Little penguin (*Eudyptula minor*) diet at three breeding colonies in New Zealand

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Abstract: At-sea shifts in food quality and availability can affect populations of marine birds; however, it is difficult to evaluate the impacts of changes in prey composition and availability without some baseline information on diet composition. The little penguin (*Eudyptula minor*) is a common inshore-feeding seabird in New Zealand and Australia. To date, only two dietary studies have been undertaken on the little penguin in New Zealand, at two widely separated locations. This study recorded diet of little penguins during the chick-rearing stage of breeding at three colonies in southern New Zealand. Sixty-nine stomach samples were acquired via the stomach flushing technique at Banks Peninsula, Oamaru, and Stewart Island. Prey composition differed between each site: (1) at Oamaru, Graham's gudgeon (*Grahamichthys radiata*) occurred most frequently (100%) and contributed the most to meal mass (92.1%); (2) at Banks Peninsula arrow squid (*Nototodarus sloanii*) occurred most frequently (87.5%), but two fish species – slender sprat (*Sprattus antipodum*) (33.9%) and ahuru (*Auchenoceros punctatus*) (37.4%) – contributed most to meal mass; and (3) at Stewart Island arrow squid occurred most frequently (91.3%), and contributed most to meal mass (73.1%). Little penguins take a wide diversity of species, and may switch between species, probably in response to temporal variation in availability. In New Zealand, little penguins ate higher proportions of lower quality cephalopods than those in Australia. As top predators in the marine ecosystem, changes in little penguin diet may indicate changes occurring in the inshore marine ecosystem.

Keywords: *Eudyptula minor*; little penguin; New Zealand; prey availability; prey quality; seabird; stomach contents; stomach flushing

Introduction

The little penguin (*Eudyptula minor*) is a common seabird with a broad distribution across New Zealand and Australia (IUCN 2011). Although classified as a species of least concern, in New Zealand many little penguin populations are in decline due to land-based factors such as human encroachment and introduced predators (Johannesen et al. 2002; Miskelly et al. 2008). Seabird populations are also vulnerable to changes in the marine environment, as a result of competition with fisheries (Cury et al. 2011) and fluctuating oceanic conditions (Schreiber & Schreiber 1984; Perriman et al. 2000; Ropert-Coudert et al. 2009), which can reduce the abundance and availability of preferred prey. Increases in sea surface temperatures caused by El Niño Southern Oscillation (ENSO) events can cause the prey of little penguins to inhabit different areas or become locally scarce, disrupting regular breeding and affecting whole breeding populations (Perriman et al. 2000; Numata et al. 2004; Robinson et al. 2005; Ropert-Coudert et al. 2009).

During the breeding season, little penguins are central-place foragers, restricted to foraging areas close to their nest, and are therefore vulnerable to small regional changes in prey abundance and distribution (Chiaradia et al. 2007). In Australia, changes in food availability for the little penguin have resulted in delays to the start of the breeding period and a subsequent reduced likelihood of the production of a second clutch, increased mortality of chicks, and poor adult and chick body condition, resulting in reduced chick immunity and longer fledging periods (Reilly & Cullen 1981; Nisbet & Dann 2009; Chiaradia et al. 2010). In New Zealand, the lack of information about diet makes it impossible to identify any changes in prey availability that may occur, which may be responsible for seasons of poor reproductive success.

To date only two studies have determined little penguin diet at two locations in New Zealand: diet at the Oamaru penguin colony was monitored over the course of a year in 1994/95 (Fraser & Lalas 2004) and diet was sampled during one week at Codfish Island in 1984 (van Heezik 1990). Since little penguin populations in Australia have been shown to be vulnerable to changes in food availability and quality (Chiaradia et al. 2010), this may also be the case in New Zealand. Establishing base-line information on diet is a necessary step towards understanding the potential impacts of changes in prey abundance and availability on little penguin populations. In addition, because little penguins are top predators in marine ecosystems, fluctuations in their populations can indicate complex regional changes in the marine environment (Cherel & Weimerskirch 1995; Chiaradia et al. 2010).

The objective of this study was to establish diet composition of little penguins at three colonies in southern New Zealand during the chick-rearing phase of breeding, when penguins are most vulnerable to changes in prey availability and prey quality. We also sampled penguins at the Oamaru colony to investigate possible changes in diet over time since the study by Fraser & Lalas (2004).

