Trophic niche of seabirds on the Barton Peninsula, King George Island, Antarctica

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ABSTRACT

Drastic sea ice retreats in the Antarctic Peninsula, and the consequent environmental changes have brought about the consequences of biological adaptation and food competition. The isotopic niche is reflected by the ecological position and functional role of a species, which can be altered depending on these environmental changes. We assessed the isotopic niche and trophic positions (TP) of 3 seabirds on the Barton Peninsula, King George Island, Antarctica, to understand ecological interaction among the species. The average TP of Antarctic krill (*Euphausia superba*) (hereafter "krill") (2.6 ± 0.1) was estimated by using the compiled published data of the compound-specific nitrogen isotope ratio of glutamic acid and phenylalanine in the Southern Ocean, and TP values of the seabirds based on that of krill to be reliable according to ecological knowledge. Our results on the overlap of the isotopic niches of seabirds suggests potential diet competition among the consumers, such as the brown skua (*Stercorarius antarcticus*) and south polar skua (*Stercorarius maccormicki*), whereas the distinct and broad isotopic niche width of kelp gulls (*Larus dominicanus*) suggesting that their adaptation through general-ization was related to their extended habitat and various food sources. Our research indicates that isotopic niche of seabirds reflects their survival strategy for food competition. Consequently, these seabirds can be easily influenced by alternative food sources, including terrestrial and human-derived sources, by rapid environmental changes, indicating that they are valuable as key environmental species and require long-term monitoring in the Antarctic Peninsula.

1. Introduction

Glacier and sea ice retreat is one of the main results of climate change in the western Antarctic Peninsula, which has experienced rapid climate change in recent years (Vaughan et al., 2003; Turner et al., 2005; Davies et al., 2012). Recently, changes in the marine benthic community were identified according to the distance from the glacier in the nearshore of Marian Cove, King George Island, Antarctic Peninsula, where rapid glacial retreat of approximately 1.7 km occurred from 1956 to 2012 (Moon et al., 2015). A drastic marine environmental change signifi-cantly affects marine organisms, as mentioned earlier, and their preda-tors, such as penguins, skuas, seals and whales (Laws, 1977; Croxall, 1992; Reid and Croxall, 2001). Consequently, environmental change

and the alteration of food sources lead to variation in the ecological position and functional roles of the organisms in the ecosystem, which is known as their ecological niche (Hutchinson, 1957). Different species may coexist by segregating their foraging space, time and items to avoid competition under limited resources (e.g., Kiszka et al., 2011; Lee et al., 2021). A species has to adapt to variable environmental conditions and must use different techniques to capture food and retain its foraging habitat to remain a "specialist"; a species can also be a "generalist", which involves fewer costs but requires avoiding competition (Wilson and Yoshimura, 1994; Carnicer et al., 2008). This adaptation of a species is projected onto the niche width and direction in the isotope space, which is represented in biplot space using dual isotopes (e.g., Sato et al., 2002; Bearhop et al., 2004).

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Carbon stable isotopes indicate food sources and habitats (DeNiro and Epstein, 1978), and nitrogen isotopes provide information on the trophic position (TP) (Post, 2002). Therefore, using the x-axis as food availability represented by carbon isotopes and the y-axis as trophic linkages represented by nitrogen isotopes in isotope space can provide information on the ecological niche, which is called the "isotopic niche" (Bearhop et al., 2004; Cherel et al., 2007; Newsome et al., 2009). Furthermore, the isotopic niche was reinforced by Bayesian metrics, which can provide a niche width of community and robust spatiotemporal comparison of the niches in the isotope space based on the Stable Isotope Bayesian Ellipses in R (SIBER) (Jackson et al., 2011).

Narębski Point (Antarctic Specially Protected Area (ASPA) No. 171) is located on the southeastern coast of the Barton Peninsula (Fig. 1). Every year various seabirds, as well as penguins, migrate and inhabit for breeding to this area during the austral summer period. According to the faunal survey of Narębski Point in 2011/12 austral summer, 2621 pairs of chinstrap penguins, 2351 pairs of gentoo penguins and several nests of predators, such as brown skua, south polar skua and southern giant petrel, were confirmed in this area (ATCM, 2011). Scientists manage and monitor this area to protect its ecological value. However, there is still a lack of understanding of the foraging behavior and adaptation mechanisms of the various seabirds related to the variation in food sources due

to environmental changes. Climate change will affect the niches of seabirds. Based on the changes in niches, we will be able to predict the direction of adaptation to changes in the environments of seabirds. However, to our knowledge, no studies have investigated the isotopic niches of seabirds in the Antarctic Peninsula except penguins. Therefore, it is necessary to understand the variation in the niches and the adaptation of seabirds in the Antarctic Peninsula to understand their ecological functions and protect them from anthropogenic effects. In the present study, we investigated food competition and adaptation mechanisms based on the isotopic niches and TPs of the 3 seabirds on the Barton Peninsula, Antarctica. It should be emphasized that isotopic niches can provide comparative information through long-term observations in the study area.

