



Foraging ecology of the common dolphin *Delphinus delphis* revealed by stable isotope analysis

Katharina J. Peters^{1,2,*}, Sarah J. Bury³, Emma L. Betty¹, Guido J. Parra⁴,
Gabriela Tezanos-Pinto^{1,5}, Karen A. Stockin¹

¹Cetacean Ecology Research Group, School of Natural and Computational Sciences, Massey University, Auckland 0745, New Zealand

²Global Ecology, College of Science and Engineering, Flinders University, Adelaide 5001, South Australia

³National Institute of Water and Atmospheric Research, Greta Point, 301 Evans Bay Parade, Hataitai, Wellington 6021, New Zealand

⁴Cetacean Ecology, Behaviour and Evolution Lab, College of Science and Engineering, Flinders University, Adelaide 5001, South Australia

⁵Molecular Ecology of Aquatic Vertebrates Lab (LEMVA), Los Andes University, Bogota 11711, Colombia

ABSTRACT: Dolphins are among the largest and most diverse predators in marine ecosystems, but our understanding of their foraging ecology, which is crucial for ecosystem management, is poor. *Delphinus delphis* (common dolphins) are found in tropical and temperate waters globally. Stomach content studies indicate they are opportunistic predators that feed locally on abundant small pelagic schooling fish, but information is lacking on how their diet may vary seasonally and with ontogeny. We investigated effects of body length, sex, season, and year on *D. delphis* diet in the Hauraki Gulf, New Zealand, using carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) stable isotope analysis of 56 skin samples collected during 13 years (2004–2016). Dolphin $\delta^{15}\text{N}$ values changed with body length, suggesting ontogenetic dietary variation. Nitrogen isotope values were higher in austral autumn/winter compared to spring/summer, whilst $\delta^{13}\text{C}$ values decreased throughout the study period, suggesting temporal changes in primary productivity likely affecting the dolphins' diet. Sex had a minor effect on dolphin $\delta^{13}\text{C}$ values, with male and female isotopic niches overlapping by 62.6% and 45.2% (respectively). Our results provide a baseline for detecting future changes in the trophic ecology of *D. delphis* in a key habitat in New Zealand and highlight their role as a sentinel species in this coastal ecosystem.

KEY WORDS: Isotopic niche · Delphinids · Hauraki Gulf · New Zealand · Trophic ecology

— Resale or republication not permitted without written consent of the publisher —

1. INTRODUCTION

As top-level predators, cetaceans play an essential functional role in the marine ecosystem (e.g. Bowen 1997, Heithaus et al. 2008, Kiszka et al. 2015). Given their large size and their high energetic demands, cetaceans have the capacity to consume large quantities of prey and hence strongly influence the systems in which they reside (e.g. Coyle et al. 2007, Kiszka et al. 2015, Straley et al. 2018). Furthermore, in times of increased urbanisation and development

of coastal areas, they are also vulnerable to anthropologically induced ecosystem changes. Understanding their trophic ecology provides critical information for evaluating the consequences of potential impacts via environmental change and/or human interactions on marine communities and for informing ecosystem management (Heithaus et al. 2008).

Delphinus delphis (common dolphins) are highly mobile, demonstrating a wide distribution in temperate, subtropical, and tropical waters around the globe (Perrin 2009). Although they are considered

*Corresponding author: k.peters@massey.ac.nz

one of the most abundant delphinid species, very little is known about their diet or broader feeding ecology. Analysis of stomach contents derived from fisheries bycaught and stranded individuals indicate *D. delphis* are generalist predators with a high foraging plasticity as a consequence of their opportunistic feeding on abundant species of small pelagic schooling fish or cephalopods (Silva 1999, Pusineri et al. 2007, Meynier et al. 2008b, Marçalo et al. 2018, Brand et al. 2019). These prey species are often targeted by commercial fisheries, with *D. delphis* frequently bycaught in the purse seine fishery as well as in set nets (Slooten & Dawson 1995, Stockin & Orams 2009, Thompson et al. 2013). Nevertheless, little is known about their population- or area-specific diet or seasonal and ontogenetic changes, which highlights the importance of dietary studies to inform species conservation management.

New Zealand lies at the southernmost limit of the *D. delphis*' distribution in the Pacific Ocean (Natoli et al. 2006, Amaral et al. 2012). Here, the species occurs in both coastal and oceanic habitats (Neumann 2001, Stockin et al. 2008b); however, the coastal waters of the Hauraki Gulf are considered the stronghold for the country's *D. delphis* population with a year-round occurrence of the species (Stockin et al. 2008b, Stockin & Orams 2009, Dwyer et al. 2016, Hupman et al. 2018). Analyses of mitochondrial DNA have shown genetic differentiation between dolphins from this region compared to groups from other New Zealand waters (Stockin et al. 2014), while photo-identification suggests higher site fidelity in the Hauraki Gulf compared to neighbouring regions (Neumann et al. 2002a, Hupman 2016).

The Hauraki Gulf borders the coastline of Auckland, which is New Zealand's largest city with over 1.4 million inhabitants. There is thus a wide range of anthropogenic impacts on the local marine fauna caused by tourism (Stockin et al. 2008a), fisheries (Stockin et al. 2009b), vessel strikes (Martinez & Stockin 2013, Dwyer et al. 2014), and pollution (Stockin et al. 2007). Despite the general oceanic distribution of *D. delphis*, which should logically reduce human contact with the species, the continuing year-round use of this inshore coastal sea by *D. delphis* in the Hauraki Gulf has led to their continued exposure to these impacts. Of concern is that toxin loads for *D. delphis* in the Hauraki Gulf are comparable with coastal species such as Hector's dolphins *Cephalorhynchus hectori* (Stockin et al. 2010), highlighting the vulnerability of this population (Irwin 2005).