Methods

Study sites

We sampled little penguins at three sites along the east coast of southern New Zealand: (1) Otanerito Bay (43°50.44′ S, 173°4.07′ E), on the south-east coast of Banks Peninsula, where penguins were captured at the mouth of a large cave; (2) the Oamaru Creek Colony located adjacent to the Oamaru Blue Penguin Colony (45°6.14′ S, 170°58.19′ E); and (3) Ackers Point (46°53.44′ S, 168°9.51′ E) outside the town of Oban on Stewart Island (Fig. 1).

Diet sampling

We captured individual penguins after dusk when they were returning to their nests, choosing penguins with hard, distended stomachs to ensure only individuals with full stomachs were sampled. We collected stomach samples from 23 birds at Oamaru between 25 and 29 November, 24 at Banks Peninsula between 2 and 4 December, and 22 at Stewart Island between 6 and 8 December 2010.

We flushed stomachs using the water-offloading technique (Wilson 1984), with a 7-mm surgical catheter attached to a 5-L commercial garden sprayer. This was inserted into the penguin's oesophagus until slight resistance was met, signalling the bottom of the stomach. Seawater was slowly streamed into the penguin's stomach until signs of regurgitation occurred. We then removed the catheter, turned the bird upside down, and gently massaged its stomach to facilitate regurgitation. Stomach contents were transferred to 1-L sealable pottles and frozen within 3 h of collection. After flushing birds a maximum of three times, we administered ~40 ml of diluted Vytrate, an oral rehydration solution, via a tube to prevent dehydration. We marked all individuals on their chest with a non-toxic permanent marker to prevent recapture, released them at the point of capture and monitored them for signs of stress for an hour. We sampled at a different location each night at each site to avoid sampling both parents from the same chick on consecutive nights. We surveyed sites the next day to ensure all penguins sampled from the previous night were in good health.

Stomach contents analysis

Each stomach sample was thawed, then drained using a 1000μm fine-mesh sieve and transferred to black dissecting trays. We removed, counted and dried diagnostic prey items such as otoliths, bones and beaks, and stored whole items such as skulls and intact bones or flesh in 90% ethanol. Where possible, we identified otoliths to species level using Furlani et al. (2007) and Smale et al. (1995) and expert advice (C. Lalas, pers. comm.).

We measured the upper beak of paired cephalopod beaks (from the tip of the beak to the right-angle protrusion roughly halfway along the beak), and the lower beak in the absence of a match, to the nearest micrometre, using photographic Olympus DP2-BSW application software. For samples that contained more than 20 stomatopod larvae or otoliths per species ($n >$ 20), we randomly subsampled 20 stomatopod larvae and 20 otoliths. We removed any otolith that showed signs of a high degree of digestion, as it was deemed to be from a previous foraging trip. In samples with less than 20 otoliths, we paired otoliths by length to avoid pseudoreplication.

We used a Canon EOS 5D with a 50mm macro lens set at 1:2 to take high-resolution photographs of groups of 20 otoliths placed on a black background. We added a white reference circle with an exact diameter to each photograph, using Adobe Photoshop Elements 9.0. Using photo recognition software, we measured the maximum length and width of individual otoliths to the nearest 0.01 mm in comparison to the reference circle (Mattern & Ellenberg 2012).

We applied regression equations, derived from a reference collection of squid beaks and fish otoliths, relating beak and otolith lengths to total body length (cm), total fish length (cm) and mass (g) of individual squid and fish species respectively (Table 1). Measurements of stomatopod larvae were taken from the tips of the eyes to the telson spines and an analysis of variance (ANOVA) was used to detect differences in lengths between samples. When no differences were found, 20 stomatopod larvae were sampled from the least degraded sample and individually weighed. The average of these weights was then applied to all samples when determining proportional contribution. Stomatopod larvae could not be identified to species due to their larval stage and digested state.

