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SHORT REPORT FOR CHARR SPECIAL ISSUE

Marine organisms transported by seabirds may contribute significantly to Arctic charr diet in coastal High-Arctic lakes

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Abstract
The rich marine resources along the western coast of Spitsbergen (Svalbard) have given rise to colonies of breeding seabirds, which likely represent an important vector of nutrient transport from marine to terrestrial environments. These seabirds may also supply additional nutrients to lakes via their droppings, while bathing and/or when being attacked by other birds during flight to their nest sites. To study the importance of such droppings in the diet of freshwater fish, we sampled Arctic charr by gillnetting during a three-week period in the oligotrophic Lake Arresjøen in northwestern Svalbard. Marine fish and invertebrates made up more than 12% of the dry weight of the stomach contents of Arctic charr larger than 24 cm captured in the littoral zone. This suggests that the seabird transport of marine organisms contributes directly to the diet of Arctic charr in coastal High-Arctic lakes, but this contribution may also give a higher load of mercury and polychlorinated compounds.

Keywords Seabirds · Marine nutrients · Droppings · Fish diet

Introduction

High-Arctic lakes are characterized by short ice-free periods (1–3 months), low water temperatures, low nutrient input, low primary production, and often with Arctic charr *Salvelinus alpinus* being the only freshwater fish (Hammer 1989). Even in clear-water Arctic lakes, annual phytoplankton production is generally low, in the range of 4–8 g cm^{-2}, with far lower production in turbid lakes (Hobbie 1964). The zooplankton biomass is similarly low in Arctic lakes (Hammar 1989), and zooplankton usually accounts for a small part of the Arctic charr diet (Svenning et al. 2007). The input of terrestrial carbon to Arctic lakes seems to be low as well (Hecky and Hesslein 1995), mainly due to the absence of bushes and trees which contribute a large amount of allochthonous material to lakes in subalpine areas (Larsson et al. 1978).

In some Arctic areas, however, seabirds may represent important linkages between their marine feeding areas and their terrestrial breeding environments and may provide significant quantities of marine-derived nutrients (Polis et al. 2004), leading to increased production, especially in nutrient-limited lakes in the High Arctic. For instance, on the northwestern coast of Spitsbergen, Svalbard, rich marine resources have given rise to seabird colonies with thousands of breeding individuals, which are transporting, not only large amounts of guano (excrement) into lakes' catchment areas (Evenset et al. 2007), but also marine invertebrates and fish directly into lakes. In a small lake situated on Amsterdam Island, in northwestern Spitsbergen, Svalbard, the presence of feathers, bird droppings, and remains of marine crustaceans as well as marine fish was found in some stomachs of Arctic charr (Hammar 2000). Although the lake is situated around 2–3 m above sea level and separated from the sea by an approximately five meter mounds, the stomach contents found in the Arctic charr stomachs indicated a marine source of food provided by the various marine bird species observed visiting this coastal lake (Hammar 2000). In the coastal lake Nordlaguna, Jan Mayen, separated from the sea by a sand bank and situated only 1–2 m a.s.l. (see Larsen et al. 2021), Skreslet (1973) also found herring scales in some stomachs of Arctic charr.

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As far as we know, records from Hammar (2000) and Skreslet (1973) represent the only findings of a partly marine diet in the landlocked Arctic charr and, although their findings were from lakes located very close to the sea, the potential importance of a marine diet in Arctic freshwater fishes should not be ignored. During a survey in late summer in Lake Arresjøen on Danskøya, northwestern Spitsbergen, Svalbard, we observed several attacks by Arctic Skuas (*Stercorarius parasiticus*) and Glaucous gulls (*Larus hyperboreus*) on seabirds returning from sea and, in some cases, the attacked birds dropped their prey which sometimes ended up either in the lake or areas around the lake.

According to the findings of Hammar (2000) and Skreslet (1973), we hypothesized that these droppings might represent a significant food resource for the landlocked Arctic charr population in the lake. We captured fish by gillnetting, and analyzed their stomach contents to confirm whether dropped prey items from seabirds were picked up by Arctic charr and to evaluate the contribution of allochthonous marine food in the diet of Arctic charr.

