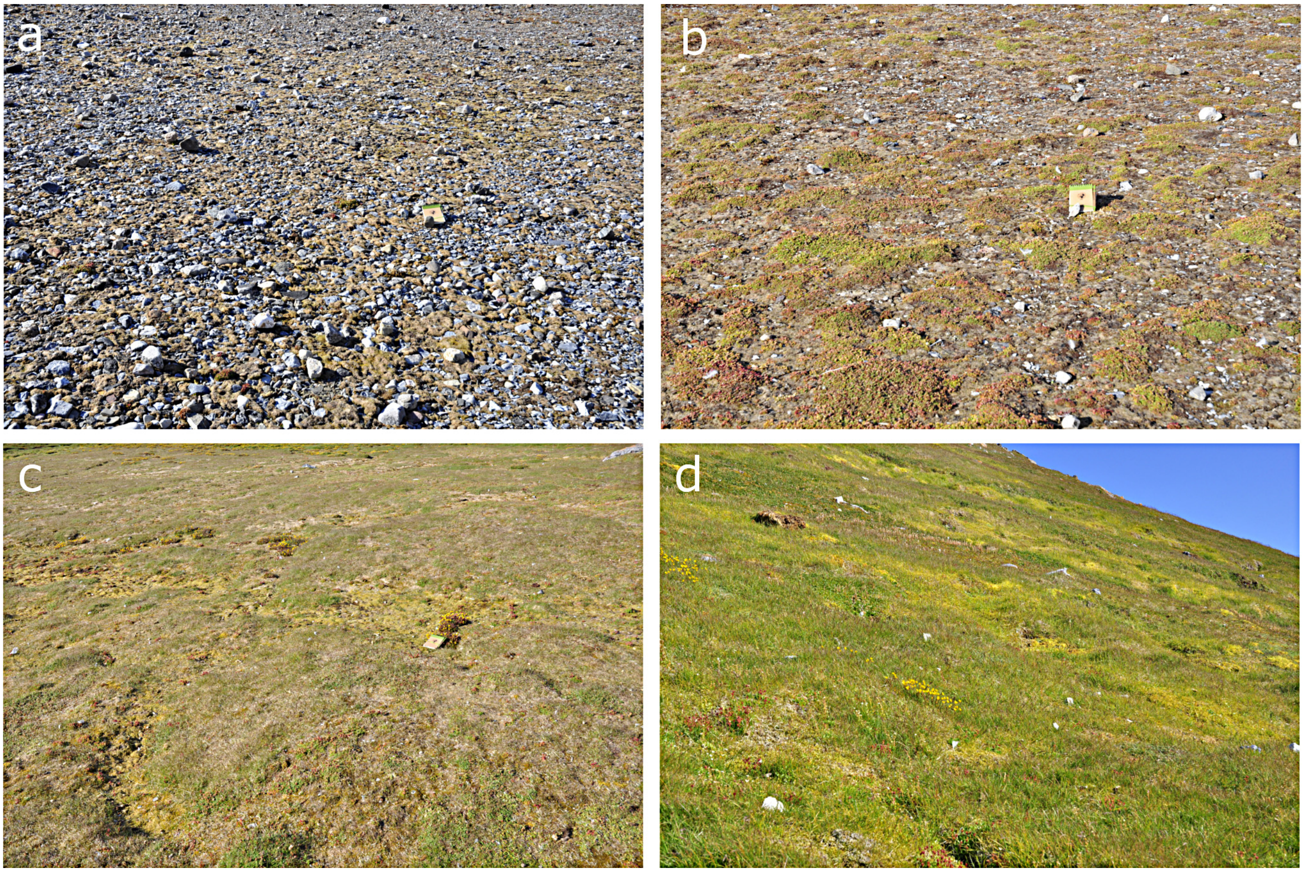


**Figure 3** Types of terrestrial vegetation used for calculating biomass in Hornsund and Kongsfjorden.

**Table 2** Carbon sources in both fjords (summer biomass values); the total carbon content calculated for each fjord is given in brackets.