Statistical analysis

For each prey item, at each study site, we calculated the frequency of occurrence (FO%: the proportion of the total number of stomachs from that site that a species occurred in), the proportional number contribution (N%), and proportional weight contribution (W%). We used Simpson's Reciprocal Index of Diversity to represent prey diversity for each site (Simpson 1949). We tested for differences in prey diversity, average number of prey items eaten per bird, and individual prey sizes between sampling sites using univariate general linear models (GLMs) and used post-hoc Tukey HSD tests to identify where differences lay. All statistical tests were carried out in R version 2.13.0 (R Development Core Team 2005).

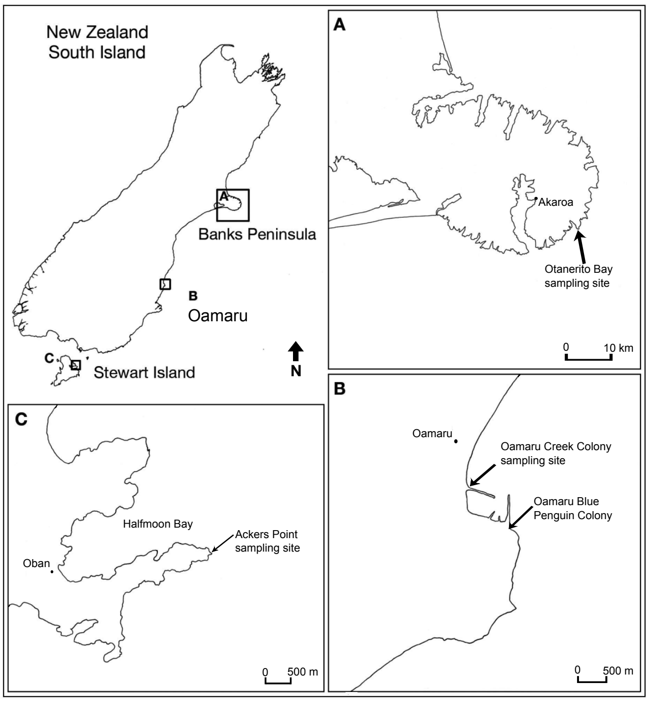

Figure 1. Little penguin sampling sites in southern New Zealand.

Results

Prey diversity

Twelve prey species were identified across all penguin stomach samples: 10 fish species, one cephalopod, and one crustacean (Table 2). Prey diversity varied between study sites ($F_{2, 66} = 5.663$, $P < 0.01$; Fig. 2); diversity at Oamaru was lower than at Banks Peninsula ($P < 0.01$) and Stewart Island ($P < 0.05$),

Table 1. Regression equations developed for prey species derived from a reference collection of fish otoliths and squid beaks determining fish fork length (FL), total length (TL) and mass, using otolith length (OLmm), and cephalopod dorsal mantle length (DML), TL and mass using break upper rostral length (URL).

Prey species	Prey length	Prey length (cm)	Prey mass (g)
Ahuru (*Auchenoceros punctatus*)	TL	$1.409 \times OL^{1.404}$	$0.0107 \times OL^{4.375}$
Barracouta (*Thyrsites atun*)	FL	$3.157 \times OL^{1.190}$	$0.119 \times OL^{3.722}$
Estuary stargazer (*Leptoscopus macropygus*)	TL	$1.505 \times OL^{1.386}$	$0.022 \times OL^{4.331}$
Graham's gudgeon (*Grahamichthys radiata*)	TL	$5.046 \times OL^{0.600}$	$0.938 \times OL^{3.196}$
Red cod (*Pseudophycis bachus*)	TL	$0.764 \times OL^{1.577}$	$0.0036 \times OL^{4.780}$
Slender sprat (*Sprattus antipodum*)	FL	$5.625 \times OL^{0.916}$	$1.079 \times OL^{3.322}$
Arrow squid (*Nototodarus sloanii*)	DML	$7.832 \times URL^{0.711}$	$9.299 \times URL^{2.186}$
	TL	$12.355 \times URL^{0.755}$	

Table 2. Fine-scale frequency of occurrence, proportional contribution by number and proportional contribution by weight of prey species consumed by little penguins at Oamaru, Banks Peninsula and Stewart Island; number of birds in brackets.