Commercial fisheries pose a serious threat to many cetacean populations (Read et al. 2006), through

direct interactions (e.g. bycatch or entanglement; DeMaster et al. 2001) and via competition where populations suffer resource depletion because their prey are being heavily targeted by fisheries. Meynier et al. (2008b) analysed stomach contents of *D. delphis* from different locations on New Zealand's North Island and found a diverse range of fish and squid prey species, with arrow squid *Nototodarus* spp., jack mackerel *Trachurus* spp., and anchovy *Engraulis australis* being the most prevalent. Dolphins from both coastal and offshore waters fed on neritic and oceanic prey, which suggests that animals that occupy the Hauraki Gulf likely move offshore at night to feed within the deep scattering layer (Meynier et al. 2008b). In New Zealand waters, *D. delphis* are the primary bycatch of the jack mackerel trawl fishery (Thompson et al. 2013), highlighting the overlap in target species of both fisheries and dolphins.

Given that the Hauraki Gulf has been previously identified as an important area for feeding (Stockin et al. 2009a) and reproduction (Stockin et al. 2008b), a broader insight to *D. delphis* foraging ecology is important for management purposes. Feeding habits of oceanic species are naturally difficult to observe, and most available information stems from stomach content analysis of stranded or bycaught animals. Such studies are useful as they allow exact taxonomical identification of prey items, however, they only give a snapshot of prey items ingested immediately ante mortem (Pierce & Boyle 1991). Additionally, findings are biased towards prey that takes longer to be digested and hence can still be detected hours after being consumed, which can cause the overestimation of some prey species (Santos et al. 2001). Analyses of nitrogen and carbon stable isotope values ($\delta^{15}\text{N}$ and $\delta^{13}\text{C}$, respectively) can provide a more long-term measure of all assimilated prey (DeNiro & Epstein 1978, Minagawa & Wada 1984, Peterson & Fry 1987).

Many studies have successfully used nitrogen and carbon isotopes to elucidate the foraging ecology of dolphins (Niño-Torres et al. 2006, Méndez-Fernández et al. 2013, Browning et al. 2014, Loizaga de Castro et al. 2016, Giménez et al. 2017b, 2018), with $\delta^{15}\text{N}$ values providing information on trophic level (Minagawa & Wada 1984, Post 2002) and $\delta^{13}\text{C}$ values indicating likely carbon sources relating to feeding habitat (Rubenstein & Hobson 2004). Depending on the turnover rate of the chosen tissue type, stable isotope studies can provide information relating to diet and habitat usage over different time frames, e.g. blood analysis gives information spanning days compared to skin which represents

weeks to months (Giménez et al. 2016), muscle which can represent months to years, and teeth which can represent the entire lifetime (Walker & Macko 1999).

Here, we aim to better understand the foraging ecology of *D. delphis* in the Hauraki Gulf. Specifically, we use $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ from skin samples of *D. delphis*, as well as muscle or mantle tissue samples of their prey to investigate (1) their isotopic niche, (2) the overlap of isotopic niche between sexes (i.e. evidence for sexual segregation and resource partitioning), (3) effects of body length as a proxy for age on relative trophic position, (4) changes in isotopic values over time and across seasons, and (5) proportions of different prey types in their diet.

2. MATERIALS AND METHODS

2.1. Study area

The Hauraki Gulf ($36^{\circ}10'$ to $37^{\circ}10'$ S, $174^{\circ}40'$ to $175^{\circ}30'$ E) is a shallow (maximum depth 60 m) in-shore sea bordering the north-eastern coastline of Auckland on New Zealand's North Island. With its warm temperate climate and waters influenced by the subtropical East Auckland Current, the Hauraki Gulf is an extremely productive ecosystem (Booth & Søndergaard 1989) harbouring high biodiversity, particularly of marine mammals (Stockin et al. 2008b, Hupman et al. 2015, Dwyer et al. 2016, Tezanos-Pinto et al. 2017, Barlow et al. 2018, Zaeschmar et al. 2020).

2.2. *Delphinus delphis* and prey sampling

We obtained a total of 56 skin samples from stranded or beach-cast *Delphinus delphis* in the Hauraki Gulf between 2004 and 2016, and from one animal that was found dead floating in the middle of the gulf (Fig. 1, Table 1, see Table S1 in the Supplement at www.int-res.com/articles/suppl/m652p173_supp.pdf for raw data). Sex was determined either genetically or anatomically during necropsy.

Based on stomach content data from Meynier et al. (2008b), 10 fish and cephalopod species were expected to be *D. delphis* prey according to their contribution to stomach contents (>4% in reconstituted weight) of *D. delphis* by-caught or stranded in waters around the North Island, both inside and outside of the Hauraki Gulf. We sampled lateral muscle (fish) and mantle tissue (cephalopod) of 8 of the prey species for stable isotope analysis (Table 2), and ob-

