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Length-weight Relationship, Condition Factor and Diet of the Two Dominant Fish Species *Notothenia rossii* Richardson, 1844 and *N. coriiceps* Richardson, 1844 (Nototheniidae) in the Shallow Coastal Waters of Livingston Island, South Shetland Islands, Antarctica

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Abstract: The study presents data about the two dominant fish species *Notothenia rossii* Richardson, 1844 and *N. coriiceps* Richardson, 1844 in the shallow coastal waters of the Livingston Island. Length-weight relationship, as well as the Fulton's and the relative condition factors and the diet of both species were studied. A total of 115 specimens of *N. rossii* and 18 of *N. coriiceps* were caught near the Bulgarian Polar Base in the South Bay. The average total length and weight of *N. rossii* were 232.8 mm and 180.4 g, respectively, while in *N. coriiceps* they were 324.4 mm and 556.8 g. The exponent *b* values of the length-weight relationship in both species were close to 3, indicating an isometric growth, but not statistically different from 3 since the calculated *p* -value was above 0.05. The average values of the Fulton's and the relative condition factors in *N. rossii* were 1.32 and 1.65, respectively, while the values of the same factors in *N. coriiceps* were 1.50 and 2.10, respectively, which indicated very good general condition of the fish. Overall, ten dietary classes were recorded in *N. rossii* and five in *N. coriiceps*, but only two of them (krill and amphipods) formed a total of 84.1% and 79.3% of the species diet, respectively.

Key words: length-weight relationship, condition factor, diet, Notothenioidei, coastal area, Livingston Island

Introduction

Fish play an important role in the Antarctic marine ecosystem and have been intensively studied over the last decades (e.g., Kock 1992, Hureau 1994, Barrera-Oro 2002, Barrera-Oro & Casaux 2008, Kock et al. 2012). These studies have shown that the fish fauna of the Southern Ocean is taxonomically limited, highly endemic and dominated by the fishes of the suborder Notothenioidei (Eastman & McCune 2000, Eastman & Sidell 2002, Casaux et al. 2003, Eastman 2005). Notothenoidei possess a range of unique morphological, physiological and biochemical adaptations to life in cold waters and represent about 45% of all fish species known in the Antarctic region, which comprises about 95% of the fish biomass in the shelf zone (Eastman 2005). The ecology of the group is comparatively well known as numerous ecological studies, mainly on fish diet (e.g., Richardson 1975, Targett 1981, Daniels 1982) and the importance of notothenioids in the Antarctic food web (e.g., Eastman 1985, Barrera-Oro 2002), have been undertaken.

Notothenia rossii Richardson, 1844 and *N. coriiceps* Richardson, 1844 (Nototheniidae) have a wide distribution in the Antarctic region. In the coastal area of the South Shetland Islands, *N. coriiceps* is the dominant species (Barrera-Oro 2002), whereas the population of *N. rossii* is still in the process of recovery after the commercial overfishing in the 1970s (Barrera-Oro & Marschoff 2007, Eastman et al. 2011, Marschoff et al. 2012).

The length-weight relationship of both species in the area of the South Shetland Islands have been recently studied by Eastman & Sidell (2002), Eastman et al. (2011) and Park et al. (2017), but all the data are coming only from the King George and Brabant Islands. Similarly, aspects of the biology of both species including the diet composition and condition factor have been published by Casaux et al. (1990), Kamler (2002), Fanta et al. (2003), Barrera-Oro & Casaux (2008), Raga et al. (2014), but again, only for the populations from the King George and Elephant Islands. There is still no published information about these biological parameters of *N. rossii* and *N. coriiceps* from the area of the Livingston Island.

The fish fauna of the Livingston Island and especially the biology and ecology of the species is poorly explored. The only large-scale survey was conducted by Olaso et al. (1997) using an Agassiz trawl drag. That study was focused on the aquatory around the Livingston and the Deception Islands as well as the Orleans Channel. It reported a total of 30 fish species belonging to five orders (Perciformes, Mictophiformes, Gadiformes, Ophidiiformes and Rajiformes). The order Notothenioidei was represented by 21 species and dominated in abundance. According to the authors, the most common species in the catch were *Gobionotothen gibberifrons, Gobionotothen marionensis, Lepidonotothen nudifrons* and *Lepidonotothen larseni*. First data on the fish in the area of the Bulgarian Antarctic base “St. Kliment Ohridski” were published by Metcheva et al. (2010); they studied the bioaccumulation of toxic elements in *N. coriiceps*. Later Beltcheva et al. (2011) published brief information about the body length and weight as well as the diet composition of the same species. Recently, Uzunova et al. (2021) reported the found of five fish species in the coastal area around the Bulgarian base, without giving information on their biology and ecology. No specific research has been conducted so far on the biological parameters of the fish in the shelf waters of the South Bay, Livingston Island.