2. Materials and methods

2.1. Sample collection

The collection of seabird samples was carried out during the 2012–2013 (Dec.–Feb.) around the Narębski Point (Antarctic Specially Protected Area (ASPA) No. 171) and King Sejong Station on the Barton Peninsula, King George Island (Fig. 1). Two kinds of penguins and seven
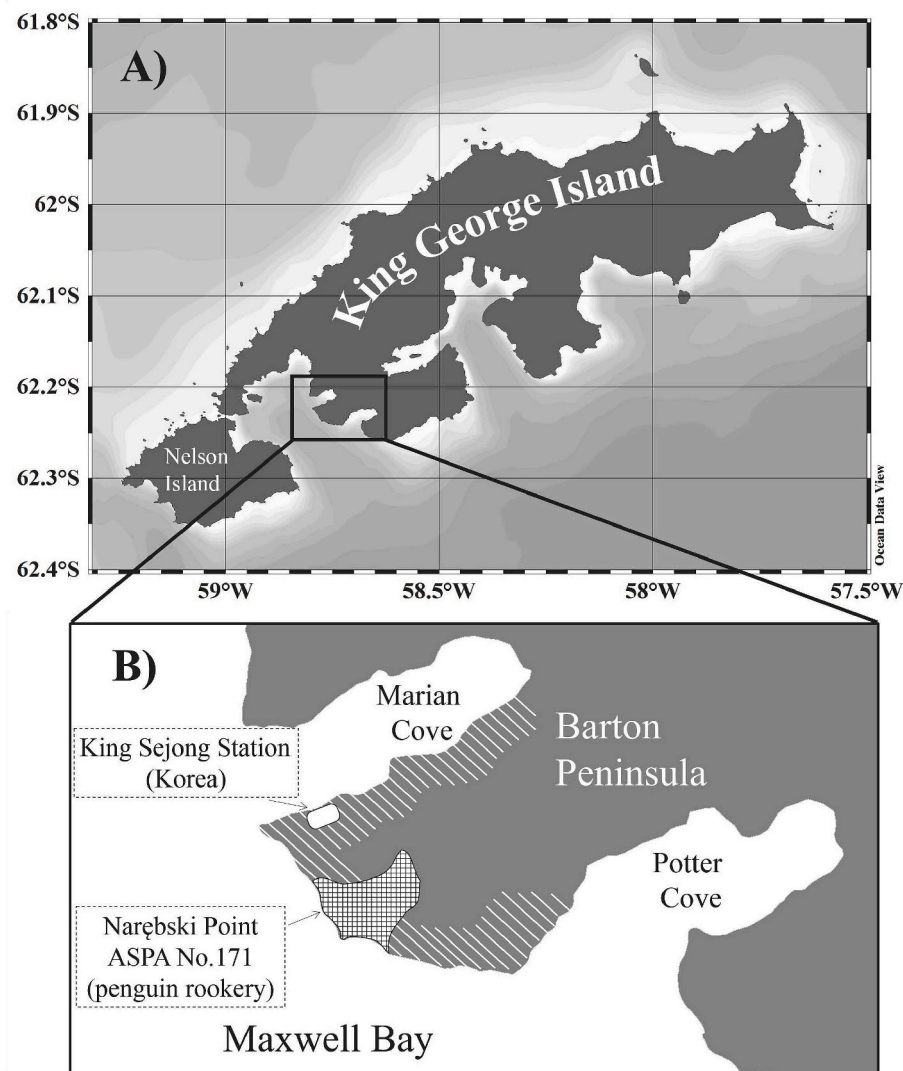

Fig. 1. (A) Location of King George Island, Antarctica and (B) study area on the Barton Peninsula. Blood samples of seabirds and marine organisms were collected from shaded areas (diagonal lines), including the penguin rookery (Narębski Point, Antarctic Specially Protected Area (ASPA) No. 171) and the coastline of the Barton Peninsula.

species of birds were confirmed to breed based on faunal survey of Narębski point in the 2012/13 period (ATCM, 2013). Three predominant seabird species Kelp gull *Larus dominicanus*, brown skua *Stercorarius antarcticus*, and south polar skua *Stercorarius maccormicki* were captured by hand near the breeding nests. One milliliter of whole blood samples was taken from the brachial vein of adult seabirds, and the handling time was less than 3 min. In the case of the kelp gulls, blood samples were collected from juveniles who were independent of their parents and had not yet reached the age of first molting, when their feathers grow in completely. The collected blood samples were transferred into 2 ml tubes and stored at −20 °C.