Materials and methods

Study area. Lake Arresjøen (79°40′ N, 10°47′ E) is situated on Danskøya, northwestern Spitsbergen, Svalbard (Fig. 1). The lake is small (0.35 km^2) with a maximum depth of 32 m, located in a low valley about 250 m from the seashore and 15 m a.s.l. Unlike most lakes on Svalbard, Arresjøen receives only minor drainage from glaciers, and surface drainage is poor. The permafrost seals the subsoil, and snow melt only provides a flush of water in late spring. The length of the ice-free season is approximately 2–3 months, i.e., the lake is ice covered for about 9–10 months each year from around September/October to June/July, with ice thicknesses up to 1.8–2 m in late May. In late summer (August), the water column is completely mixed, with temperatures ranging from around 6.5 °C at the surface to 6.3 °C at the bottom (Svenning 2015). Transparency (Secchi depth) is around 7.5 m. Lake Arresjøen is oligotrophic but probably receives nutrients from seabirds nesting in the catchment. Arctic charr—the only freshwater fish in Lake Arresjøen—is landlocked, i.e., sea ascendance is impossible (Svenning and Borgstrøm 1995).

Fish sampling in Lake Arresjøen was performed by gillnetting in the littoral (0–15 m), pelagic, and profundal zones (15–32 m) from 26 July to 13 August 2002. Gillnets with mesh sizes 8, 10, 12.5, 15, 18.5, 22, 26, 33, 39, and 45 mm (bar mesh) were used. The gillnets used in the littoral and profundal zones were 40 m long and 1.5 m in height, while those set from the surface in the pelagic zone were 40 m long and 3 m in height. The nets were set in the afternoon and pulled or checked the day after. Each fish was measured (fork length; nearest to 1 mm) and weighed (wet weight; nearest to 1 g). The size of the sampled Arctic charr varied from 100 to 621 mm ($n = 326$). Most fish were caught in the littoral ($n = 179$) and profundal zone ($n = 163$), while only 6 individuals were caught in the pelagic zone. The mean size of the sampled fish was 250 (100–621; $std = 160$), 144 (100–530; $std = 67$), 297 (100–582; $std = 222$) mm, in the littoral, profundal, and pelagic habitat, respectively. Shortly after capture, each stomach was cut at the upper esophagus

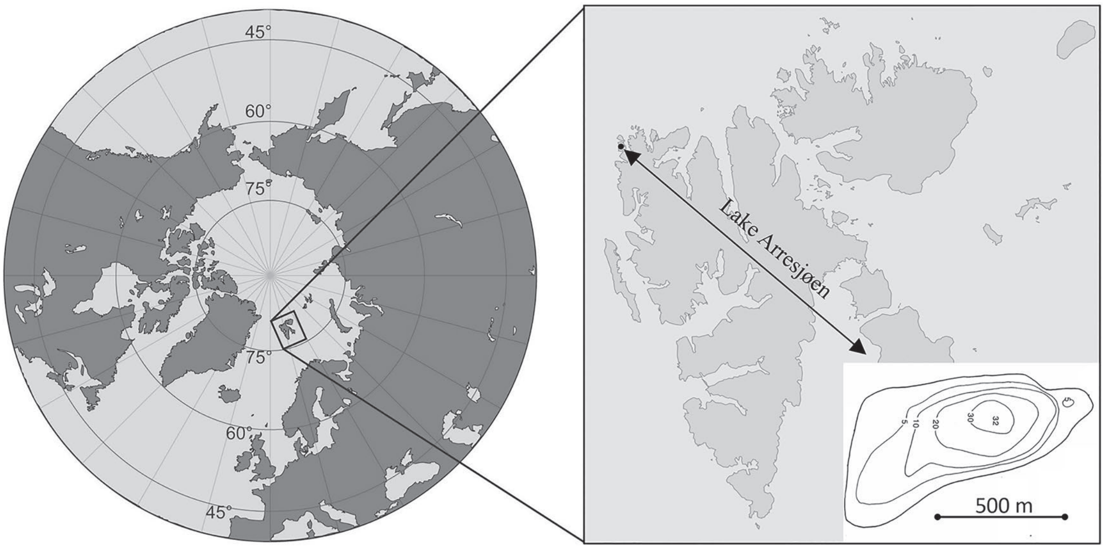

Fig. 1 Location and contour map of Lake Arresjøen, Svalbard, with contour lines (5, 10, 20, and 30 m)