Prey species	Frequency of occurrence			Proportional contribution by number			Proportional contribution by weight		
	Oamaru (n = 23)	Banks Peninsula (n = 24)	Stewart Island (n = 22)	Oamaru (n = 23)	Banks Peninsula (n = 24)	Stewart Island (n = 22)	Oamaru (n = 23)	Banks Peninsula (n = 24)	Stewart Island (n = 22)
Cephalopods									
Arrow squid (*Nototodarus sloanii*)	91.3	87.5	91.3	4.5	16.8	4.6	4.8	14.6	73.1
Fish									
Slender sprat (*Sprattus antipodum*)	26.1	62.5	59.1	0.2	7.3	1.1	2.7	33.9	10.4
Graham's gudgeon (*Grahamichthys radiata*)	100.0	12.5	13.6	94.4	0.2	0.2	92.1	0.1	0.5
Red cod (*Pseudophycis bachus*)	4.3	33.3	63.6	0.0	10.5	0.9	-	14.0	8.8
Ahuru (*Auchenoceros punctatus*)	0.0	75.0	9.1	0.0	59.3	0.0	-	37.4	0.5
Long-snouted pipefish (*Stigmatopora macropterygia*)	0.0	4.2	22.7	0.0	0.1	0.6	-	-	-
Seahorse	0.0	12.5	13.6	0.0	0.5	0.3	-	-	-
Barracouta (*Thyrsites atun*)	4.3	0.0	4.5	0.0	0.0	0.0	0.1	-	1.2
Estuary stargazer (*Leptoscopus macropygus*)	13.0	0.0	0.0	0.2	0.0	0.0	0.2	-	-
Unidentified fish A	13.0	41.7	0.0	0.7	5.3	0.0	-	-	-
Unidentified fish B	0.0	0.0	54.6	0.0	0.0	6.6	-	-	-
Crustaceans								-	-
Stomatopod larvae	0.0	0.0	59.1	0.0	0.0	85.7	-	-	5.5

but no difference was found between prey diversity at Banks Peninsula and Stewart Island ($P = 0.70$; Fig. 2).

Frequency of occurrence

Fine-scale (species-level) and broad-scale (fish vs cephalopods vs crustaceans) FO%, N% and W% for prey items consumed at all three sampling sites are shown in Tables 2 and 3. Fish species occurred most frequently in samples from Oamaru (100%) and Banks Peninsula (87.5%). Crustaceans were absent at both these sites but were taken by penguins at Stewart Island, occurring in 59.1% of stomach samples (Table 2).

Overall, arrow squid were consumed most frequently, occurring in 91.3% of stomach samples from Oamaru and Stewart Island, and 87.5% of stomach samples from Banks Peninsula (Table 2). Graham's gudgeon occurred in 100% of the stomach samples at Oamaru, but only 13.6% and 12.5% of stomach samples at Stewart Island and Banks Peninsula respectively. Two species of fish were too small and too digested to be identified, one occurred frequently only at Stewart Island, and another larger species at Oamaru and Banks Peninsula.

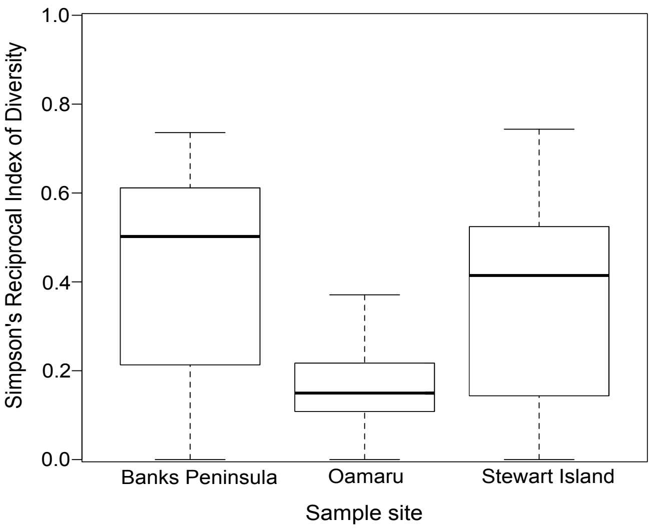

Figure 2. Boxplots of Simpson's Reciprocal Index of Diversity for prey items consumed by little penguins at Banks Peninsula, Oamaru and Stewart Island. The bold line represents the median; the box, the upper and lower quartiles; and the dotted lines, the range.