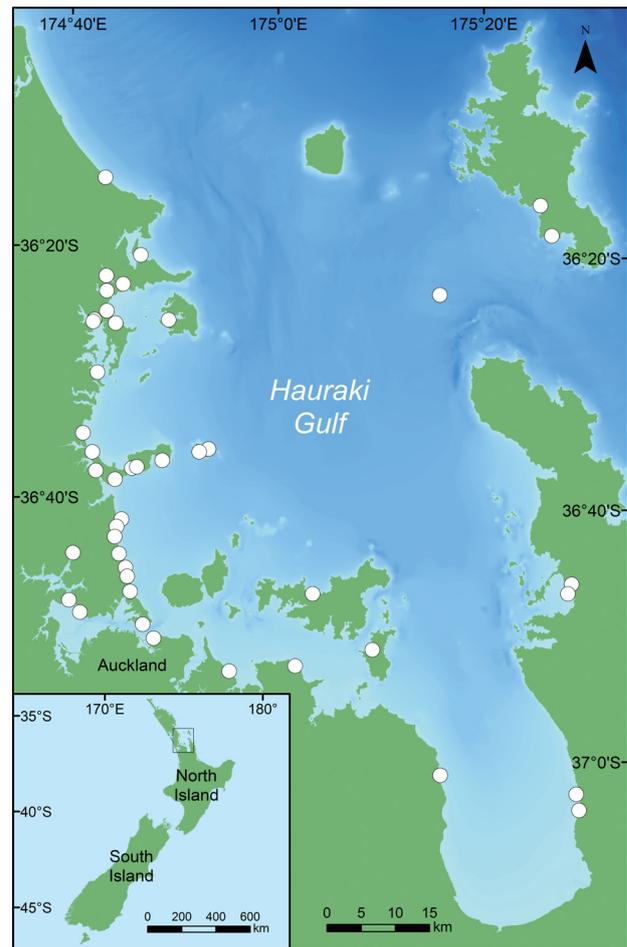


Fig. 1. Hauraki Gulf with sample locations (white dots). Bathymetry is depicted with darker shades of blue representing deeper waters (reprinted from NIWA under a CC BY license, with permission from NIWA original copyright 2012; Mackay et al. 2012). Inset: location of Hauraki Gulf in relation to the North Island of New Zealand

tained isotopic values from Davenport & Bax (2002) for *Lampanyctodes hectori* (Hector's lanternfish). We were unable to obtain samples or values from the literature for *Epigonus* sp. (cardinal fish) from Oceania, and hence could not include this species in our analyses. All prey tissues were preserved frozen at -20°C . Dolphin tissues were either preserved frozen at -20°C or stored in 70% ethanol prior to analysis. These 2 storage methods were considered comparable given the observation of Hobson et al. (1997a) who showed no isotopic difference between frozen tissues and those stored in 70% ethanol. Using a stainless-steel scalpel, we cut approximately 10 mg of each dolphin skin sample into very fine slices and then freeze-dried them for at least 24 h. Prey samples were oven-dried for at least 48 h at 60°C , and

Table 1. Suess-corrected carbon and nitrogen isotope values and sample sizes for different (a) sexes, (b) seasons and (c) years of *Delphinus delphis* carcasses recovered from the Hauraki Gulf 2004–2016. Values are means \pm 1 SD

	All individuals				Weaned individuals only (\geq 170 cm body length)			
	$\delta^{15}\text{N}$ (‰)	$\delta^{13}\text{C}$ (‰)	n	Sex (m, f [n])	$\delta^{15}\text{N}$ (‰)	$\delta^{13}\text{C}$ (‰)	n	Sex (m, f [n])
(a) Sex								
Female	14.88 \pm 1.26	-16.49 \pm 0.79	33		14.67 \pm 1.4	-16.28 \pm 0.7	19	
Male	14.81 \pm 1.46	-16.56 \pm 0.84	23		14.35 \pm 1.4	-16.78 \pm 0.9	14	
(b) Season								
Autumn/winter	15.43 \pm 0.75	-16.51 \pm 0.90	30	13, 17	15.38 \pm 0.8	-16.39 \pm 0.9	16	8, 8
Spring/summer	14.19 \pm 1.55	-16.53 \pm 0.70	26	10, 16	13.73 \pm 1.4	-16.60 \pm 0.7	17	6, 11
(c) Year								
2004	13.36 \pm 0.53	-16.04 \pm 0.64	9	2, 7	13.28 \pm 0.5	-16.04 \pm 0.7	7	1, 6
2005	14.13 \pm 1.83	-16.37 \pm 0.98	8	5, 3	14.06 \pm 2.0	-16.50 \pm 1.0	7	4, 3
2006	15.34 \pm 0.36	-15.59 \pm 0.2	4	1, 3	15.19	-15.47	1	0, 1
2007	16.06 \pm 0.75	-16.04 \pm 0.58	4	0, 4	15.73 \pm 0.4	-16.27 \pm 0.4	3	0, 3
2008	15.57 \pm 1.69	-15.68 \pm 0.54	2	2, 0	–	–	–	–
2009	14.85 \pm 0.28	-15.97 \pm 0.59	3	1, 2	14.84 \pm 0.4	-15.64 \pm 0.2	2	1, 1
2010	15.36 \pm 1.5	-16.68 \pm 0.26	2	2, 0	14.30	-16.49	1	1, 0
2011	14.81 \pm 1.06	-17.03 \pm 0.56	8	3, 5	14.76 \pm 1.3	-17.00 \pm 0.6	5	3, 2
2012	16.15 \pm 0.53	-16.63 \pm 0.36	5	3, 2	16.06 \pm 0.6	-16.68 \pm 0.5	3	1, 2
2013	15.92 \pm 0.12	-17.53 \pm 0.21	3	2, 1	15.92	-17.53	1	1, 0
2014	15.6 \pm 0.52	-17.47 \pm 0.45	3	1, 2	15.30	-17.12	1	1, 0
2015	14.99 \pm 1.25	-17.25 \pm 0.25	4	1, 3	14.26 \pm 1.5	-17.40 \pm 0.3	2	1, 1
2016	12.71	-17.35	1	0, 1	–	–	–	–

Table 2. Potential prey of *Delphinus delphis*: fish and cephalopod species, sample size (n), and tissue $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ values (mean \pm 1 SD ‰) of fish (muscle) and cephalopod (mantle). Species were selected based on their maximum % reconstituted mass (% M) found in *D. delphis* stomachs by Meynier et al. (2008b). Group statistics are provided where species were combined

