



Title	Diets and body condition of polar cod (<i>Boreogadus saida</i>) in the northern Bering Sea and Chukchi Sea
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5 **Diets and body condition of polar cod (*Boreogadus saida*)**

6 **in the northern Bering Sea and Chukchi Sea**

7

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20

21 **Abstract** To understand trophic responses of polar cod *Boreogadus saida* (a key species
22 in Arctic food webs) to changes in zooplankton and benthic invertebrate communities
23 (prey), we compared its stomach contents and body condition between three regions
24 with different environments: the northern Bering Sea (NB), southern Chukchi Sea (SC),
25 and central Chukchi Sea (CC). Polar cod were sampled using a bottom trawl and their
26 potential prey species in the environment were sampled using a plankton net and a
27 surface sediment sampler. Polar cod fed mainly on appendicularians in the NB and SC
28 where copepods were the most abundant in the environment, while they fed on
29 copepods, euphausiids, and gammarids in the CC where barnacle larvae were the most
30 abundant species in plankton samples on average. The stomach fullness index of polar
31 cod was higher in the NB and SC than CC, while their body condition index did not
32 differ between these regions. The lower lipid content of appendicularians compared to
33 other prey species is the most plausible explanation for this inconsistency.

34

35 **Keywords:** gelatinous zooplankton, lipid content, prey availability, regional differences,
36 stomach fullness

37

38

Introduction

39 Arctic marine communities are experiencing changes in the timing of formation and
40 retreat of sea ice and increases in seawater temperatures (Leu et al. 2011, Grebmeier
41 2012). Polar cod (*Boreogadus saida*) is an abundant epipelagic fish found throughout
42 the Arctic Ocean (Ponomarenko 1968; Bradstreet et al. 1986; Cohen et al. 1990), which
43 feeds on pelagic zooplankton (copepods, hyperiids) and benthic crustacean (gammariids
44 and mysids; Craig et al. 1982; Rand et al. 2013), and is an important food for other fish,
45 marine mammals and seabirds (Welch et al. 1992). Thus this species is a key component
46 in Arctic marine food webs (e.g., Hop and Gjørseter 2013). To understand how changes
47 in Arctic marine food webs may impact polar cod, a study of their trophic responses
48 (changes in diet and energy stores) to differences in zooplankton and benthic
49 invertebrate communities across regions with different environments was conducted.

50 The diets of polar cod have been studied in the Bering, Chukchi, and Beaufort
51 seas (Lowry and Frost 1981), the northern Bering Sea (Cui et al. 2012), the northeastern
52 Chukchi Sea (Coyle et al. 1997), and the western Beaufort Sea (Rand et al. 2013). These
53 studies reported that polar cod opportunistically fed on prey species that were available
54 in a given depth range and region. Thus, regional differences in their stomach contents
55 may reflect prey selection by polar cod and regional variations in prey availability.
56 Further, regional variations in the abundance and quality of diets, i.e., lipid content, as
57 well as marine physical conditions including water temperature, may influence growth
58 rates of polar cod (Hop et al. 1997).

59 To understand how regional differences in the availability of zooplankton and
60 benthic invertebrates relate to the diet, feeding success and energy stores of polar cod,
61 we examined their stomach contents, stomach fullness and body condition, and the

62 abundance of zooplankton and marine invertebrate as potential prey in the water column
63 and in sediment. We compared these between three regions with different marine
64 environments and communities (Grebmeier et al. 2006, Eisner et al. 2013) during the
65 summer of 2013: the northern Bering Sea (NB), southern Chukchi Sea (SC), and central
66 Chukchi Sea (CC) (Fig. 1).