| Biomass source | Hornsund | Kongsfjorden | Reference |
|---|---|---|---|
| Microplankton [gC m$^{-2}$] (100 m water column) | 0.8 (94 tC) | 2.5 (70 tC) | Smoła et al. (2016) |
| Mesozooplankton [gC m$^{-3}$] | 0.050 (549 tC) | 0.075 (893 tC) | Ormanczyk et al. (2017) |
| Macroplankton [gC m$^{-3}$] | 0.040 (140 tC) | 0.135 (415 tC) | Ormanczyk et al. (2017) |
| Fish [tC fjord$^{-1}$] | 2.2 | 18.8 | Szczucka et al. (2017) |
| Pelagic bacteria [gC m$^{-2}$] (100 m water column) | 1.2 | 0.7 | Ameryck et al. (2017) |
| Meiofauna [gC m$^{-2}$] (top 1 cm) | 0.45 (58 tC) | 0.2 (63 tC) | Grzelak et al. (2016) |
| Macrofauna [gC m$^{-2}$] | 4 (791 tC) | 10 (1413 tC) | Zaborska et al. (2016) |
| Benthic bacteria [gC m$^{-2}$] (top 1 cm) | 0.11 | 0.52 | Ameryck et al. (2017) |
| Macroalgae [tC fjord$^{-1}$] | 1282 | 1936 | Smoła et al. (2016) |
| Terrestrial vegetation [tC fjord$^{-1}$] watershed area | 600 | 290 | Present work |
| Food consumed by sea birds in July (30 days) [tC fjord$^{-1}$] | 5573 | 3047 | Węsławski et al. (2006) |
| Organic carbon in suspended matter [mgC dm$^{-3}$] | 0.19 | 0.33 | Present work |

and 81% in Hornsund and Kongsfjorden, respectively (Table 2). The biomass proportion in the sediment shows the greater importance of meiofauna in Hornsund and the greater significance of macrofauna in Kongsfjorden (Fig. 5).

Carbon accumulation and burial is greater in Hornsund (Table 3), whereas carbon mineralization is disproportionally higher (3 vs. 50%) in Kongsfjorden, owing to the fresh, marine origin of organic matter (up to 50% in Hornsund and up to 80% in Kongsfjorden) (Table 3). The rates of carbon accumulation in the surface sediments of both fjords are almost equal (42.6 and 32.5 gC m$^{-2}$ year$^{-1}$), although the carbon content per gram of sediment in Hornsund is more than twice as high as in Kongsfjorden (Table 2). These differences result from the fact that the sediment accumulation rate in Kongsfjorden is twice as fast as in Hornsund. Carbon accumulation in the surface sediments of both fjords was higher than the highest values reported for Storfjorden in Svalbard — from 5.5 to 17.2 gC m$^{-2}$ year$^{-1}$ (Winkelmann and Knies, 2005) — as well

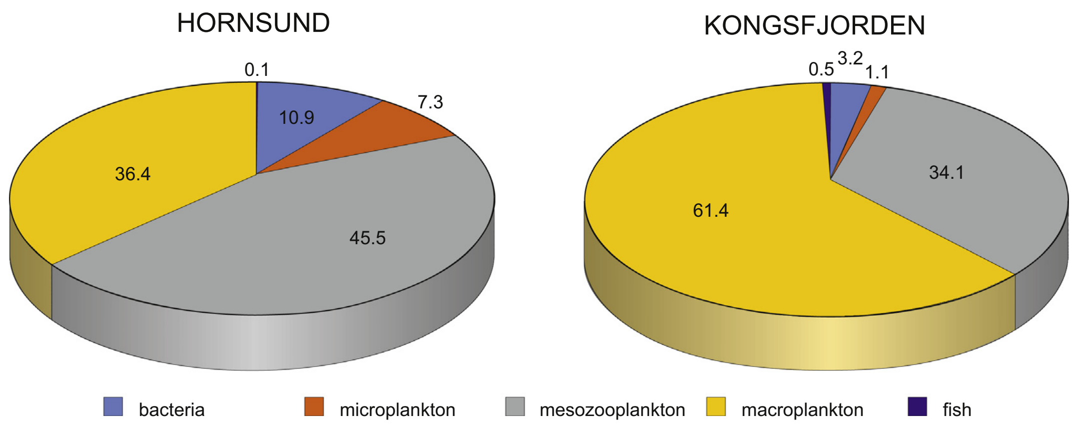


**Figure 4** Percentage of biomass in the water column of the two fjords — expressed in gC $m^{-3}$ (for data, see Table 2).