The main aim of this study is to provide information on the length-weight relationship, condition factor and diet of the two dominant fish species *N. rossii* and *N. coriiceps* in the shallow coastal waters of the Livingston Island.

Materials and Methods

The field survey was carried out in the period 18 January – 26 February 2020, during the 28th Bulgarian Antarctic Expedition to the Bulgarian Antarctic base “St. Kliment Ohridski” on the Livingston Island. The island is part of the South Shetlands archipelago situated west of the Antarctic Peninsula. It is extending about 73 km in east-northeast to west-southwest direction and is separated from the peninsula by the Bransfield Strait. The surface area is 798 km^2 and nearly 90% of it is occupied by glaciers and permanent snow cover (Ivanov & Ivanova 2014). The Bulgarian base is located in the South Bay and operating since 1989. During the study, the surface water temperature in the area varied between 2.2 and 4.7ºC.

Most of the fish were caught in the coastal waters near the Bulgarian base at two locations: Hesperides Point (62.64659° S; 60.37604° W) and Johnsons Dock (62.65832° S; 60.36789° W) (Fig. 1) at a depth between 5-25 meters. A total of 115 specimens of *N. rossii* and 18 specimens of *N. coriiceps*

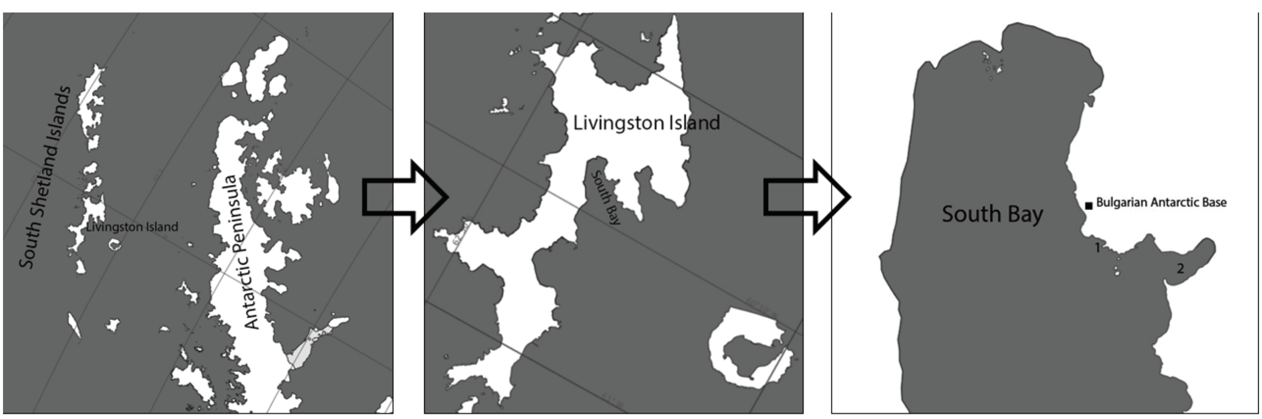

Fig. 1. Map of the South Shetland Islands region (left) with location of the Livingston Island (centre) and South Bay (right): 1. Hesperides point; 2. Johnsons Dock. (Source: SCAR Antarctic Digital Database, modified).

were collected using Zodiac boats mostly by Nordic type multi-mesh gill nets, bottom fish traps and fishing rod. All caught fish were measured to the nearest 1 mm total length (*TL*) and wet weighed to the nearest 1 g (*W*) at the laboratory of the "St. Kliment Ohridski" research station.

The length-weight relationship was expressed using the equation $W = aTL^b$ (Le Cren 1951, Ricker 1975), where *a* was the intercept and *b* was the slope of the logarithmically-transformed relation. The parameters *a* and *b* were estimated using linear regression with the logarithmically transformed equation $\log W = \log a + b \log TL$ (Ricker 1973). The degree of correlation among the variables was evaluated using the determination coefficient R^2. ANOVA was used to evaluate the statistical significance of the regression model detected when $p < 0.05$. To verify if *b* was statistically significantly different from the expected or theoretical value ($b = 3$), *t*-test was performed. While a statistically significant difference of *b* from 3 implies an allometric growth either positive or negative ($p < 0.05$), an isometric growth was assigned when *b* was not statistically different from 3 ($p > 0.05$).