Species	Common name	n	% M	$\delta^{15}\text{N}$	$\delta^{13}\text{C}$
Group 1					
<i>Sardinops neopilchardus</i>	Pilchard	10	13	12.45 \pm 0.4	-18.44 \pm 0.5
<i>Seriotelella</i> sp.	Warehou	8		13.00 \pm 0.3	-18.75 \pm 0.6
<i>Nototodar</i> sp.	Arrow squid	9	11.3	13.17 \pm 0.8	-19.01 \pm 0.5
Group 2					
<i>Hyporhamphus ihi</i>	Garfish	10	7.7	13.32 \pm 0.5	-18.04 \pm 0.3
<i>Trachurus</i> sp.	Jack mackerel	10	12	13.49 \pm 0.6	-18.48 \pm 0.3
<i>Conger wilsoni</i>	Conger eel	10	10.5	13.54 \pm 0.3	-18.31 \pm 0.4
<i>Engraulis australis</i>	Anchovy	8	5.2	13.75 \pm 0.4	-18.05 \pm 0.6
Group 3					
<i>Lampantodes hectoris</i>	Hector's lanternfish	10	6.3	10.6 \pm 0.4 ^a	-19.8 \pm 0.2 ^a
Group 4					
<i>Mugil cephalus</i>	Grey mullet	10	41.6	12.85 \pm 0.6	-15.45 \pm 1.6

^aObtained from Davenport & Bax (2002)

then ground and homogenised using a mortar and pestle.

Since the dolphin samples were collected over a time span of 13 yr (2004–2016), we applied a correction of -0.022‰ yr^{-1} (Quay et al. 2003) to the carbon isotope values of dolphin samples to account for changes in the $\delta^{13}\text{C}$ values of atmospheric carbon di-

oxide (CO_2) due to the burning of fossil fuels, termed the 'Suess effect' (Keeling et al. 1979, Quay et al. 2003). While Borrell et al. (2018) found regional differences in temporal shifts in $\delta^{13}\text{C}$ values in the skin of fin whales *Balaenoptera physalus*, ranging from -0.027 for samples from Iceland to -0.016 for samples from Spain, there are no studies to date assessing this for *D. delphis*. However, the estimate of -0.022‰ yr^{-1} from Quay et al. (2003) falls within the range reported by Borrell et al. (2018), and potential differences are likely to be negligible. We were only able to obtain contemporary prey samples in 2018, and therefore corrected all carbon isotopic values of dolphin samples to 2018.

2.3. Stable isotope analysis

We sealed 0.5–1.0 mg of dried homogenised sample into tin capsules which we analysed using a DELTA V Plus continuous flow isotope ratio mass spectrometer linked to a Flash 2000 elemental analyser with a MAS 200 R autosampler (Thermo Fisher

Scientific). CO₂ and nitrogen (N₂) reference gas standards were introduced to the mass spectrometer with every sample analysis. ISODAT (Thermo Fisher Scientific) software was used to calculate δ¹⁵N values against atmospheric air, and δ¹³C values relative to the international standard Carrara Marble NSB-19 (National Institute of Standards and Technology, NIST). This was further calibrated against the original Pee Dee Belemnite (PDB) limestone standard and then corrected for ¹⁷O. Carbon and nitrogen isotope data were corrected via a 2-point normalisation process using international NIST standards (Paul et al. 2007) (see the Supplement for further details). Repeat analysis of international NIST standards produced data accurate to within better than 0.15‰ for both δ¹⁵N and δ¹³C, and a precision of better than 0.22‰ for δ¹⁵N and 0.24‰ for δ¹³C.

Isotopic ratios were calculated as:

$$\delta X = [(R_{\text{sample}}/R_{\text{standard}})] \times 1000 \quad (1)$$

where X is ¹³C or ¹⁵N, and R_{sample} and R_{standard} are the ¹³C/¹²C and ¹⁵N/¹⁴N ratios in the sample standard, respectively. See the Supplement for more details on analytical protocol.

2.4. Lipid correction

Cetacean skin is known to have a high lipid content (Lesage et al. 2010, Ryan et al. 2012, Giménez et al. 2017c), which can lead to decreased δ¹³C values due to the ¹²C enrichment in the lipids (DeNiro & Epstein 1978). Several of our bulk isotope sample analyses had a mass ratio of carbon and nitrogen (C:N) > 3.5, indicating residual lipid content of the tissue and lipid contamination of the carbon isotope value (Post et al. 2007, Yurkowski et al. 2015, Skinner et al. 2016). Likewise, some fish species have a high fat content which, unless the lipids are removed, can confound the interpretation of the carbon isotope data. To account for the effect of lipid content on δ¹³C values, tissue samples need to either be lipid-extracted chemically *a priori*, or results need to be mathematically corrected *a posteriori* (normalisation). A combination of these 2 methods can also be used by chemically analysing a subset of the samples to then developing a mathematical correction formula specific to species, tissue type, and geographical location. Using this taxa- and tissue-specific mathematical correction has cost-benefits compared to chemical lipid extraction of all samples.

To develop a mathematical normalisation formula specific to our study species, we lipid-extracted a sub-

set of 13 samples for *D. delphis* and 11 samples of prey species, selected to cover the range of C:N mass ratio values (from 2.9–5.4). Freeze-dried material was subsampled and wrapped in GF/C filters prior to lipid extraction on a DIONEX 200 accelerated solvent extraction system (ASE). Samples were transferred to 22 ml s/s ASE cells and extracted 3 times with dichloromethane at 70°C and 1500 psi for a static hold time of 5 min. All samples were heated to 40°C in an oven overnight following extraction, to evaporate any traces of solvent prior to isotope analysis.