67

68 **Materials and Methods**

69 Sampling of polar cod

70 Sampling was conducted aboard the T/S *Oshoro-Maru* (Hokkaido University, Japan) at
71 12 stations (St; Fig. 1) at depths between 34 and 68 m during July 4–17, 2013. Polar cod
72 were collected during the daytime using an otter bottom trawl (10 mm cod-end mesh
73 size). The net was towed for 15 min over the seafloor at a speed of 3–4 knots. With a
74 given towing speed and warp length, the width and height of the mouth opening were
75 estimated to be 23.6–25.2 m and 4.3 m, respectively, when the net was towed over the
76 seafloor. The depth of the head-rope was monitored by an attached depth sensor and
77 was 3.5–4.3 m above the sea floor. Thus the foot-rope was assumed to be in contact
78 with the seafloor. The area swept by the bottom trawl at each station was computed as
79 the horizontal mouth opening multiplied by the towing distance (based on towing speed
80 and duration). The density of polar cod was calculated as the number of fish per unit
81 survey area. The net might capture some polar cod when it was going down to and up
82 from the seafloor but we could not separate these from fish caught when the net was
83 contacting the seafloor.

84

85

86 Size and stomach contents of polar cod

87 Two hundred and thirty eight fish samples were frozen at -20°C immediately after
88 collection and stored until analysis. The samples were thawed in flowing water, weighed
89 individually using an electronic balance (0.1 g) and their total length was measured (1
90 mm). Stomachs were removed and preserved in 10% v/v borax buffered formalin.
91 Stomach contents were weighed using an electronic balance (0.1 mg). To evaluate the
92 current feeding success and energy stores, the stomach fullness index (stomach contents
93 mass / body mass without stomach contents $\times 100$) and the body condition index (body
94 mass without stomach contents / total length³ $\times 10^6$) were calculated for each fish.

95 To examine prey composition, prey items were separated into taxonomic groups
96 using a stereoscopic microscope, weighed (0.1 mg) again, and counted. Stomach
97 contents of all individuals collected at a given station were combined (excluding 27
98 empty stomachs). The prey composition at each station was summarized by the index of
99 relative importance, $\text{IRI \%} = F_i \times [N_i + W_i]$ (Pinkas et al. 1971), where N_i is the
100 numerical percentage of prey i , F_i is the percentage of stomachs containing prey i , and
101 W_i is the mass percentage of prey i . We categorized taxonomic groups following Rand
102 et al. (2013). Our results indicated that these prey groups accounted for 92% IRI and the
103 remaining zooplankton was characterized as “others”.

104

105 Zooplankton and benthic invertebrates in the environment

106 To determine density of potential prey species in the environment, pelagic zooplankton
107 and benthic invertebrates were collected on the same day and at the same place as the
108 bottom-trawl. Pelagic zooplankton was collected with a NORPAC net (mouth diameter
109 45 cm, mesh size 335 μm , flow-meter attached) towed vertically with a speed of 1 m/s

110 in day-light hours or at night. Since the net was towed from 5 m above the seafloor to
111 the surface, sampling biases attributed to daily vertical migration of zooplankton can be
112 ignored. Samples were preserved in 5% v/v borax buffered formalin. During post-cruise
113 analyses, these zooplankton samples were sorted, counted, and identified to the lowest
114 identifiable taxon, and categorized into the same groups as those used in the diet
115 analysis. Total wet mass of each sample was measured (0.01 g). Density of pelagic
116 zooplankton sampled by the NORPAC net was calculated as the number of individuals
117 or total mass per unit effective area (m^2) of water filtered (the filtered volume divided
118 by the towing depth).

119 Benthic invertebrates were collected using a Smith-McIntyre grab (0.1 m^2), with
120 three replicate samples at each station. The sediments were washed using a 1 mm
121 mesh-sieve and prey items were fixed in buffered 10% formalin, and then preserved in
122 70% ethanol. As potential prey for polar cod, gammariids were counted and weighed.
123 Density for benthic gammariids was calculated as mass per unit area of the grab
124 sampler.

125 In addition, potential prey species near the seafloor, in particular appendicularians,
126 were observed using a ROV (*Arkas*, Kowa Company, Ltd., Japan) equipped with 150
127 mm parallel lasers. The ROV was moving 1–2 m above the seafloor with a speed of
128 0.1–0.2 m/s while recording video images. From these video-images, we scored the
129 abundance of appendicularian houses during every 10-second window as either 0
130 (absence), 1 (1–2 houses), 2 ($3\text{--}10^2$ houses), or 3 ($>10^2$ houses) for a total of 300
131 seconds at each station and defined the score at each station as the maximum score
132 recorded.