Potential food sources for the seabirds were collected from Marian Cove (Table 1). Krill samples (n = 5) that swept over the pier in front of King Sejong Station were picked up with tweezers and transferred into a zipper bag. Black rockcod (*Notothenia coriiceps*) were collected by fishing in front of the penguin rookery at Narębski Point. Antarctic silverfish (*Pleuragramma antarcticum*), which were dropped by a skua feeding a chick, were obtained from a south polar skua nest. Antarctic limpets (*Nacella concinna*) were collected by hand from the shoreline in front of the King Sejong Station. Collected samples were transferred in a zipper bag and stored at −20 °C.

2.2. Stable isotope analysis

Fish muscle tissue was collected at the laboratory. The Antarctic limpet shell samples were removed, and whole tissues were taken because of the small size of the individuals used for analysis. Fish, Antarctic limpet, krill and blood samples were freeze-dried and homogenized using a mortar and pestle. Krill samples (n = 5) were pooled for stable isotope analysis. We could not obtain individual stable isotope values for krill. The nitrogen isotope value of krill was only used for estimating the trophic position of seabirds.

Lipids were removed from these samples using chloroform/methanol (2/1, v/v in triplicate) for carbon isotope analysis (modified from Choi et al., 2017). Nontreated samples were used for nitrogen isotope analysis. Carbon and nitrogen stable isotope ratios were determined using an elemental analyzer (Euro EA3028, EuroVector, Milan, Italy) coupled with an isotope ratio mass spectrometer (Isoprime, GV instrument, Manchester, UK). The analytical precision (1 σ standard deviation) was obtained from international isotopic references (IAEA–CH–6 and N-1); the precision was ±0.14‰ and ±0.11‰ for carbon and nitrogen, respectively. Isotopic compositions were expressed in the δ notation as follows:

$$\delta X(‰) = \left(\left(\frac{R_{sample}}{R_{reference}} \right) - 1 \right) \times 1000 \tag{1}$$

where X is carbon or nitrogen and R is the corresponding ratio of $^{13}C/^{12}C$ or $^{15}N/^{14}N$ relative to the Vienna Peedee Belemnite and to atmospheric nitrogen, respectively.

2.3. Estimation of avian trophic position

The TP of seabirds was estimated using the nitrogen stable isotope ratios between seabirds and krill. The nitrogen stable isotope value of krill was used as the isotopic baseline in the study area. The equation for the TP was modified from Post (2002) as follows:

$$TP_{birds} = \frac{(\delta^{15}N_{birds} - \delta^{15}N_{base})}{TDF} + TP_{base} \tag{2}$$

The trophic discrimination factor (TDF) of seabirds was obtained using the mean value (2.9‰) of previously reported data for the whole blood of seabirds (Cherel et al., 2005 and references therein). The systematic error of TP was estimated by the analytical error of the nitrogen isotopes divided by the TDF value and expressed as ± σ.

Here, we assigned krill as the base food chain in equation (2). The $\delta^{15}N$ value of krill is obtained from the pooled krill sample from 5 individuals in the study area (Table 1). The nitrogen isotope ratio data of phenylalanine ($\delta^{15}N_{phe}$) and glutamic acid ($\delta^{15}N_{glu}$) in a consumer can provide information on the isotopic baseline and trophic elevation (e.g., Chikaraishi et al., 2009; Bowes and Thorp, 2015; McMahon and McCarthy, 2016). As a result, the TP of krill can be estimated without a basal food source for the krill by the nitrogen isotope analysis of phenylalanine and glutamic acid. Moreover, it is possible to calculate a relatively accurate TP regardless of the spatial and temporal variation in the isotopic baseline for krill in the environment. Therefore, to obtain TP_{base} in equation (2), we compiled published data on $\delta^{15}N_{phe}$ and $\delta^{15}N_{glu}$ in krill from previous studies conducted in the Southern Ocean (Schmidt et al., 2004, 2006, Table 2).