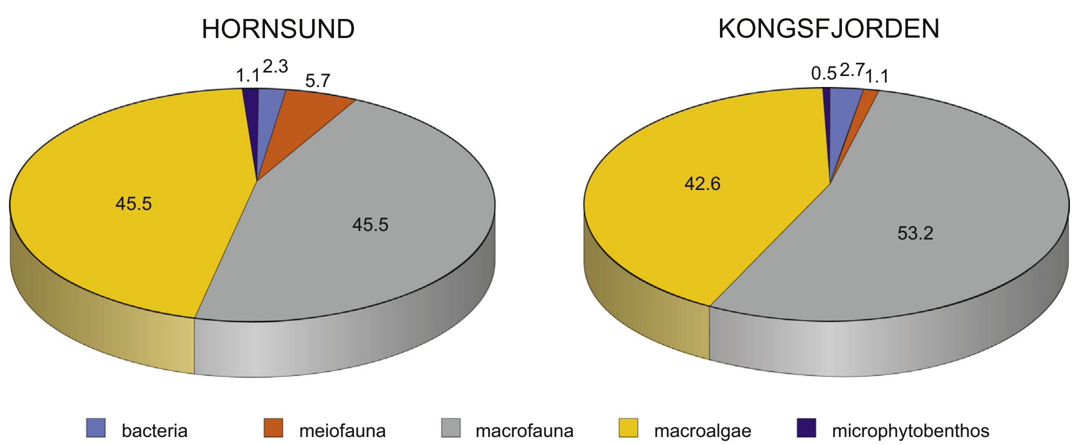


**Figure 5** Percentage of organic carbon in sediment — expressed in gC $m^{-2}$ (for data, see Table 2).

**Table 3** Carbon fate in the two fjords.

| Process | Hornsund | Kongsfjorden |
|---|---|---|
| Carbon content in sediment [gC $m^{-3}$] (top 1 cm) | 252.4 | 98.3 |
| Carbon content in sediment [mg $g^{-1}$] | 14.2 | 5.46 |
| Carbon accumulation [gC $m^{-2}$ $year^{-1}$] (top 1 cm) | 43.2 | 32.5 |
| Mass accumulation rate of sediment [g $m^{-2}$ $year^{-1}$] | 3041 | 5947 |
| Carbon burial [gC $m^{-2}$ $year^{-1}$] | 41.4 | 16.3 |
| Carbon mineralization (in top 20 cm) [gC $m^{-2}$ $year^{-1}$] | 1.3 (3%) | 16.2 (50%) |

Modified from Zaborska et al. (2016).

as those from a Greenland fjord (Glud et al., 1998). In Young Sound (NE Greenland), the benthic carbon mineralization was 70% per annum (Thamdrup et al., 2007).

In general, the seabirds in Spitsbergen colonies feed their nestlings between mid-July and mid-August. During that brief period most of the marine food is carried to the colonies, where excreta and food remnants discarded by juveniles and adults become buried; during the rest of the year, the birds feed and excrete mostly away from the nesting area (Stempniewicz et al., 2007; Stempniewicz, 1990). Carbon burial is effectively enhanced in a bird-dominated fjord, compared to a bird-poor fjord (Figs. 6 and 7).

The type of the seabirds' food plays a substantial role in biogeochemistry: Zwolicki et al. (2013) presented the difference in N and P deposition in two types of seabird colonies in Hornsund: more P in fish eaters (kittiwakes and Brünnich's guillemots) and more N in the colonies of crustacean eaters (little auks).

Assumptions of the birds excreta nutrition effect on the coastal marine ecosystem and relations between bird colony

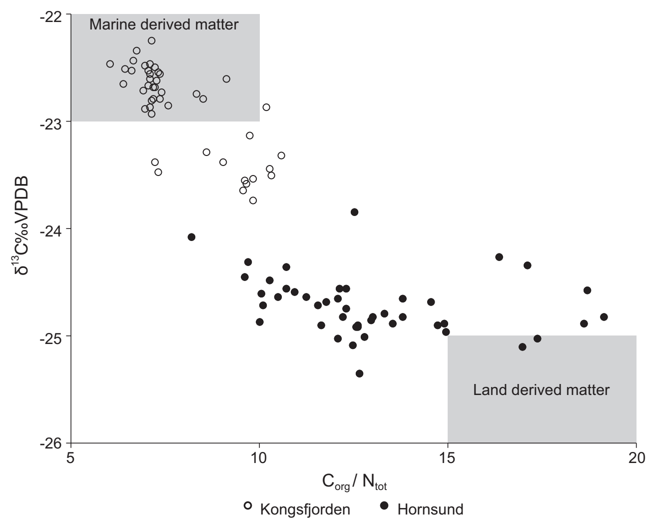


**Figure 6** Origin and degree of degradation of organic matter in surface sediments in Kongsfjorden and Hornsund. Modified from Zaborska et al. (2016).