133

134 Statistics

135 To examine regional differences in total length, stomach fullness index and body
136 condition index of polar cod, we conducted multiple comparisons using the Steel-Dwass
137 pairwise non-parametric test.

138

139 **Results**

140 Size and stomach contents of polar cod

141 Polar cod were most abundant at St05 (Fig. 1). No fish were collected at St03 and a
142 single fish was collected at St04. Polar cod collected in the NB and the SC were larger
143 than those collected in the CC (Steel-Dwass test, $P < 0.01$, Table 1). The stomach fullness
144 indices were higher in the NB and SC than in the CC, while body condition indices did
145 not differ between the regions (Table 1).

146 Prey items were found in 211 stomachs out of 238 fish collected. Although the
147 percentage IRI of each prey type varied between the stations (Fig. 3), the average %IRI
148 across stations within the region showed that appendicularians (Fig. 2a) were the most
149 dominant prey found in the polar cod stomachs collected in the NB (47%) and SC
150 (50%), while in the CC appendicularians were completely absent (Fig. 3). In the CC,
151 polar cod fed on a variety of prey including copepods, gammarids, and euphausiids
152 (Fig. 3).

153

154 Zooplankton and benthic invertebrates in the environment

155 In the water column, copepods were abundant in the NB ($47 \times 10^3/m^2$, the average
156 density across stations within the region), copepods ($50 \times 10^3/m^2$) and barnacle larvae
157 ($44 \times 10^3/m^2$) were abundant in the SC, while barnacle larvae ($22 \times 10^3/m^2$) were more

158 abundant than copepods ($12 \times 10^3/\text{m}^2$) in the CC (Fig. 4a). Appendicularians were less
159 common than other taxa in the NB ($4 \times 10^3/\text{m}^2$) and SC ($10 \times 10^3/\text{m}^2$), and were rare in
160 the CC ($1 \times 10^3/\text{m}^2$). The total biomass of zooplankton in the water column varied
161 between stations (Fig. 4b) but the regional average was greatest in the SC ($54 \text{ g}/\text{m}^2$),
162 followed by the NB ($43 \text{ g}/\text{m}^2$) and the CC ($17 \text{ g}/\text{m}^2$, Fig. 4b). The biomass of
163 gammariids in the sediments varied by station and did not show apparent regional
164 differences (Fig. 4c).

165 The most conspicuous items in ROV video-image were the houses (3–4 cm
166 length) of appendicularians (Fig. 2b). High scores (3) at St06 and St07 (Fig. 4d)
167 indicated that appendicularians were abundant in the SC.

168

169

Discussion

170 Diet of polar cod

171 Given the geographic scope of the study, sampling effort (only 2–5 stations for each of
172 three regions) was rather low, and the variability of the prey consumed (Fig. 3) and that
173 of the zooplankton and benthic invertebrates available in the environment across the
174 stations (Fig. 4) appeared to be high. Nevertheless, some clear patterns emerged. In
175 particular, appendicularians seemed to be a major component of polar cod diets in the
176 northern Bering Sea (NB) and in the southern Chukchi Sea (SC) but were completely
177 absent in the polar cod stomachs in the central Chukchi Sea (CC). Since
178 appendicularians were less abundant than copepods at stations in the NB and SC, the
179 regional variation in the diet of polar cod could not be explained by the composition of
180 zooplankton in the environment. However, the absence of appendicularians in polar cod
181 diets in the CC is consistent with their absence or very low abundance in zooplankton

182 samples.