Table 3. Broad-scale frequency of occurrence, proportional contribution by number and proportional contribution by weight of prey species consumed by little penguins at Oamaru, Banks Peninsula and Stewart Island; numbers of birds in brackets.

	Oamaru (n = 23) %	Banks Peninsula (n = 24) %	Stewart Island (n = 22) %
Frequency of occurrence			
Fish	100	87.5	81.8
Cephalopods	91.3	87.5	91.3
Crustaceans	0	0	59.1
Proportional number contribution			
Fish	95.5	83.2	9.7
Cephalopods	4.5	16.8	4.6
Crustaceans	0	0	85.7
Proportional contribution by weight			
Fish	95.2	85.4	21.4
Cephalopods	4.8	14.6	73.1
Crustaceans	0	0	5.5

Proportional contribution by numbers and mass

Penguins at Oamaru and Banks Peninsula ate the highest number of fish, which accounted for 95.5% and 83.2% of all prey types eaten respectively, and crustaceans were the most numerous prey items at Stewart Island (85.7%; Tables 2 & 3). Individuals at Oamaru ate larger numbers of Graham's gudgeon compared with other species; while at Banks Peninsula more ahuru, and Stewart Island more stomatopod larvae were consumed (Table 2). There was no significant difference in the number of prey items eaten between sites (Oamaru, $\mu = 146 \pm 92$; Banks Peninsula, $\mu = 66 \pm 111$; Stewart Island, $\mu = 191 \pm 397$; $F_{2, 66} = 1.63$, $P = 0.203$).

Fish contributed most to meal mass at Oamaru (95.2%) and Banks Peninsula (85.4%), but at Stewart Island cephalopods comprised the greatest mass (73.1%; Table 3). Most of the mass consumed at Oamaru was Graham's gudgeon, while penguins at Banks Peninsula ate a greater mass of ahuru, whereas at Stewart Island arrow squid contributed greatest to meal mass (Table 2).

Prey size

Estimated prey mass and length for the main prey items are given in Table 4. Total prey length varied between sample sites ($F_{2, 1627} = 418.4$, $P < 0.001$; Table 4); prey items taken at Banks Peninsula were significantly longer than at Oamaru ($P < 0.001$; Fig. 3) and at Stewart Island ($P < 0.001$). Prey items taken at Oamaru were larger on average than at Stewart Island ($P < 0.001$).

The average prey item mass varied between sampling sites ($F_{2, 1627} = 93.92$, $P < 0.001$). Individuals at Banks Peninsula consumed heavier prey items than at Oamaru ($P < 0.001$) and Stewart Island ($P < 0.001$). There was a trend for prey at Oamaru to be a greater mass than prey at Stewart Island ($P = 0.06$).