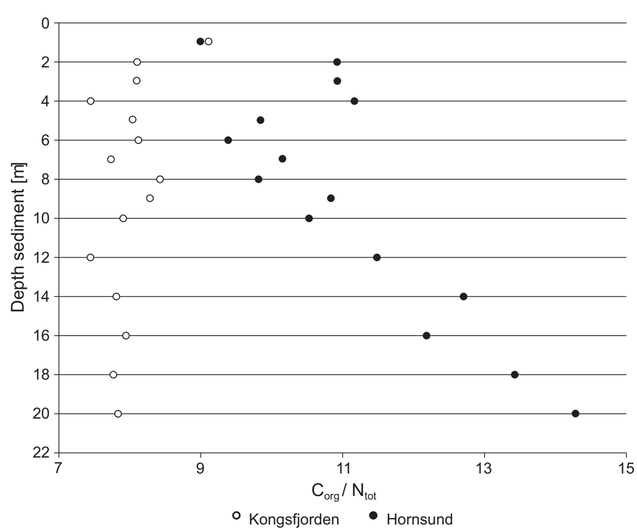


**Figure 7** Degree of decomposition of organic matter in surface sediments (Kongsfjorden and Hornsund).
Modified from Zaborska et al. (2016).

and adjacent waters were discussed in the literature (Stempniewicz, 1990; Wainright et al., 1998; Zelickman and Golovkin, 1972).

Assuming here that 10% of the terrestrial plant biomass is lost annually through weathering and being washed into the sea, we obtained 0.2 gC m$^{-2}$ of seabed, whichmakes an important contribution to the carbon balance of the fjords. If to this we add direct input from seabirds — assuming that 10% of the seafood delivered to the colonies ends up there as excreta and leftovers — we have at least 500 and 300 tonnes of C delivered to the two fjords annually (during one month of chick feeding), an amount similar to that estimated from tundra carbon.

The high percentage of terrestrial organic matter can be explained by the higher amount of organic carbon stored in the ornithogenic tundra (Table 3), which yields 595 and 266 tonnes of carbon in Hornsund and Kongsfjorden, respectively.

Another possible explanation for the disproportionally high terrestrial proportion of organic carbon in Hornsund might be a riverine outflow. However, there are only small rivers in both areas, discharging between 0.03 and 0.095 km$^3$ year$^{-1}$ according to Lefauconnier (personal communication) and Węsławski et al. (1995). This is in contrast to Young Sound (NE Greenland), where a riverine discharge ranges from 0.1 to 0.3 km$^3$ per annum (Mernild et al., 2007), thereby providing 1—6 thousand tonnes of terrestrial carbon, which is equal to 40% of the local sediment carbon pool (Mernild et al., 2007; Rysgaard and Sejr, 2007).

The different rocks that are ground by the glaciers may also carry different carbon loads, but there is no statistical difference in the proportion of organic carbon in glacial suspensions in the two fjords (Zaborska et al., 2016). Suspended POC in both fjords contains almost pure marine fresh carbon in summer (Zaborska et al., 2016), which suggests that terrestrial carbon is delivered as a bedload transport or that it sinks faster than the marine component. A further possibility, but which is very difficult to verify, is the release of organic deposits from below the glacier foot (tundra) from previous warm periods (the climate optimum 7—9 thousand years ago) — J. Jania, personal communication. Yet another possibility of terrestrial carbon transport is advection, often regarded as a key factor in fjord biogeochemistry (Aksnes et al., 1989), but the West Spitsbergen Current that supplies water to both fjords does not carry measurable amounts of terrestrial carbon (Kuliński et al., 2014; Winkelmann and Knies, 2005).

There is a growing amount of information that glaciers may supply fjords with much more than freshwater alone — there are nutrients, organic carbon from aerial deposition, mineral and refractory carbon as well as the microbes (Hagvar et al., 2016; Wynn et al., 2007).

We need to learn more about the melting glacier contribution to carbon budget in fjords, yet from the information available the seabirds and their nutrition input into ornithogenic tundra are the most likely explanation of high values of terrestrial carbon in Hornsund fjord sediments.

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