183 The reason why polar cod fed on appendicularians in the NB and SC in spite of
184 high abundances of copepods were unclear. Gelatinous appendicularians contain
185 proportionally less lipid (<0.1%–0.5% in wet weight) than copepods (1.3%–5.7%),
186 gammariids (approximately 18%), and euphausiids (2.2%–10.7%; Nomura and Davis
187 2005). Thus polar cod in our study did not appear to select prey based on lipid content.
188 The ROV images showed the large appendicularian houses that were easily detected by
189 human eye (Fig. 2a). Appendicularians are also preyed upon by Pacific salmon and
190 Gadiformes, presumably because they move slowly and lack a hard carapace (Purcell et
191 al. 2005). Thus we hypothesize that polar cod feed selectively on appendicularians
192 because their large and conspicuous houses and slow swimming speeds make them
193 easily available as prey.

194

195 Stomach fullness and body condition of polar cod

196 The stomach fullness index of polar cod collected in the NB and SC was greater than in
197 the CC, possibly reflecting the higher biomass of zooplankton in the water column in
198 the SC and NB than CC. Matsuno et al. (2011) also found that the total biomass of
199 zooplankton was higher in the SC than in the CC. Inflow of nutrient-rich water from the
200 Pacific (Eisner et al. 2013) induces higher primary production in the SC than CC, which
201 presumably explains higher zooplankton abundances. This high primary production,
202 seasonal ice cover and shallow water depth may also support a larger biomass of benthic
203 communities in the NB and SC (Grebmeier et al. 2006). In addition to the availability of
204 prey, water temperature might influence foraging activities and hence stomach fullness.
205 The prey consumption rate of walleye pollock (*Gadus chalcogrammus*) is known to

206 increase with temperature in the laboratory (Kooka et al. 2007). Water temperatures at
207 the seafloor in our study, however, were highest in the SC (0.8°C –1.3°C), followed by
208 the CC (–1.7°C ––0.8°C) and then the NB (–1.7°C ––1.6°C); indicating that ambient
209 temperature might not explain observed differences in stomach fullness.

210 The higher stomach fullness in the NB and SC was not associated with higher
211 body condition indices in these regions. This was possibly because polar cod had a
212 lower quality diet consisting of a high proportion of gelatinous appendicularians in the
213 NB and SC. Similarly, Kaga et al. (2013) reported that chum salmon (*Oncorhynchus*
214 *keta*) had small lipid stores when they fed on gelatinous zooplankton. Another
215 explanation could be that the body condition index reflects the total amount of food
216 eaten during a few weeks or a month before sampling while the stomach fullness index
217 reflects the current food intake. Thus the lower stomach fullness in the CC might not be
218 reflected in body condition. Further study of stable isotope values or fatty acid
219 signatures in the tissue of polar cod can help identify prey species consumed over a
220 longer period and improve our understanding of regional variation in the bioenergetics
221 of polar cod.

222

223 Ecological implications

224 The reduced sea-ice coverage has been proposed to favor a phytoplankton/zooplankton
225 dominated ecosystems over a sea-ice algae/benthos ecosystem (Grebmeier 2012), while
226 the expansion of warmer Pacific water into the southern Arctic Ocean induced the
227 dominance of warm water copepod species (Matsuno et al. 2011, Questtel et al. 2013).
228 Climate change may also influence the distribution and abundance of gelatinous
229 zooplankton. Kattner et al. (2007) hypothesized that, in the Arctic Ocean, the recent

230 increases in water temperature and freshwater inflow may result in increased
231 abundances of gelatinous zooplankton. Deibel et al. (2005) also suggested that the
232 abundance and the biomass of appendicularians, which have a short life-cycle, will
233 increase rapidly in Arctic polynyas if the open waters surrounded by sea-ice appear
234 earlier in the season and remain longer. Thus these expected climate-induced changes in
235 pelagic zooplankton and benthic invertebrate communities, either to the gelatinous
236 zooplankton or to warm water living copepods may influence the diet and body
237 condition of polar cod, and hence their recruitment as has been found in Atlantic cod
238 (*Gadus morhua*; Rätz and Lloret 2003).

239

240

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248

249

Ethical Statement

250 This work was funded by Green Network of Excellence program (lead by T Kikuchi) of
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252 Faculty of Fisheries Sciences, Hokkaido University. The authors declare that we have
253 no conflicts of interest. This article does not contain any studies with human participants

254 performed by any of the authors. This article does not contain any studies including
255 animals that require the permission from Ethics Committee of Hokkaido University.
256 Informed consent was obtained from all individual participants included in the study.