The TP of krill was estimated by the following equation suggested by Chikaraishi et al. (2009) based on the compiled published data.

$$TP_{krill} = \frac{\delta^{15}N_{Glu} - \delta^{15}N_{Phe} - 3.4}{7.6} + 1 \tag{3}$$

2.4. Isotope model and statistics

Stable isotope Bayesian ellipses in R (SIBER) based on a Bayesian model were used to determine the isotopic niche between seabirds using the R program (Jackson et al., 2011; R Core Team, 2015). We also calculated the layman metric of convex hull total area (TA), the standard ellipse area corrected for small sample size (SEAc) and the overlap proportion based on SIBER. The data were statistically analyzed using SPSS 12.0 software (SPSS Inc. Chicago, IL). Values are represented as the mean ± standard deviation (SD).

3. Results

The $\delta^{15}N$ values of birds were not significantly different between species (one-way ANOVA, Scheffe's multiple range test, $F_{2,37} = 2.255$, $p = 0.119$). However, $\delta^{13}C$ of seabirds were significantly different between species (one-way ANOVA, Scheffe's multiple range test, $F_{2,37} = 16.988$, $p > 0.001$). In particular, the kelp gull (−19.3 ± 2.1‰, $n = 10$)

Table 1
Information on the samples and $\delta^{13}C$ and $\delta^{15}N$ values of 3 seabirds and potential food sources on the Barton Peninsula.

Species	Common name	Sampling date	Samples (n)	Mean of $\delta^{13}C$ (‰)	SD[a] of $\delta^{13}C$	Mean of $\delta^{15}N$ (‰)	SD of $\delta^{15}N$	Age
Seabirds								
Larus dominicanus	Kelp gull	Jan.–Feb. 2013	10	−19.3	2.1	9.9	0.5	Juvenile
Stercorarius antarcticus	Brown skua	Jan. 2013	13	−22.1	1.2	10.4	0.8	Adult
Stercorarius maccormicki	South polar skua	Jan.–Feb. 2013	17	−22.5	1.1	10.5	0.6	Adult
Potential food sources								
Euphausiacea superba	Antarctic krill	Jan. 2013	5 (pooled)	−27.8	n.d.	4.8	n.d.	
Pleuragramma antarcticum	Antarctic silverfish	Dec. 2012–Jan. 2013	13	−22.9	0.5	8.8	0.3	
Notothenia coriiceps	Black rockcod	Dec. 2102–Feb. 2013	6	−19.5	1.0	11.3	0.4	
Nacella concinna	Antarctic limpet	Jan. 2013	4	−15.1	1.3	8.6	1.3	

[a] SD = standard deviation.

Table 2

$\delta^{15}N$ values of glutamic acid and phenylalanine in Antarctic krill (data from Schmidt et al., 2004, 2006). Trophic position values based on $\delta^{15}N$ of amino acids were estimated by the equation suggested by Chikaraishi et al. (2009).

Region	Station	Sample type	$\delta^{15}N$ (‰) of glutamic acid	SD*	$\delta^{15}N$ (‰) of phenylalanine	SD	Trophic Position	References
South Shetland Is.		Abdominal segment 3 (female)	13.8	0.7	-0.7	0.6	2.5	Schmidt et al., 2004
		Remaining body (male)	13.2	0.5	-1.4	0.3	2.5	Schmidt et al., 2004
		Remaining body (female)	12.1	0.7	-2.5	0.2	2.5	Schmidt et al., 2004
South Georgia	St. 1	Abdominal segment	15.6	0.4	-1.2	0.7	2.8	Schmidt et al., 2006
↑	St. 2	Abdominal segment	14.6	0.6	-1.7	1.0	2.7	Schmidt et al., 2006
	St. 3	Abdominal segment	12.9	0.1	-2	0.7	2.5	Schmidt et al., 2006
↓	St. 4	Abdominal segment	13.8	0.1	-2.2	0.7	2.7	Schmidt et al., 2006
Southern Scotia Sea	St. 5	Abdominal segment	13.7	0.2	-1.1	0.4	2.5	Schmidt et al., 2006
Mean			*13.7*		*-1.6*		*2.6*	
SD			*1.1*		*0.6*		*0.1*	

*SD = standard deviation

revealed a relatively heavier and broader range of $\delta^{13}C$ than in other birds (Scheffe's multiple range test, $p > 0.001$). On the other hand, the $\delta^{13}C$ and $\delta^{15}N$ signatures from brown skua and south polar skua showed statistical similarity (one-way ANOVA, $F_{1,28} = 0.684$, $p = 0.415$ for $\delta^{13}C$ and $F_{1,28} = 0.005$, $p = 0.944$ for $\delta^{15}N$).