Fulton's condition factor (*K*) was estimated according to the equation:

$$K = 100\frac{W}{TL^3},$$

where *W* was the weight of fish in g and *TL* was the total length in cm.

In addition, the relative condition factor (*Kn*) was estimated according to the equation proposed by Le Cren (1951):

$$Kn = \frac{W}{aL^b},$$

where *W* was the observed weight in g and aL^b was the estimated weight calculated from the length-weight relationship slope and intercept values.

Because of time and space constraints, only a limited number of fish could be analysed for diet (37 specimens of *N. rossii* and 4 specimens of *N. coriiceps*). After measuring and weighing, the fish were dissected and stomachs were removed. Their contents were detached, weighed and determined to the nearest taxonomic group under a binocular microscope.

The percentage representation of each dietary item was expressed as a relative percentage volume (%*Vi*) according to the formula:

$$\%Vi = 100\ x\ (\frac{Vi}{\Sigma Vi}),$$

where *Vi* was the percentage volume of food item *i* (summed for all stomachs) and Σ*Vi* represented the total percentage volume of all dietary items (summed for all stomachs).

Frequency of occurrence (%*Fi*) was expressed as the percentage of the stomachs containing dietary item *i* according to the formula:

$$\%Fi = 100\ x\ (\frac{ni}{n}),$$

where *ni* was the number of fish with dietary item *i* in the stomach and *n* was the total number of fish the stomachs of which contained food items.

The index of preponderance (*IP*) was used to quantify the relative importance of each dietary item according to Natarajan & Jhingran (1961):

$$IP = \frac{\%Vi\ x\ \%Fi}{\Sigma\%Vi\ x\ \%Fi},$$

where %*Vi* was the percentage volume of dietary item *i* and %*Fi* was the frequency of occurrence of dietary item *i* (see above).

All statistical calculations, plots and tables were done using MICROSOFT Office 2010 Excel software.

Results

Length-weight relationships

The average total length and weight of *N. rossii* were 232.8 (range 151-356) mm and 180.4 (46-584) g, respectively (Table 1), while in *N. coriiceps* they were 324.4 (256-485) mm and 556.8 (255-1675) g, respectively (Table 2).

The length-weight relationship was calculated for all 115 specimens of *N. rossii*. The parameters *a* and *b* were estimated using linear regression (Fig. 2) of the logarithmically transformed equation: $\log W = 3.0657 \log TL - 5.0373$, with coefficient of determination $R^2 = 0.9595$. The linear regression was significant for this species as $p < 0.05$. Although the value of the parameter *b* was different from 3 (3.0657) and showing positive allometric growth, *b* was not statistically different from 3 since $p = 0.87$, indicating isometric growth.

Following the same methodology, the length-weight relationship was calculated for 18 specimens of *N. coriiceps*. The data were well described by the gradient curve expressed by the equation included in Fig. 3. The parameters *a* and *b* were estimated by linear regression (Fig. 2) of the logarithmically-transformed equation: $\log W = 2.879 \log TL - 5.5229$, with coefficient of determination $R^2 = 0.9714$. The linear regression was significant for this species as $p < 0.05$. Although the value of the parameter *b* was different from 3 (2.8796) and showing negative allometric growth, we calculated that actually *b* was not statistically different from 3 ($p = 0.17$), indicating isometric growth.

Condition factor

The values of the Fulton's (K) and the Relative (Kn) condition factors for *N. rossii* are represented in Table 1. The average value for K was 1.32 and only in one specimen it was below 1.00, while Kn varied between 1.18-2.40 (average 1.65).

The values of the Fulton's and the Relative condition factors for *N. coriiceps* are represented in Table 2. The values for K in all specimens were above 1.00 (average 1.50) and the values of Kn varied between 1.67-2.37 (average 2.10).

The more heavily rugged body with large, wide, depressed head of *N. coriiceps* explained the higher values of both condition factors. On the other hand, *N. rossii* is more gracile, with more laterally compressed and streamlined body.