For both the dolphin and prey samples, we calculated a δ¹³C lipid-correction factor using linear regression analysis of the δ¹³C values of the original whole (non lipid-extracted) and lipid-extracted samples (see the Supplement for correction formulae). Using this factor, we mathematically corrected all non-lipid extracted δ¹³C values for samples with C:N mass ratios > 3.5. For samples with C:N mass ratios < 3.5, we used the original non-lipid corrected δ¹³C values. As lipid extraction can affect δ¹⁵N values, we used the non-lipid extracted δ¹⁵N values for all samples.

2.5. Data analysis

We analysed the relationship between δ¹⁵N and δ¹³C values and a set of explanatory variables using generalised additive models (GAMs; Hastie & Tibshirani 1990) with the ‘mgcv’ package (Wood 2001) in R version 4.0.0 (R Core Team 2020). GAMs are flexible as they implement a nonparametric smoothing function instead of parametric terms, allowing both linear and complex nonlinear relationships between variables within the same model (McCullagh & Nelder 1989). Our predictive variables were body length (as a proxy of age, fitted as a continuous variable), year (fitted as a continuous variable), sex, and season (fitted as factors). The variable season had 2 levels and was defined as austral spring/summer = September–February and austral autumn/winter = March–August. We built 31 models with Gaussian distribution and an identity link function for each of the δ¹⁵N and δ¹³C values, using all possible combinations of the 4 predictive variables, with the smoothers for the continuous variables, body length and year, fitted with and without the interaction for sex. To prevent overfitting, we set gamma to 1.4 (Wood 2017). We selected the optimal model based on the corrected Akaike’s information criterion adjusted for small sample size (AIC_C) (Burnham et al. 2011) and the % deviance explained. We adjusted the number of basis

functions (k) for the top-ranked models and checked the final models for normality and obvious patterns in the residuals.

We used 6 different Layman metrics ($\delta^{15}\text{N}$ range, $\delta^{13}\text{C}$ range, total area, mean distance to centroid, mean nearest neighbour distance, and standard deviation of nearest neighbour distance) to compare isotopic niches between adult males and females (see the Supplement for definition of metrics). We bootstrapped all Layman metrics with replacement ($n = 10\,000$, indicated with a subscript 'boot') based on the smallest sample size in the data set ($n = 14$) to enable statistical comparison between males and females (Manly 1997, Jackson et al. 2012). To further assess niche widths and isotopic niche overlap between sexes, we followed a Bayesian approach using multivariate ellipse-based metrics (Jackson et al. 2011). This method is particularly useful when comparing groups with small sample sizes, as it corrects for the influence of outliers. We calculated standard ellipse areas (SEAs), which are the bivariate equivalent to standard deviation in univariate analyses. We also calculated SEA corrected (SEA_C) to minimize bias introduced by small sample sizes. In addition, we calculated SEA_B (Bayesian SEA) using 1000 posterior draws to statistically compare niche width between sexes. We used SEA_B to calculate the niche overlap between males and females, calculated as the proportion of the total SEA_B for each sex, respectively. We calculated all metrics using the R package SIBER (Stable Isotope Bayesian Ellipses in R; Jackson et al. 2011, R Core Team 2020). To ensure that unweaned animals were excluded, we only used individuals with body length ≥ 170 cm (conservative estimate of the body length at the end of the nursing period derived from inflection point in GAM which was ~ 160 cm) for this and all further analyses.

2.6. Mixing models

Mixing models estimate the contribution of different prey sources to the diet of their consumer, while incorporating isotopic discrimination factors and uncertainties in isotopic values of both sources and consumers (Stock et al. 2018). The accuracy of dietary studies via isotopic analyses depends largely on the selection of appropriate diet-to-tissue discrimination factors and tissue turnover rates (Phillips et al. 2014). Being a metabolically active tissue, cetacean skin has a relatively fast turnover rate compared to other tissues such as muscle or bone, with a half-life

of ~ 30 d (Giménez et al. 2016). In this study, we used the discrimination factors of $1.01 \pm 0.37\%$ (mean \pm SD) for $\delta^{13}\text{C}$ and $1.57 \pm 0.52\%$ for $\delta^{15}\text{N}$, derived from the longest available feeding experiment (350 d) available on bottlenose dolphins *Tursiops truncatus* (Giménez et al. 2016). Mixing models are sensitive to a large number of sources (in our case 9 prey species; Table 2) combined with a low number of isotope ratios (in our case 2: $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$). We therefore grouped several prey species using Ward's hierarchical cluster analysis based on their mean isotopic values (Table 2). To test whether our data met the point-in-polygon requirement for every consumer (i.e. all consumer isotopic values must lie within a polygon bounded by the isotopic signatures of the sources; Phillips & Gregg 2003), we computed a simulated mixing polygon (Smith et al. 2013).

3. RESULTS

3.1. Intraspecific variation in stable isotope values

The model that best fitted the $\delta^{15}\text{N}$ data retained body length, sex, year, and season as covariates, with both body length and year fitted for each sex separately (Table 3, Fig. 2). This model explained 71.9% of the deviance. Female $\delta^{15}\text{N}$ values decreased until ~ 160 cm body length, then increased. Males did not show the same increase in $\delta^{15}\text{N}$ values after ~ 160 cm; instead, values steadily decreased with increasing body length.

Between years, $\delta^{15}\text{N}$ values of females were variable, with high values in 2007 and 2014 and low values in 2004, 2010, and 2016. Males showed a gradual increase in $\delta^{15}\text{N}$ values which plateaued from 2012 onwards. During the austral autumn/winter season, $\delta^{15}\text{N}$ values were higher compared to those in spring/summer (Fig. S1).