The $\delta^{15}N$ values of Antarctic silverfish were not significantly different from those of Antarctic limpet (two-sample *t*-test, $df = 15$, $p = 0.85$). Black rockcod had relatively heavier carbon (-19.5 ± 1.0‰, $n = 6$) and nitrogen (11.3 ± 0.4‰, $n = 6$) isotopic values than most of the avian samples.

The TA calculated for the south polar skua (5.89), brown skua (4.99) and kelp gull (4.19) spanned wide ranges of both $\delta^{13}C$ and $\delta^{15}N$ values (Table 3). However, SEAc of kelp gull (2.77), which showed a broad range in $\delta^{13}C$ (-19.3 ± 2.1‰), was higher than south polar skua (2.28) and brown skua (2.35). However, there was no overlap between kelp gull and other seabirds. The overlap between south polar skua and brown skua was 53% (Table 3).

Table 3

Proportion of overlap area between the avian standard ellipse area (40% prediction) and the estimated values of the convex hull total area (TA) and standard ellipse area corrected for small size (SEAc) of each species in a cross-plot of avian $\delta^{13}C$ and $\delta^{15}N$ estimated by Stable Isotope Bayesian Ellipses in R (SIBER).

	S. antarcticus	*S. maccormicki*	*L. dominicanus*
S. antarcticus		0.53	0.00
S. maccormicki			0.00
L. dominicanus			
TA	4.99	5.89	4.19
SEAc	2.35	2.28	2.77

4. Discussion

4.1. Trophic position of krill and seabirds

Nitrogen stable isotopes can support trophic information (DeNiro and Epstein, 1981; Minagawa and Wada, 1984; Vander Zanden et al., 1997). The $\delta^{15}N$ value of the baseline, TP of basal organisms and TDF value are needed to estimate consumer TP (Post, 2002). However, it is difficult to obtain a durable baseline $\delta^{15}N$ value for primary producers or primary consumers because of their spatiotemporal variation and their different turn-over time in contrast to that of consumers. For this reason, the nitrogen isotope values of krill, which is considered to be the baseline of the avian food chain in the Southern Ocean, varied in space and time (over a year), even though they were collected during the same season in austral summer (see Table 4). Moreover, the TP of krill may not be exactly 2 which is the value of the primary consumer. Interestingly, the estimated $TP_{glu/phe}$ of adult krill appeared to be homogeneous (TP = 2.6; see Table 2) with a small deviation (± 0.1) less than the systematic error for this technique (± 0.2, Chikaraishi et al., 2009). The stability of the $TP_{glu/phe}$ of krill suggests that they have a strong preference for prey without significant spatial and temporal variation in the austral summer. Krill change their diet according to their life stage to avoid interspecies food competition with juvenile krill (e.g., Frazer, 1996; Schmidt et al., 2003, 2006; Zhang et al., 2017). For instance, adult krill preferentially foraged mesozooplankton rather than particulate organic matters to avoid food competition with juveniles in Prydz Bay, and the carbon isotopic values of adult krill were lighter than those found in juveniles (Zhang et al., 2017). Therefore, a constant $TP_{glu/phe}$ of krill means maintaining this feeding strategy and strong preference of krill for prey during the austral summer in the Southern Ocean. Regarding this homogeneity, we used the $TP_{glu/phe}$ of krill as the base of the food chain to estimate the TP of seabirds in austral summer.

The estimated TP values of the south polar skua were very similar to those of the brown skua (Fig. 2). Here, we noted a difference of 2 trophic level between the TP of these seabirds and krill (see Fig. 2). It is

Table 4
Compiled dataset of δ^{13}C and δ^{15}N values for Antarctic krill reported in the Southern Ocean.