Discussion

Prey diversity and composition

Prey choice for many seabird species is determined by the

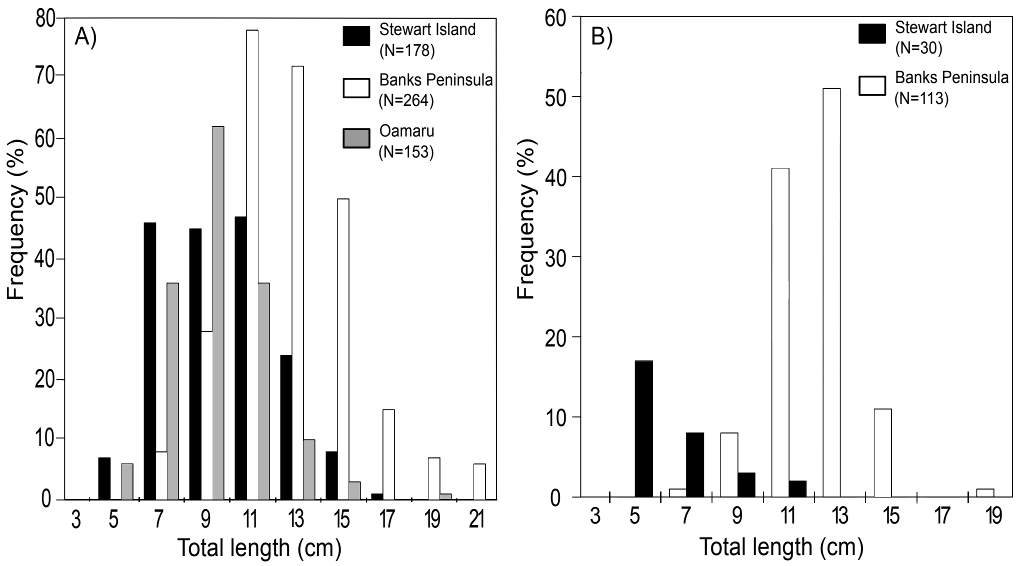

Figure 3. The length-frequency distributions of calculated total length for (a) arrow squid and (b) red cod in little penguin stomach samples from Oamaru, Banks Peninsula and Stewart Island.

Table 4. The estimated mass (g) and length (mean ± SD) calculated from otoliths and regression equations of major prey species found in little penguin stomach samples at Oamaru, Banks Peninsula and Stewart Island; number of prey items in brackets.

Prey species	Oamaru		Banks Peninsula		Stewart Island	
	Mean prey length (cm)	Mean prey mass	Mean prey length (cm)	Mean prey mass	Mean prey length (cm)	Mean prey mass
Arrow squid	9.4 ± 2.0 (153)	4.8 ± 3.7	12.7 ± 2.7 (264)	11.4 ± 7.6	9.7 ± 2.4 (178)	5.3 ± 3.7
Slender sprat	16.9 ± 1.9 (7)	59.6 ± 23.4	16.5 ± 3.1 (108)	60.2 ± 35.6	15.4 ± 2.5 (43)	45.3 ± 24.79
Graham’s gudgeon	6.6 ± 0.5 (400)	4.4 ± 1.4	6.9 ± 0.5 (3)	5.6 ± 1.8	6.5 ± 0.4 (2)	3.1 ± 1.0
Red cod	-	-	12.3 ± 1.6 (113)	17 ± 7.4	6.2 ± 2.0 (30)	3 ± 3.3
Ahuru	-	-	10.5 ± 3.6 (157)	8.2 ± 10.5	-	-
Estuary stargazer	8.9 ± 1.3 (6)	6.1 ± 2.8	-	-	-	-
Stomatopod larvae	-	-	-	-	13.71 ± 1.65 (mm) (135)	0.02 ± 0.006 (30)

regional availability of individual prey species as well as their nutritional value. In Australia, little penguins have small foraging ranges (<20 km; Collins et al. 1999) and are generalist consumers, eating a diversity of prey items including fish, cephalopods, and crustaceans, but concentrating on nutritionally valuable species such as pilchards (*Sardinops* sp.) and anchovies (*Engraulis australis*; Klomp & Wooller 1988; Montague & Cullen 1988). A limited aerobic capacity and small gape size restrict little penguins to feeding on small, pelagic schooling fish, no deeper than ~70 m (Bethge et al. 1997; Ropert-Coudert et al. 2006). Diet composition typically varies between penguin colonies as a consequence of their small foraging range and varying abundances of their preferred prey, which are influenced by local conditions such as ocean temperature and bathymetry (Gales & Pemberton 1990; Cullen et al. 1991; Chiaradia et al. 2007, 2012).

Species composition of little penguin stomach samples in this study and in the studies of Fraser & Lalas (2004) and van Heezik (1990) indicate that little penguins in New Zealand are also generalist foragers of small inshore species, able to switch between a number of prey species. The higher number of species recorded at Oamaru by Fraser & Lalas (2004); i.e. 22 c.f. 12 in the present study and 6 at Codfish Island (van Heezik 1990) likely reflects the longer sampling period (monthly throughout one year).

Graham’s gudgeon and arrow squid have been consistently important species at Oamaru. In this study Graham’s gudgeon, which is a small schooling fish that grows to a maximum of ~6.5 cm (Paulin & Roberts 1992), occurred in all stomachs, and accounted for 92% of meal mass. Fraser and Lalas (2004) also reported a high occurrence of Graham’s gudgeon during November 1994 (80% of stomachs), although this dropped significantly to 20% in December and 0% in January 1995 when this species was replaced with slender sprat and pigfish (*Congiopodus* sp.). Little penguins may switch between these species depending on availability. Likewise, estuary stargazers, a fish that was absent during the 1994/95 study, but present in 2010, could be a substitute prey item during periods of low abundance of other species, such as slender sprat, which made a greater contribution to the diet during the same month of sampling in the 1994/95 study.