257

258

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332

Figure legends

333

334

335 **Fig. 1** Sampling stations (St) and abundance of polar cod (catch per unit effort as
336 number of fish per km² of bottom-trawling net-haul area) in the northern Bering Sea
337 (NB), southern Chukchi Sea (SC) and central Chukchi Sea (CC). No fish were collected
338 at St03.

339

340 **Fig. 2** The body of appendicularians observed in the stomach of apolar cod collected at
341 St02 in the northern Bering Sea (a), and ROV image showing the floating houses of
342 appendicularians at St07 in the southern Chukchi Sea (b)

343

344 **Fig. 3** The percentage composition of prey taxa, shown by the index of relative
345 importance (%IRI), found in the stomachs of polar cod collected in the northern Bering
346 Sea (NB), southern Chukchi Sea (SC) and central Chukchi Sea (CC). Sample sizes
347 (number of stomachs) are shown at the top of bars.

348

349 **Fig. 4** The numerical abundance of each prey taxa (a) and the total biomass of
350 zooplankton (b) in the water column samples collected by NORPAC net tows (4.79–
351 7.61 m³ water volume), the biomass of benthic gammarids in the sediment samples
352 collected by a Smith-McIntyre grab (0.1 m²) (c), and the score of the approximate
353 numerical abundance of appendicularians (0, absence; 1, 1–2 houses; 2, 3–10² houses; 3,
354 >10² houses) observed by ROV (d) at each station (Fig. 1) in the northern Bering Sea
355 (NB), southern Chukchi Sea (SC) and central Chukchi Sea (CC). The number or mass
356 per unit area (m²) are shown. For (a) and (b) the effective area of the NORPAC net tow

357 was calculated as the filtered volume divided by the depth of tow and the densities are

358 presented as the number or mass per unit effective area.

359

360

Table 1 Total length, stomach fullness index (proportional stomach content mass to body mass) and body condition index (residual of the size corrected body mass) of Polar cod in the central Bering Sea, southern Chukchi Sea and central Chukchi Sea. Mean±SD, ranges and sample sizes are shown. Regional difference was examined using Steel-Dwass test.

	Northern Bering Sea (NB)	Southern Chukchi Sea (SC)	Central Chukchi Sea (CC)	Steel-Dwass test		
				t-statistic (p-value)		
				NB vs. SC	NB vs. CC	SC vs. CC
Total Length (mm)	155.9±27.8 (110.0–230.0, 23)	140.2±30.4 (87.0–196.0, 78)	117.2±25.4 (72.0–186.0, 130)	1.9 (<i>p</i> =0.13)	5.3 (<i>p</i> <0.01)	5.0 (<i>p</i> <0.01)
Stomach fullness index	0.8±0.4 (0.1–1.8, 29)	0.9±0.8 (0.0–4.5, 78)	0.7±0.9 (0.0–5.8, 131)	0.8 (<i>p</i> =0.69)	3.4 (<i>p</i> <0.01)	3.3 (<i>p</i> <0.01)
Body condition index	7.1±0.3 (6.2–7.7, 23)	6.9±0.5 (5.6–8.4, 78)	6.9±0.6 (5.2–8.5, 129)	1.6 (<i>p</i> =0.24)	1.7 (<i>p</i> =0.22)	0.1 (<i>p</i> =0.99)