Analyses of $\delta^{13}\text{C}$ showed similar results to those of $\delta^{15}\text{N}$ (Fig. 2), with the top-ranked model retaining body length, year, and season as variables, explaining 65.7% of the deviance (Table 3). However, while the smoother for body length was fitted for each sex separately, indicating an interaction between sex and body length, sex was not retained as an interaction effect for year. Carbon isotope values in females decreased with increasing body length until ~ 160 cm and then increased. Following the patterns of the nitrogen isotope data, males did not show the same increase in $\delta^{13}\text{C}$ values after ~ 160 cm that was expressed in females; instead, values steadily decreased with increasing body length.

Table 3. The 3 best generalised additive models for *Delphinus delphis* (a) $\delta^{15}\text{N}$ and (b) $\delta^{13}\text{C}$ values. The top-ranked model (shaded in grey) for $\delta^{15}\text{N}$ included body length (fitted for each sex separately), sex, year (fitted for each sex separately), and season. For $\delta^{13}\text{C}$, the top-ranked model retained body length (fitted for each sex separately), year, and season. Significant variables in each model are given in **bold**, number of basis function (k) for the smoothers are given for final models. LL: log-likelihood; % DE: % deviance explained; ΔAIC_C : difference in Akaike's information criterion (AIC_C) of the current and top-ranked model; $w\text{AIC}_C = \text{AIC}_C$ weight

#	Model	R^2	LL	% DE	df	ΔAIC_C	$w\text{AIC}_C$
(a) $\delta^{15}\text{N}$							
1	$\sim s(\text{length}, \text{by} = \text{sex}, k = 14) + s(\text{year}, \text{by} = \text{sex}, k = 13) + \text{season}$	0.654	-59.55	71.9%	12.30	-	0.72
2	$\sim s(\text{length}, \text{by} = \text{sex}) + s(\text{year}, \text{by} = \text{sex}) + \text{sex} + \text{season}$	0.647	-59.51	71.9%	13.29	0.33	0.13
3	$\sim s(\text{length}, \text{by} = \text{sex}) + s(\text{year}) + \text{season}$	0.607	-63.86	67.2%	11.08	4.61	0.07
(b) $\delta^{13}\text{C}$							
1	$\sim s(\text{length}, \text{by} = \text{sex}, k = 12) + s(\text{year}, k = 12) + \text{season}$	0.600	-36.74	65.7%	9.84	-	0.69
2	$\sim s(\text{length}, \text{by} = \text{sex}) + s(\text{year}) + \text{sex} + \text{season}$	0.591	-36.83	65.6%	10.74	2.96	0.16
3	$\sim s(\text{length}, \text{by} = \text{sex}) + s(\text{year}, \text{by} = \text{sex}) + \text{season}$	0.616	-33.70	69.2%	12.89	3.75	0.11

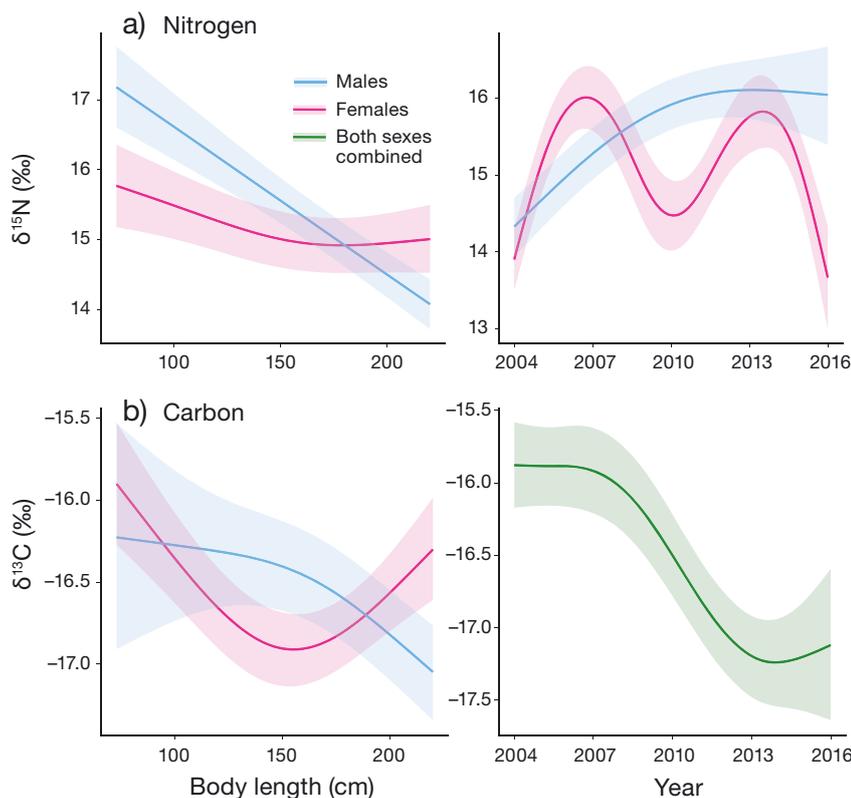


Fig. 2. Generalised additive model (GAM) smooth terms for the final models showing intraspecific isotopic variation in *Delphinus delphis*. Effect of body length and year on (a) nitrogen and (b) carbon isotope values. Lines: estimated smoothers; shaded areas: $2\times$ the standard error of the estimated smooth function. As per the final model, for nitrogen, the smooth term is fitted with an interaction for sex, with data for females shaded in pink and males shaded in blue for both body length and year. For carbon, the smooth term is fitted with an interaction for sex only for body length, while for year, the smooth term is estimated for both sexes combined (shaded in green). The GAM for nitrogen explained 71.9% of the deviance, and the one for carbon explained 65.7%

Throughout the study period (2004–2016), $\delta^{13}\text{C}$ values decreased for both sexes. Although mean values for $\delta^{13}\text{C}$ did not differ between seasons (Table 1), season was retained in the final model (for visualisation see Fig. S1).