Diet analysis

All the fish caught and analysed by us had stomachs containing food remains. Most of the remains were identified as benthic invertebrates such as krill (*Euphausia superba*), amphipods and isopods. Less often, we found molluscs, polychaete worms, fine gravel and macroalgae remains. Overall, ten dietary classes were recorded in *N. rossii* and five in *N. coriiceps*, but only two of them (krill and amphipods) formed a total of 84.1% and 79.3% of the species diet, respectively. Six dietary classes oc-

Table 1. Descriptive statistics for *Notothenia rossii* (n = 115).

Descriptors	***TL* [mm]**	***W* [g]**	***K***	***Kn***
Mean	232.83	180.44	1.32	1.65
Standard Error	3.52	8.65	0.01	0.02
Median	235	176	1.31	1.64
Standard Deviation	37.79	92.72	0.14	0.18
Kurtosis	0.80	5.22	3.49	3.89
Skewness	0.17	1.64	1.10	1.20
Range	151-356	46-584	0.94-1.92	1.18-2.40
Confidence Level (95.0%)	6.9809	17.1280	0.0265	0.0332

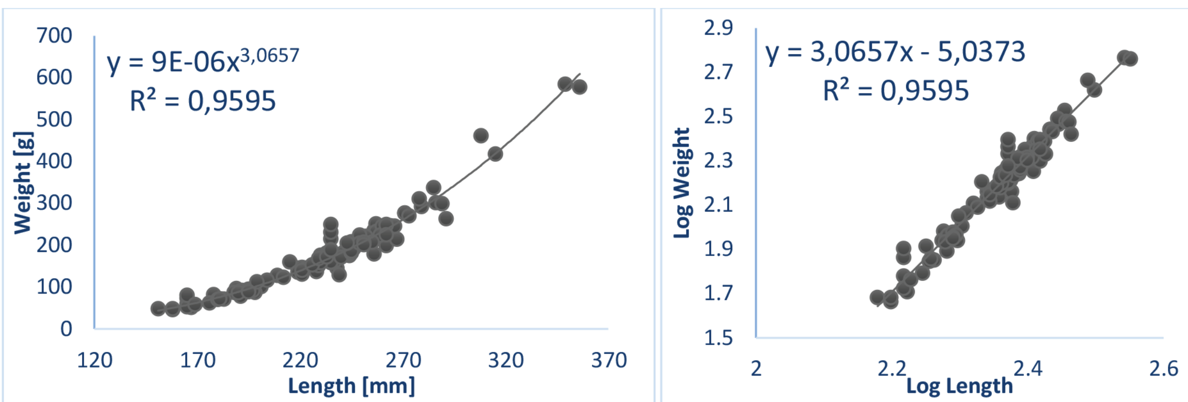

Fig. 2. Length-weight relationship for *Notothenia rossii* (left) and same relationship expressed using a linear equation (right)

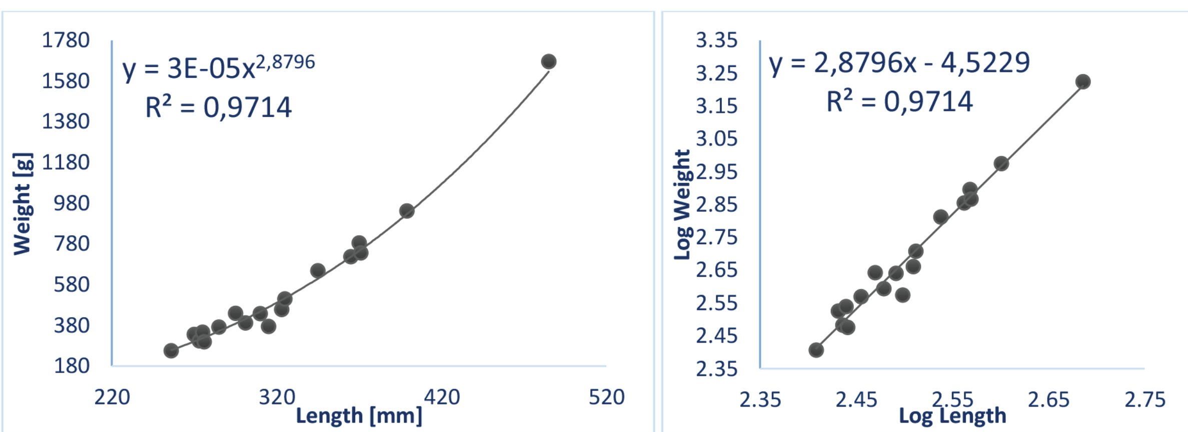

Fig. 3. Length-weight relationship for *Notothenia coriiceps* (left) and same relationship expressed using a linear equation (right).