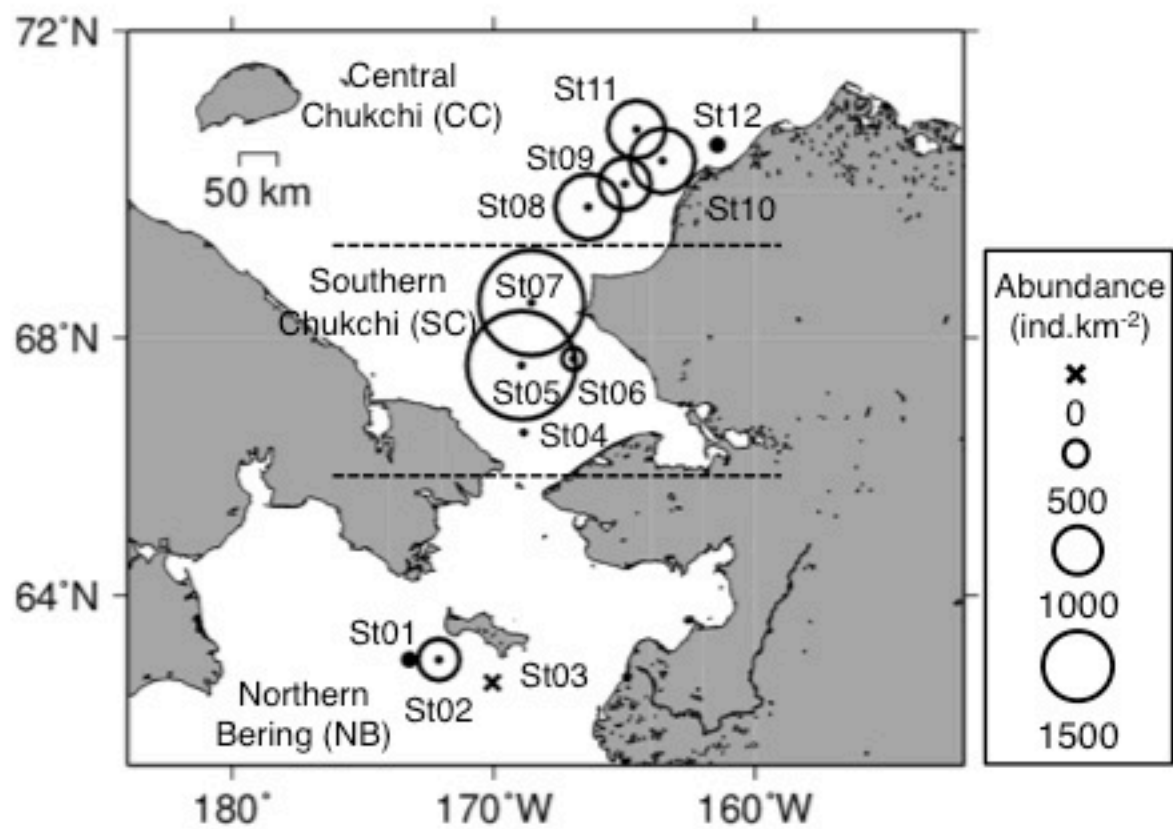
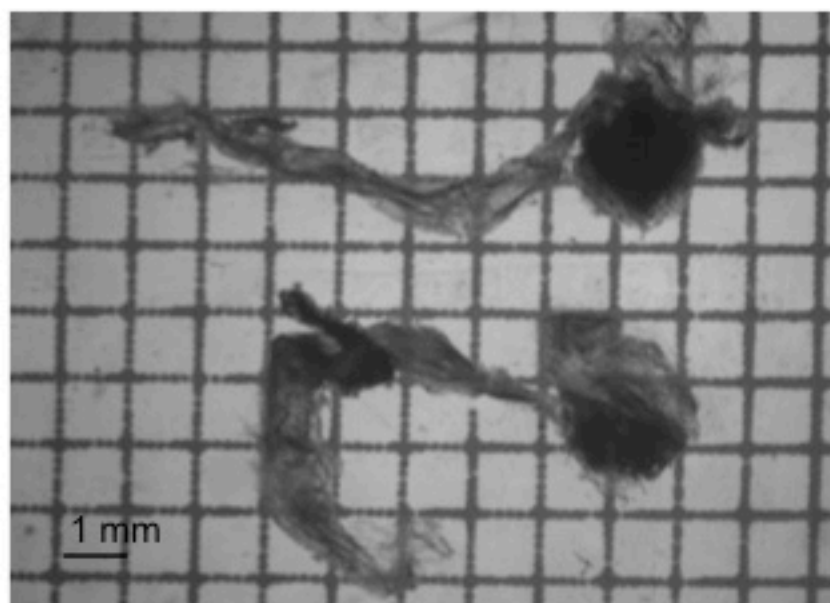