| Region	Stage	Sampling date	Samples (n)	δ^{13}C (‰)	SD*	δ^{15}N (‰)	SD	Comment	References
Lazarev Sea	Juvenile	Apr. 1999	23	−31.1	0.7	2.1	0.9	Whole body	Schmidt et al. (2003)
	Adult	Apr. 1999	20	−31.3	0.7	3.6	0.4	Whole body	Schmidt et al. (2003)
South Georgia	Juvenile	Jan. 1996	20	−26.3	1.5	3.5	0.6	Whole body	Schmidt et al. (2004)
	Male	Jan. 1996	3	−22.7	2.3	5.3	0.4	Whole body	Schmidt et al. (2004)
	Gravid female	Jan. 1996	3	−22.6	1.0	4.0	0.3	Whole body	Schmidt et al. (2004)
South Shetland Is.	non-gravid Female	Mar. 2000	6	−27.2	0.5	3.8	0.2	Whole body	Schmidt et al. (2004)
	Juvenile	Mar. 2000	9	−25.1	0.9	4.2	0.4	Whole body	Schmidt et al. (2004)
	Gravid female	Mar. 2000	9	−28.3	0.7	2.9	0.4	Whole body	Schmidt et al. (2004)
	Juvenile	Jan. 2007 & 2009	33	−26.9	0.7	2.6	0.3	Whole body	Polito et al. (2013) and references therein
	Adult female	Jan. 2007 & 2009	88	−26.4	1.0	3.5	0.7	Whole body	Polito et al. (2013) and references therein
	Adult male	Jan. 2007 & 2009	59	−26.7	1.0	3.3	0.6	Whole body	Polito et al. (2013) and references therein
Southern Scotia Sea	Male subadult	Jan. 2003	5	−27.7	0.8	3.2	0.5	Muscle tissue	Schmidt et al. (2006)
	Female adult	Jan. 2003	3	−26.7	0.8	3.9	0.4	Muscle tissue	Schmidt et al. (2006)
South Georgia	Male adult	Feb. 2003	3	−21.0	0.3	5.3	0.3	Muscle tissue	Schmidt et al. (2006)
	Female adult	Feb. 2003	3	−21.0	1.5	5.2	0.8	Muscle tissue	Schmidt et al. (2006)
Prydz Bay	Juvenile	Dec. 2012–Mar. 2013	9	−27.5	1.31	1.7	0.7	Whole body	Zhang et al. (2017)
	Adult	Dec. 2012–Mar. 2013	10	−27.5	1.15	2.8	0.58	Whole body	Zhang et al. (2017)
Marian Cove	Pooled	Jan. 2013	5	−27.8	n.d.	4.8	n.d.	Whole body	This study
Mean				**−26.3**		**3.6**			
SD				**2.9**		**1.0**			

*SD = standard deviation.
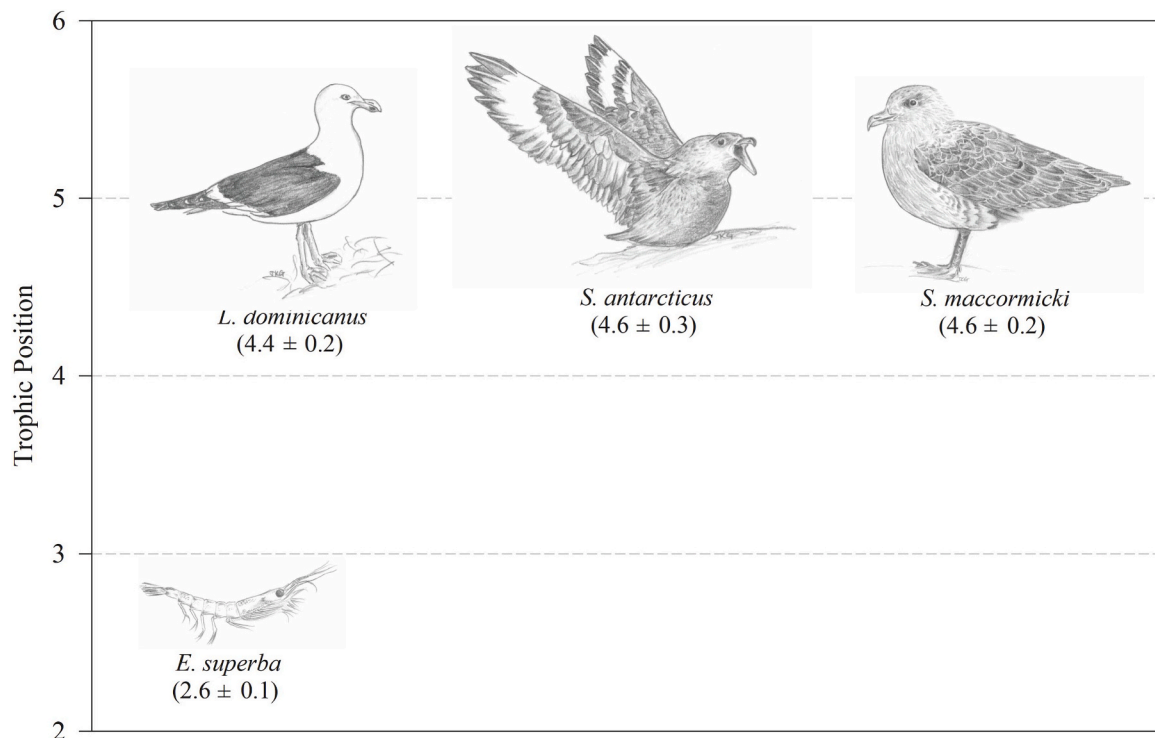
Fig. 2. Estimated trophic positions of Antarctic krill and 3 seabirds. Trophic position values were estimated using the trophic position of a base of the food chain (Antarctic krill = 2.6 ± 0.1, see Table 2) and trophic discrimination factor (TDF = 2.9‰) from previously reported data for avian whole blood (Cherel et al., 2005 and references therein).