3.2. Isotopic niche metrics of males and females

Weaned male and female dolphins had relatively similar values for all isotopic niche metrics, although males were slightly more likely (61.2%; 79% probability) to have higher values than females. Contrastingly, SEA_B was more likely to be larger for females (81.4%; Table 4). Similarity of niche space was also demonstrated by an SEA_B overlap of 62.6% for males and 45.2% females (Fig. 3).

3.3. Mixing models

Hierarchical cluster analysis of prey data identified 4 distinct clusters (prey groups), of which 2 comprised only one species (Fig. S2, Table 2: Groups 3 and 4). However, the biplot (Fig. 4a) showing isotopic values for prey clusters and individual dolphins indicates

Table 4. Isotopic niche metrics (including the 6 Layman metrics) for weaned (≥ 170 cm body length) male and female *Delphinus delphis*. See the Supplement for metric definitions. SEA: standard ellipse area; SEA_C : standard ellipse area corrected for small sample size; SEA_B : Bayesian SEA; TA: total area; CD: mean distance to centroid; MNND: mean nearest neighbour distance; SDNND: standard deviation of nearest neighbour distance. Subscript 'boot' indicates that the value (mean) has been generated via bootstrapping

Metrics	Males	Females	Probability (%)
N	14	19	
SEA	3.81	2.80	
SEA_C	4.14	2.96	
SEA_B	2.10	2.76	81.4 F > M
$\delta^{15}N$ range	4.32	4.15	
$\delta^{15}N$ range _{boot}	4.00	3.86	64.6 M > F
$\delta^{13}C$ range	3.04	2.69	
$\delta^{13}C$ range _{boot}	2.60	2.15	77.4 M > F
TA	7.72	7.49	
TA _{boot}	7.21	5.65	74.4 M > F
CD	1.49	1.39	
CD _{boot}	1.41	1.32	63.4 M > F
MNND	0.62	0.38	
MNND _{boot}	0.48	0.44	61.2 M > F
SDNND	0.29	0.26	
SDNND _{boot}	0.43	0.31	79.0 M > F

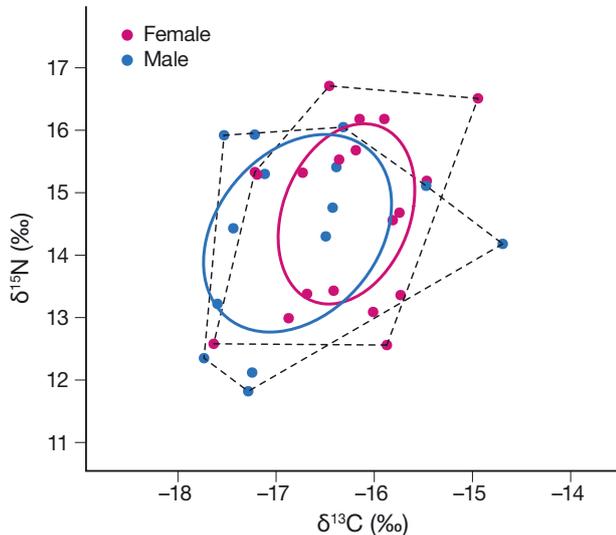


Fig. 3. Standard ellipse area corrected for small sample size (solid lines) and convex hull area (dotted line) for weaned (≥ 170 cm body length) *Delphinus delphis* males and females. Ellipse areas hold 40% of the data

that the data are not suitable for the use of mixing models. This was confirmed by the mixing polygon (Fig. 4b), showing 21% (7/33) of isotopic values for individual dolphins fell outside the 95% mixing region.