Fig. 1

(a)



(b)



Fig. 2

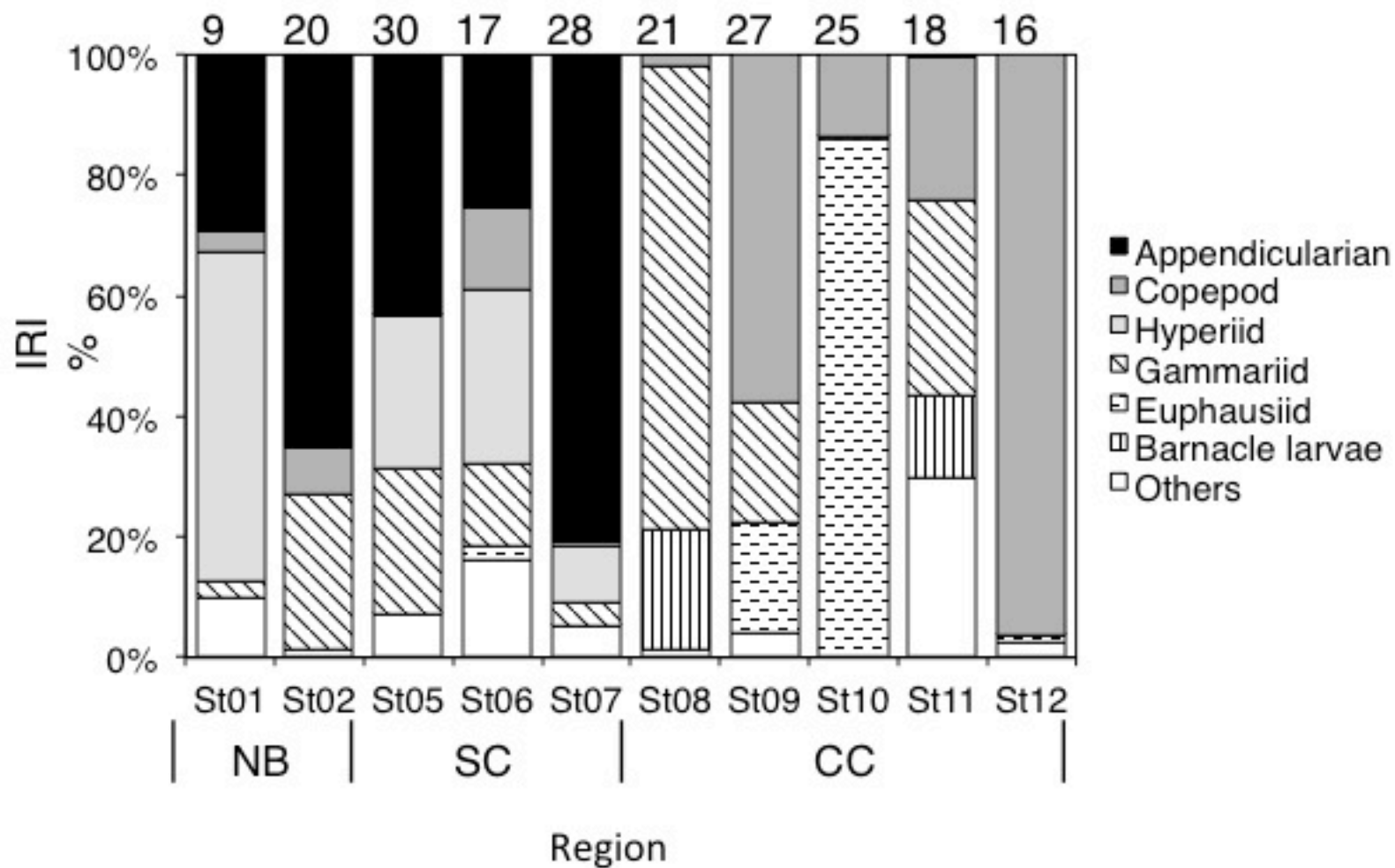