noteworthy that this aligns with previous studies on the dietary preference of penguins for krill and Antarctic seabirds as predators of the chicks and eggs of penguins (e.g., Ridoux, 1994; Casaux and Barrera-Oro, 2006; Dimitrijević et al., 2018).

The estimated TP of kelp gulls was 4.4 ± 0.2. Considering the wide range of $\delta^{13}C$ values of kelp gulls, their food sources seemed to vary during the austral summer. For instance, the potential food sources, e.g., Antarctic silverfish, black rockcod and Antarctic limpet, also indicated higher $\delta^{13}C$ values in this study (−22.9 ± 0.5‰, −19.5 ± 1.0 and −15.1 ± 1.3‰, respectively; Table 1). This means that the major 'base of the food source' for kelp gulls was alternative food sources, not krill. However, we estimated TP values using the $TP_{glu/phe}$ of krill as the base of the food web in this study. This is not within the basic assumption for the estimation of TP. Therefore, the actual TP value of kelp gulls may differ from the results we have presented.

Polito et al. (2019) reported that it was possible to force the mean nitrogen isotope value of krill predators by 2.4‰ due to the variation in the individual stable isotope values of krill based on the results of global generalized linear models. These potential changes (2.4‰) in the krill predator isotope values can significantly impact the systematic error for the TP estimate (0.8). However, the systematic error of the estimated TP of seabirds in this study did not exceed ±0.4. The highest error (±0.3) occurred in brown skua, with a standard deviation of $\delta^{15}N$ ±0.8 (see Fig. 2 and Table 1). Changes in the individual $\delta^{15}N$ values of krill could cause fluctuations in the $\delta^{15}N$ of seabirds (Polito et al., 2019). However, it seems that this error was reduced in the process of subtracting the $\delta^{15}N$ value of krill in the TP calculation (see Eq. (2) in Materials and Methods). It is expected that the composition of the diet may have a more significant effect on the TP of predators than individual variations in the $\delta^{15}N$ of prey. Because of the restricted information on food sources in this study, it may have some limitations in explaining the precise trophic linkages and their relationships with variations in TP (e.g., Kelp gull). However, the estimated TP of seabirds reasonably considered avian foraging behavior compared to those of previous biological observations.

4.2. Ecological niche and competitions

Recently, kelp gull habitats were reported to be expanding to the Antarctic Peninsula, possibly related to the increase in ice-free area (e.g., Lee et al., 2017; Parnikoza et al., 2018). In the present research, the individual isotopic values of kelp gulls had a very broad range and hence a large isotopic niche width (Fig. 3). Kelp gulls occasionally feed on various sources, such as mollusks, fish and crustaceans, near shallow littoral zones (Favero et al., 1997). This suggests that wide habitats and large opportunity for various food sources for the kelp gull may lead to large individual variations in $\delta^{13}C$ values and isotopic niches. The distribution of the stable isotope values of Antarctic silverfish, black rockcod and Antarctic limpet shows their potential as food sources in the study area (see Table 1). Kelp gulls are known as important predators of

Antarctic limpet, which can represent an inshore carbon source (Favero et al., 1997). Considering this fact, the greater $\delta^{13}C$ value of kelp gull indicated that they may have more inshore prey than other species (e.g., Newsome, et al., 2007; Cherel and Hobson, 2007; Lee et al., 2021). From another point of view, it also suggests that the isotopic niche of kelp gull could be easily affected by terrestrial sources and human-derived organic matter (c.f. Frixione et al., 2012). Therefore, it should be noted that kelp gull has potential as an indicator of the influence of these allochthonous sources by climate change.