and at the pyloric sphincter, and the content was preserved in 96% ethanol until examined in the laboratory. In the laboratory the stomachs were opened and the percentage degree of fullness (0 to 100%) was determined, i.e., this is like the points method described by Hynes (1970) but employs a percentage scale. A total of 118, 39, and 6 stomachs from charr captured in the littoral, profundal, and pelagic habitats were examined, and stomach content was found in 94, 37, and 4 individuals, respectively (Fig. 2). Food items were identified and sorted, and each prey category was dried at 70 °C for 72 h, then weighed to the nearest 0.001 g, and their relative contribution (%) to stomach fullness was estimated. Sagittal otoliths were removed from the fish, preserved in 96% ethanol with a small amount of glycerol, and were used for age determination. Arctic charr otoliths from Svalbard have a distinctive zonal differentiation between summer and winter increments, even among old individuals (see Svenning et al. 2024). Thus, age determination was carried out without any additional treatment or preparation of the otoliths, except placing them in glycerol and then viewing them under a binocular microscope. Otolith/fish ages (300 out of 348 sampled fish) varied from 4 to 29 years, and with average age being 10 years (*std* 4.8 years). The five fish with marine diet were 18–24 years old.

We observed a rich bird community at the lake during the fieldwork. Both Brünnich's guillemots (*Uria lomvia*) and little auks (*Alle alle*) were nesting in cliffs around Lake Arresjøen. We also observed Arctic skuas and Glaucous gulls often attacking especially Brünnich's guillemots when they arrived from the sea with marine food/fish in their beaks. Glaucous gulls were also observed preying on young auks when they started their 'test flying' after departing from their natal nests. We also witnessed red-throated divers (*Gavia stellata*) and Arctic terns (*Sterna paradisaea*) at or on the lake, probably searching for Arctic charr.

Results

Chironomids, mainly *Microspectra insignilobus* and *Oliveridia tricornis*, dominated the diet of small-sized (10–18 cm) Arctic charr (Table 1). The Trichopteran species *Apatania zonella* was also quite frequent in diet of small-sized Arctic char, especially in the profundal zone. For larger Arctic charr (>24 cm), juvenile charr dominated their diet (>85%). However, marine organisms were also important, making up >12% of the dry weight of the diet of Arctic charr (>24 cm) captured in the littoral zone, i.e., this was the second-most important prey category for this size class (Table 1).

In total, marine prey was found in five Arctic charr, all caught in the littoral zone. The length of these five Arctic charr were in the range of 40.7–52.2 cm, amounting to 11% of captured fish larger than 40 cm. One of these Arctic charr had eaten marine crustaceans, one had eaten a sea urchin (*Irregularia*), two had eaten Polar cod (*Boreogadus saida*), and one had eaten a cottid. The length of the marine prey fish was in the range of 10–12 cm. Three of these Arctic charr had also eaten chironomids and/or caddies flies, while the two specimens consuming marine fish, had no freshwater prey items in their stomach.

The area around Arresjøen was not systematically searched, but several Polar cod were observed along the shoreline in the western end of the lake where especially Brünnich's guillemots were observed flying from the ocean and being attacked by Arctic Skuas and Glaucous gulls.

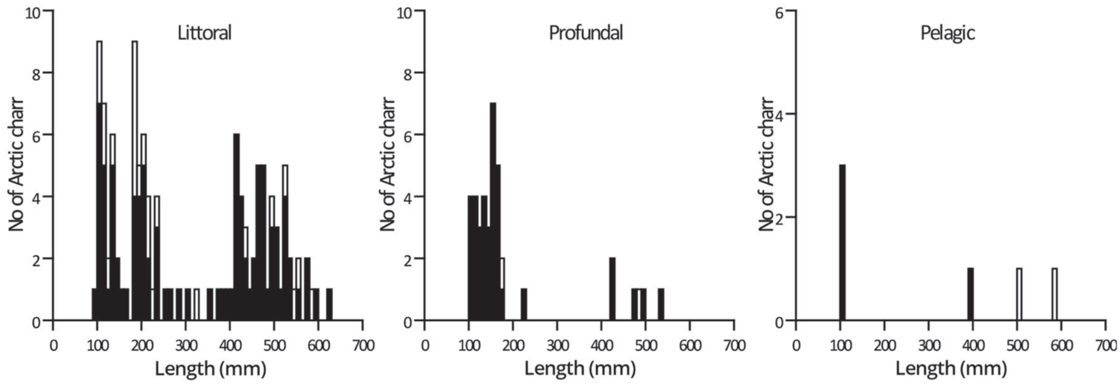

Fig. 2 Length distribution of landlocked Arctic charr sampled by gillnets in Lake Arresjøen, Svalbard, 26 July–13 August 2002, and examined for stomach contents. *Filled* and *open bars* reflect fish with and without stomach contents, respectively