curred in more than 10% of the studied specimens of *N. rossii* and the most common were amphipods and krill, which occurred in 81.1% and 40.5%, respectively. Both classes formed 54.1% and 30.0% of the food biomass, respectively. Two dietary classes (amphipods and krill) occurred in 100% of the studied specimens of *N. coriiceps* and only the krill formed 70.3% of the food biomass. The data for the *IP* values indicated slightly more opportunistic diet for *N. rossii* as compared to *N. coriiceps*. A reason for that result could be the small number of analysed specimens of the later species. According to our survey, *N. rossii* preferred mostly amphipods (*IP* = 76.435) as a food resource in the austral summer around the Livingston Island, while *N. coriiceps* fed mostly on krill (*IP* = 82.078). The later showed interesting specialisation in feeding with the large isopod *Glyptonotus antarcticus* (*IP* = 4.15), while this isopod was absent from the diet of *N. rossii* (Table 3).

Table 2. Descriptive statistics for *Notothenia coriiceps* (n = 18).

Descriptors	*TL* [mm]	*W* [g]	*K*	*Kn*
Mean	324.39	556.78	1.50	2.10
Standard Error	13.53	80.16	0.03	0.04
Median	312.50	438.00	1.48	2.09
Standard Deviation	57.40	340.09	0.12	0.17
Kurtosis	2.26	6.51	1.18	1.41
Skewness	1.36	2.31	-0.34	-0.71
Range	256-485	255-1675	1.20-1.71	1.67-2.37
Confidence Level (95.0%)	28.5432	169.1227	0.0613	0.0822

Discussion

Length-weight relationship

This is the first study of the length-weight relationship of *N. rossii* and *N. coriiceps* around the Livingston Island but similar studies have been conducted in other localities in the South Shetlands Archipelago, mostly in King George Island (Eastman & Sidell 2002, Eastman et al. 2011, Park et al. 2017). We found an isometric growth in both surveyed species as the *b* value was not statistically different from 3, which means that a slight or no change of body shape in growing late juveniles and adults occurred. These results are in contrast with the published data about the length-weight relationship of both species from other South Shetland Islands (see Table 4), as all authors find positive allometric growth. Isometric growth has been reported only for *N. coriiceps* from the South Shetland Islands by Calì et al. (2017).

According to the published information about the age estimation for both species (Barrera-Oro & Casaux 1992, Eastman et al. 2011, Calì et al. 2017), we defined that in our study the age of *N. rossii* could be estimated between 2-6 years and the

Table 3. Dietary analysis of stomach contents from the two dominant fish species caught along the shallow coastal waters of Livingston Island in 2020: *N. rossii* (n = 37) and *N. coriiceps* (n = 4). Data are presented as relative percentage volume (*%Vi*), frequency of occurrence (*%Fi*) and index of preponderance (*IP*).

Dietary class	***Notothenia rossii***			***Notothenia coriiceps***		
	%Vi	***%Fi***	***IP***	***%Vi***	***%Fi***	***IP***
Euphausiacea						
Euphausia superba	30.0	40.5	21.174	70.3	100.0	82.078
Amphipoda	54.1	81.1	76.435	9.0	100.0	10.537
Isopoda						
Ceratoseriolis trilobitoides	3.4	10.8	0.634	1.8	25.0	0.533
Glyptonotus antarcticus				14.2	25.0	4.152
Polychaeta	2.2	10.8	0.412	-	-	-
Nemertea						
Parborlasia corrugatus	2.0	2.7	0.096	-	-	-
Bivalvia	1.1	8.1	0.158	-	-	-
Gastropoda						
Nacella concinna	2.7	2.7	0.127	-	-	-
Other gastropods	0.1	2.7	0.003	-	-	-
Macroalgae	2.5	13.5	0.594	4.6	50.0	2.700
Fine gravel	1.9	10.8	0.366	-	-	-

Table 4. Values of length exponent (*b*) and *TL* for both species in different published sources.