Brown skua and south polar skua, which are known as the highest consumers on the Barton Peninsula, had similar TPs and isotopic niches (Figs. 2 and 3A). It is known that the south polar skua forages mainly for fish rather than penguins because they have a relatively small body size and fall behind in food competition against brown skua on King George Island (e.g., Peter et al., 1990). However, the overlap area in the isotopic niches between brown skua and south polar skua indicated 53% of the ellipse (Table 3). Moreover, the individual isotopic values in these two seabirds showed a widespread distribution and the high TA values, at 4.99 and 5.89, respectively (Fig. 3 and Table 3). This means that the occupancy of the penguin rookery was limited to some individuals. This was also consistent with direct observations in the study area. This means that individuals who did not occupy the penguin rookery fed on alternative food sources, such as Antarctic silverfish. Therefore, the widespread distribution and overlap of isotopic niches were due to individual differences in the composition of prey. Consequently, the brown skua and south polar skua are considered "generalists", and they seem to be adaptively adjusted alternative food sources.

The TPs and isotopic niches of Antarctic seabirds were obtained from the stable isotopic values of avian blood. Here, we noted that the isotopic signature from avian blood reflected time-integrated information from only several weeks in austral summer (Hobson and Clark, 1992; Bearhop et al., 2002). Considering the rapid environmental changes in recent years in the Antarctic Peninsula, such as large sea ice retreat and the collapse of ice shelves, further studies should be undertaken with long-term observations to understand the changes in competition and adaptation of seabirds.

5. Conclusion

The present study investigated the TPs and isotopic niches of 3 seabird species on the Barton Peninsula, Antarctica, using a stable isotopic approach. The estimated avian TPs were reasonable values considering ecological knowledge. The kelp gulls, which had broad individual variation in isotopic values, seemed to be generalists due to their extended habitat and opportunities to feed on various food sources. Meanwhile, the isotopic niches of the highest consumers on the Barton Peninsula, such as brown skua and south polar skua, suggested that there was niche segregation through foraging alternative food sources. This study suggests that a long-term study of the ecological niche of seabirds, which serves as an indicator of ecological response to climate
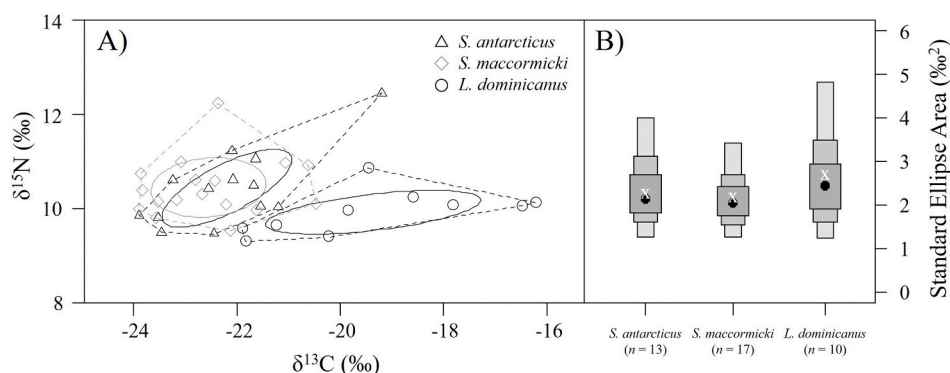

Fig. 3. (A) Dual plot of carbon and nitrogen stable isotopes of Antarctic seabirds. Individual 40% prediction standard ellipses (solid line) and convex hulls (dashed line) for each species on the Barton Peninsula. (B) Posterior distributions of the seabird species with the 50, 75, and 95% credible intervals are represented in a shaded density plot. The standard ellipse area (SEA, black dot) and corrected standard ellipse area (SEAc, white 'x') were obtained from Stable Isotope Bayesian Ellipses in R (SIBER).

change, is required.

Ethical approval

All procedures, including those involving animals, were carried out in accordance with the ethical standards of the institutional guidelines of the Animal Welfare Ethical Committee and the Animal Experimental Ethics Committee of the Korea Polar Research Institute (KOPRI, South Korea).

Author statement

J.-K. Gal and B. Choi: conceptualization, writing original draft preparation and editing.

B. Choi and J.-O. Min: sample treatment and stable isotope analysis.

B.-K. Kim, J.-O. Min and S.-Y. Ha: collection of marine organisms and validation.

J.-W. Jung, W. Y. Lee and J.-H. Kim: seabird sample collection, and identification.

K.-H. Shin, S.-Y. Ha and J.-H. Kim: supervision, review and funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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