Arrow squid occurred in most (88–91%) stomach samples at all three locations in this study. While a large number of small arrow squid contributed most to meal mass (73.1%) at Stewart Island, a smaller number of larger squid contributed <15% of total meal mass at Oamaru and Banks Peninsula. Arrow squid also occurred frequently (>50% of stomachs) in previous studies in New Zealand and made up 20% and 40% of meal mass in November and December 1994 (van Heezik 1990; Fraser & Lalas 2004). In Australian studies, arrow squid occurred less frequently (Montague & Cullen 1988; Gales & Pemberton 1990), with birds from colonies near shallow areas taking less squid and more fish (Cullen et al. 1991). Little penguins may also forage on crustaceans and cephalopods when fish are not available (Weavers 1991).

The frequent occurrence of high numbers of stomatopod larvae in stomachs at Stewart Island was unusual, in that they were absent from the other localities, and crustaceans typically occur infrequently in little penguin stomachs in both Australia and New Zealand (Cullen et al. 1991; Fraser & Lalas 2004; Chiaradia et al. 2010). Due to their small size they comprised only 5.5% of meal mass.

Red cod and ahuru were found frequently at Banks Peninsula and Stewart Island, contributing significantly to the total mass of stomach contents at Banks Peninsula. van Heezik (1990) also found red cod and ahuru in over three-quarters of stomach samples at Codfish Island, off the coast of the South Island, but they were larval fish that did not contribute significantly to overall meal mass. Red cod has also been found in stomach samples of Australian little penguins in lower frequencies (Chiaradia et al. 2010) but ahuru is found only in New Zealand waters.

Prey such as barracouta, pipefish and seahorses contributed marginally to diets in this study but have been reported in larger quantities in Australian studies (Hobday 1991; Chiaradia et al. 2003, 2010). Barracouta in particular was found to be a major prey item in Australia when other preferred prey items were absent (Chiaradia et al. 2003, 2010).

Prey quality

The quality of prey items available to seabirds influences adult and chick body condition as well as overall breeding success (Romano et al. 2006; Österblom et al. 2008; Ludynia et al. 2010; Browne et al. 2011). Little penguins in Australia often target larger, fattier fish such as pilchards and anchovies (Klomp & Wooller 1988; Hobday 1991) because they yield more energy (Harris & Hislop 1978; Hislop et al. 1991). Slender sprat may be the New Zealand equivalent of anchovies and pilchard (Hislop et al. 1991). They were eaten by >50% of penguins sampled at Banks Peninsula and Stewart Island, but only ~25% of those at Oamaru, fewer than in the 1994/95 study (Fraser

& Lalas 2004). Ahuru are a morid cod, closely related to red cod, with intermediate energy content (Vlieg 1984), and grow to a maximum total length of 13.0 cm (Cohen et al. 1990). Penguins at Banks Peninsula may have been targeting these two species because they are energetically-rich schooling fish, both becoming fattier as they age (Harris & Hislop 1978; Fraser & Lalas 2004).

Arrow squid may be less preferred prey due to their low calcium content and proteins that are difficult to assimilate (Harris & Hislop 1978; Heath & Randall 1985; Cherel & Ridoux 1992). In Australia, higher proportions of squid and crustaceans were found in diets when high quality fish were absent (Cullen et al. 1991), and Fraser and Lalas (2004) proposed that the highest occurrence of arrow squid was when larger, preferred fish species were smaller than arrow squid. The importance of arrow squid in the diet of little penguins at Stewart Island could indicate an absence of preferred prey items at this locality.

Despite regional variation in diet, little penguin populations at both Oamaru and Banks Peninsula, both of which receive protection from predators, are growing (P. Agnew, Oamaru Blue Penguin Colony, and C. Challies, pers. comms.), suggesting the food supply is more than adequate. The status of the Stewart Island population is unknown. Small inshore fish species, although different at each locality, made up the bulk of the meals, suggesting that as long as inshore populations of small fish are healthy, little penguins should be able to find enough prey to reproduce. It would be of interest to determine whether the squid-dominated diet of little penguins on Stewart Island is associated with poorer reproductive success.

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