Species	Descriptors	Present study	Eastman & Sidell (2002)	Eastman et al. (2011)	Park et al. (2017)
Notothenia rossii	**n**	115	12	164	7
	TL [mm]	233 (151-356)	394 (361-455)	189 (63-436)	275 (255-291)
	***b* value**	3.066	3.440	3.120	3.546
Notothenia coriiceps	**n**	18	8	99	30
	TL [mm]	324 (256-485)	283 (252-348)	265 (64-475)	266 (230-296)
	***b* value**	2.880	3.540	3.210	3.404

Table 5. Values of the Fulton's condition factor for both species in different published sources.

Species	Descriptors	Present study	Eastman et al. (2011)	Park et al. (2017)	Raga et al. (2014)
Notothenia rossii	**n**	115	164	7	221
	mean	1.32	1.23	1.38	
	range	0.94-1.92	0.89-1.60	1.30-1.54	1.95-2.52
Notothenia coriiceps	**n**	18	99	30	151
	mean	1.50	1.44	1.48	
	range	1.20-1.71	0.85-1.81	1.30-1.67	1.95-2.52

age of *N. coriiceps* between 5-15 years. Thus, we concluded that only *N. coriiceps* was in reproducing age and spawned in the area of the South Bay. All of the studied specimens were with released spawning products, which meant that we caught them soon after their spawning season and that could explain the lower values of exponent *b*.

Condition factor

The observed values for the Fulton's condition factor of *N. coriiceps* were slightly higher than these of *N. rossii* (Table 1 and Table 2), suggesting that *N. coriiceps* was somehow fatter with more rotund body. Unlike it, *N. rossii* had a more streamlined less rotund body and a narrower head, which was reflected in the lower condition factor. Higher values for *K* in *N. coriiceps* rather than in *N. rossii* were also reported in some previous studies (Eastman et al. 2011, Park et al., 2017).

Lack of seasonality in *K* for both species has been reported in some previous studies (Raga et al. 2014). It is directly related to the environmental trophic conditions as both species are considered benthivorous with a broad food spectrum (Barrera-Oro & Casaux 1990, Fanta 1999, Kamler 2002). The Antarctic benthic fauna demonstrates high biomass values (Knox 1994) which do not decrease during the austral winter (Clarke 1985). Thus, the observed by us values for *K* in the coastal waters of Livingston Island could be considered as representative throughout the year. The values calculated by us are quite similar to the ones reported in other studies for these species in the South Shetlands (Table 5). Only the values published by Raga et al. (2014) are somehow higher and it is interesting that they are summarised for the whole year, while all other studies, including ours, are conducted only in the austral summer.

The relative condition factor is directly connected with the length-weight relationship and it is often preferred to the Fulton's condition factor as the latter is generally influenced by many environmental and biological factors (Le Cren 1951). Both studied fish species have values for *Kn* well above 1 (Table 1 and Table 2), which according to Le Cren (1951) indicates very good general condition of the fish.