Table 1 Stomach contents of different size groups of landlocked Arctic charr captured by gillnets in the littoral, pelagic, and profundal zones in Lake Arresjøen in 2002. The relative volume of various food items is based on identified food items being dried at 70ºC for three days, weighed to the nearest 0.001 g, and presented as their relative contribution

	Littoral zone			Pelagic zone			Profundal zone		
	10–18 cm	18–24 cm	>24 cm	10–18 cm	18–24 cm	>24 cm	10–18 cm	18–24 cm	>24 cm
No. of stomachs with content	23	18	53	3		1	31	1	5
Mean degree of fullness (%)	48.5	75	18.5	76.7		9.9	53.8	9.5	33.9
Autochthonous (lake)									
Chironomidae (l, p & i)	82.6	9.8	1.8	2.8		90	38.6	95.6	
Apatania zonella (l, p & i)	13.6	2.1	1.4				55.8	4.4	
Cyclopoid copepods	1.6	1.6		97.2		10			
Chydorinae cladocerans							3.8		
Ostracods	1.4	0.8					1.8		
Springtails	0.8								
Arctic charr		85.7	84.7						100
Allochthonous (marine)									
Crustaceans			0.8						
Sea urchin			0.8						
Polar cod			8.4						
Cottidae			2.4						

Degrees of fullness range from 0 to 100%

Larvae (*l*), pupae (*p*), and imagines (*i*) of chironomids and Apatania zonella are merged

Discussion

Large individuals of old Arctic charr in Lake Arresjøen feed almost exclusively on conspecifics but, as documented in the present study, marine fish and invertebrates dropped by seabirds were their second-most eaten food items. The diet analysis of Arctic charr from Lake Arresjøen was based on samples from late July to mid-August, i.e., at the end of the breeding season for the marine birds around the lake. During the peak breeding season (mid-June to mid-July), the transport of marine food to birds' nesting sites is probably far greater, implying an increased number of droppings of marine food and, accordingly, the contribution of marine organisms in the Arctic charr diet is probably higher in the first part of summer (July). Thus, marine organisms may contribute significantly to the total diet of large Arctic charr in Lake Arresjøen during the ice-free period. The findings from our study and of Hammar (2000) who also sampled Arctic charr late in the season (23 August) in Lake Annavatn suggest that this represents a more common phenomenon in High-Arctic areas, i.e., with seabirds transporting marine food which end up in an aquatic food web and become a highly integrated part of the energy budget of large Arctic charr.

It is well known that seabirds transport vast quantities of marine-derived nutrients and pollutants to terrestrial environments, including freshwater lakes (Polis and Hurd 1996; Blais et al. 2005; Evenset et al. 2007; Choy et al. 2010; Zwolicki et al. 2013; Ziółek and Melke 2014). These allochthonous marine inputs probably increase the primary production in lake systems, especially in High-Arctic areas like the western part of Svalbard, where large seabird colonies are found (Anker-Nilssen et al. 2000). In addition, the transport of organic material from the ocean may increase the load of persistent organic pollutants and mercury both in the lake sediments and in the fish. Rognerud et al. (2002) found that the mean concentrations of Hg and sum of PCBs in Arctic charr in Lake Arresjøen were 0.2 $\mu g\ g^{-1}$ and 23 $ng\ ng^{-1}$, respectively. The largest and oldest Arctic charr in Lake Arresjøen even had Hg concentrations exceeding the guideline (0.2 $\mu g\ g^{-1}$) for subsistence fish consumption (Braune et al. 1999). The high concentrations of mercury and POPs found in large/old Arctic charr from this lake (Rognerud et al. 2002) may thus be a combined effect of bioaccumulation and a diet consisting of both small-sized Arctic charr and marine organisms.

The findings from our study, as from Skreslet (1973) and Hammar (2000), suggest that droppings of marine organisms from seabirds represents a common phenomenon in High-Arctic areas, and become a highly integrated part of the energy budget of large Arctic charr. However, at the same time, the food of marine origin may contribute to increased contamination with POPs and mercury, which makes the fish less valuable as human food.

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Declarations

Conflicts of interest The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Ethics approval The authors declare that all applicable international, national, and/or institutional guidelines for sampling, care, and experimental use of fishes for the study were followed, and all necessary approvals were obtained.

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