Fig. 3

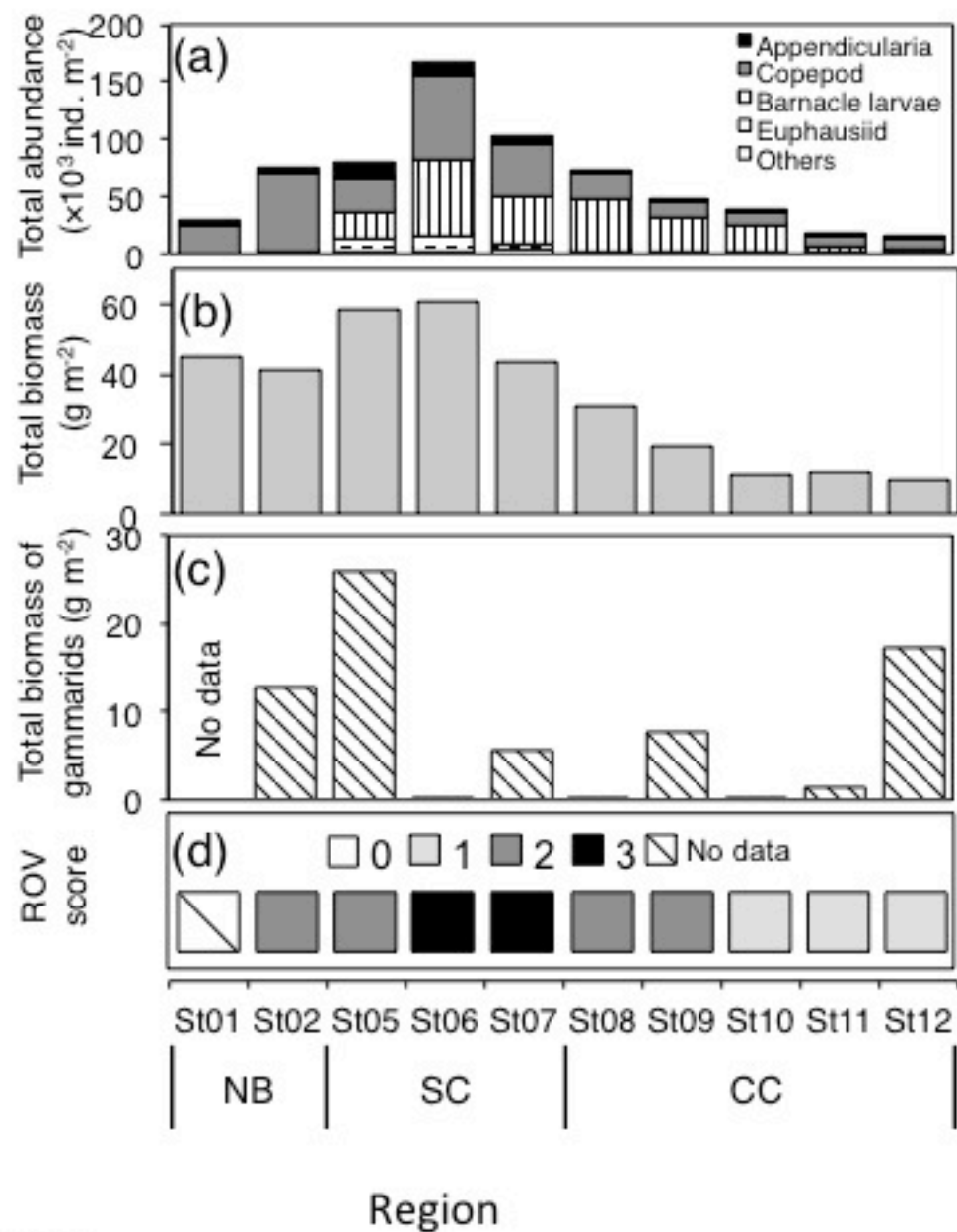


Fig. 4