Diet analysis

It is well known that in the Antarctic region of the South Shetlands, areas rich in macroalgae show greater fish diversity and biomass (Żukowski 1980, Casaux et al. 1990). Macroalgal environments are rich in prey and possible shelters from potential predators, such as cormorants, penguins and seals. The bottom substrate in the South Bay, where our survey was conducted, was dominated by rocks overgrown with abundant seaweeds, mainly of the brown algae *Desmarestia menziesii* and *Himantothallus grandifolius* (Uzunova et al. 2021). One of the sampling localities represented a strongly closed cove separated from the sea by an underwater rocky wall with sandy-gravel bottom substrate and fewer macroalgae. Everywhere we observed high biomass of bottom invertebrates and ascidians, which explains the fact that 100% of the studied fish had stomachs containing food remains. The analysis of the diet of *N. rossii* and *N. coriiceps* showed general agreement on the feeding types and feeding behaviour of these species in other areas. In general, the main food items reported here have been previously reported in their diet by other authors (Casaux et al. 1990, 2003, Barrera-Oro & Casaux 2008, Raga et al. 2014). The feeding behaviour of the two species assessed in this study is considered as benthoplanktivorous, as their diet is composed mostly of krill, amphipods and isopods (Table 3). In general, notothenioids are species with a broad food spectrum, but the predominance of a benthic diet is often described for the coastal populations of *N. coriiceps* (Barrera-Oro 2002, Kamler 2002) and *N. rossii* (Kamler 2002, Barrera-Oro & Winter 2008). According to De Witt et al. (1990), *N. coriiceps* is primarily a benthic predator, while *N. rossii* is semipelagic or benthopelagic, which means that we should expect more plankton food items in the diet of the latter. Contrawise, our results showed something different. The diet of *N. rossii* in the South Bay was dominated by benthic amphipods (*IP* = 76.435), while the diet of *N. coriiceps* was dominated mostly by krill (*IP* = 82.078). The prevalence of krill was related to its greater availability in the South Bay during the study period, which made it an easy prey for the bigger predatory fish such as *N. coriiceps*. The fact that we have caught only juvenile specimens of *N. rossii* (2-6 years old) means that the krill probably is not the main food source for the species during the young stages of its life and it is replaced by the smaller amphipods, which possess similar energetic content to krill – between 27-40% protein and between 14-27% lipid (Percy 1979). Anyway, the krill is still an important part of species' diet (*IP* = 21.174). There are other studies (Fanta et al. 2003), which also demonstrated the prevalence and preference of krill by *N. coriiceps*. According to our study, the juvenile *N. rossii* had a wider trophic spectrum as we found ten different dietary classes as compared to five in *N. coriiceps*. The main reason was probably the small number of studied stomachs of the latter species. Previous sources stated that during the austral summer, *N. coriiceps* fed on a greater diversity of prey (Casaux et al. 2003) and might feed actively by searching for prey among macroalgae due to the better-adapted pectoral fins. This is an opportunistic species and, therefore, its diet reflects the available food sources. Raga et al. (2014) reported the predominance of salps in the stomach contents during their study along the King George Island. According to them, the study period might be related to the high prevalence of these organisms in the area, as they might occasionally dominate the zooplankton community in Antarctic waters (Loeb et al. 1997). It is interesting that we did not identify salps as a food item in the stomachs of both species, although we found them in big numbers around the coast of the South Bay on 19 January 2020. It is known that algae constituted a main food item for *N. rossii* and *N. coriiceps* and they are consumed deliberately by the fish (Barrera-Oro & Casaux 1990, 1992, Casaux et al. 1990, 2003, Iken et al. 1997). We found macroalgae as a secondary food source in the diet of both species, forming a small percent of the total food volume – *%Vi* = 2.5% and 4.6%, respectively and *IP* = 0.594 and 2.700, respectively (Table 3). We cannot conclude at this stage whether this food item is deliberately selected by fish or it has been swallowed incidentally during the chasing of benthic invertebrates. The only study of the diet of *N. coriiceps* in the South Bay was conducted by Belcheva et al. (2011) and the authors reported three main dietary classes: krill (35%), copepods (24%) and algae (29%), which made approximately 90% of the gut contents. While reporting copepods as a main food item, the authors actually meant isopods (R. Mecheva, pers. com). According to our study, krill was the main food source for *N. coriiceps* (*%Vi* = 70.3), isopods were in similar amount (*%Vi* = 16) and algae were less common as a food item (*%Vi* = 4.6). Another difference was the higher percentage of amphipods (*%Vi* = 9) found by us. The reason for these differences is most probably the smaller amount of krill during the survey conducted by Belcheva et al. (2011). According to Fanta et al. (2003), when krill is scarce, *N. coriiceps* switch to benthic prey, which may be less nutritious but easier to catch.

Our study shows that although *N. rossii* and *N. coriiceps* coexist in the waters of the South Bay, their diets do not fully overlap (Table 3). Adult *N. coriiceps* are specialised in bigger prey, such as krill and large isopods, while the juvenile *N. rossii* are feeding mainly on smaller amphipods. The presence of only young individuals of *N. rossii* in the coastal waters of the South Bay is related to the life cycle of this species: juveniles remain in shallow waters until they reach a maturity and then they migrate into deep waters for spawning (Burchett 1983a, b, Knox 1994). The presence of both mature and immature fish, all with full stomachs, highlighted the importance of the inshore zone of the South Bay as a feeding habitat, with variety of microhabitats and macroalgae fields, which provide a wide range of food sources. Thus, these coastal zones are also important for the birds and mammals that depend upon fish for food.

As our study was based on relatively small number of fish caught only during the austral summer, we strongly recommend that further research should be undertaken in order to obtain more definitive conclusions. In particular, we suggest further in-depth dietary studies conducted with more specimens of different benthic species of fish, as well as detailed survey on the food availability and selectivity in feeding.

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