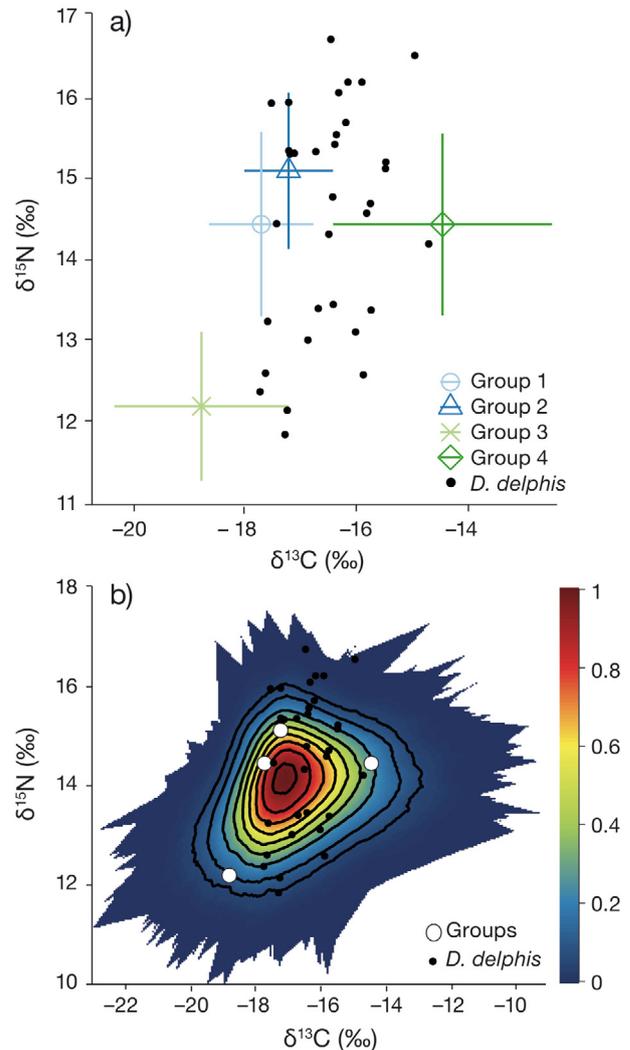


Fig. 4. (a) Isotopic values for weaned (≥ 170 cm body length) *Delphinus delphis* (individuals represented as black dots) and their potential dietary source groups (displayed as mean ± 1 SD, with incorporated diet-to-tissue discrimination factors: 1.01 ± 0.37 ‰ (mean \pm SD) for $\delta^{13}C$ and 1.57 ± 0.52 ‰ for $\delta^{15}N$). Group 1: *Sardinops neopilchardus*, *Seriolella* sp., *Nototodarus* sp.; Group 2: *Hyporhamphus ihi*, *Trachurus* sp., *Conger wilsoni*, *Engraulis australis*; Group 3: *Lampanyctodes hectoris*; Group 4: *Mugil cephalus*. (b) Mixing polygon for data presented in (a), showing individual dolphins (black dots) and potential dietary source groups (white dots). Black lines represent probability contours at 10% levels. Colour scale shows the probability that a consumer's isotopic signature can be explained by the proposed model.

4. DISCUSSION

4.1. Intraspecific variation in stable isotope values

The observed variation in $\delta^{15}N$ and $\delta^{13}C$ values of *Delphinus delphis* skin suggests ontogenetic diet changes depending on their body size, as well as dif-

ferences between the sexes, the seasons, and a gradual change throughout the study period (2004–2016), which is likely an expression of changes in primary productivity. Our finding of decreasing $\delta^{15}\text{N}$ values up to a body length of ~160 cm is consistent with findings from other studies on delphinids of similar size (e.g. Meissner et al. 2012, Giménez et al. 2017a) and likely indicates the transition of the animals' primary nutritional source from milk to live prey. When young feed on milk they are essentially feeding off the tissues of their mother and therefore express an apparent higher trophic level, where their $\delta^{15}\text{N}$ values are elevated compared to adults of the same species (Knoff et al. 2008, Newsome et al. 2010). The inflection point of the smoother at ~160 cm body length (Fig. 2) indicates that animals are weaned around this size as has been suggested by other studies on *D. delphis* (~150 cm; Giménez et al. 2017a) and for delphinids of similar body size (e.g. ~155 cm in striped dolphins *Stenella coeruleoalba*; Meissner et al. 2012, Giménez et al. 2017a). The higher nitrogen isotopic values in females where body size exceeds 160 cm is likely due to the consumption of larger prey items with elevated $\delta^{15}\text{N}$ values (Jennings et al. 2002, Ruiz-Cooley et al. 2010). While the inflection point is clearly visible for females (Fig. 2), we did not detect one for males; instead, male nitrogen isotope values steadily decreased. This finding could be due to a lower sample size in males (14) compared to females (19). However, Giménez et al. (2017a) found similar results for both sexes of *D. delphis* in the Mediterranean Sea, suggesting that individuals might not change to an isotopically higher diet when weaned, which could be the case for males here.

Conspecific competition can be reduced by resource partitioning between the sexes (Schoener 1974, Hobson et al. 1997b). Although the final model retained sex as an interaction for body length and year (for nitrogen) and for body length (for carbon) in our study, sex itself did not predict isotopic values. Additionally, both sexes had similar trophic niche space, measured using Layman metrics, and a high SEA_B overlap (males 62.6%, females 45.2%). Despite the differences in the variance in $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ values regarding body length and year, our isotopic data therefore did not indicate niche segregation between sexes in this system. In contrast to this study, Young & Cockcroft (1994) found clear differences in diet between male and female *D. delphis* in South Africa based on stomach content analyses, indicating resource partitioning between sexes. Furthermore, Neumann et al. (2002b) observed frequent sex-biased group formation in *D. delphis* in New Zealand waters,

with segregations into 'nursery groups' (adult females and calves), and 'bachelor groups' (adult males only). Regarding our results, it is important to note that isotopic values of predators do not provide insight into the exact species-specific diet of an animal. Two consumers can express similar isotopic ratios of carbon and nitrogen even if they are feeding on different prey types. The resultant predator isotopic value depends not only on the range of isotopic values of ingested prey, but the relative proportions of prey ingested, and ontogenetic, reproductive, physiological, and metabolic processes. Furthermore, our sample size prevented temporal analyses of niche metrics. It is therefore possible that *D. delphis* in the Hauraki Gulf do display some level of niche segregation, which in this instance was not detected by the stable isotope analyses.

Nitrogen isotope values changed across the study period (2004–2016), with a steady increase for males and a more variable distribution for females. Given that the city of Auckland borders the Hauraki Gulf, a possible reason for nitrogen increase in this coastal ecosystem is the increasing urbanisation of its coastal areas, with high levels of terrestrial nitrogen being washed into the sea (McClelland et al. 1997, Zeldis & Swaney 2018). Agricultural nutrient inputs strongly influence the nutrient dynamics of the Hauraki Gulf, and there is evidence for declining denitrification efficiency over time (Zeldis et al. 2004, Zeldis & Swaney 2018). However, this increase in $\delta^{15}\text{N}$ values should then also be evident in females. In addition, it should be noted that for highly mobile species such as *D. delphis*, there is a chance that some of the sampled individuals were not resident in the area, and hence their isotopic signature is not representative of the region.

Carbon isotope values can be indicative of marine ecosystem productivity, with higher values observed in productive regions (nearshore) and lower values in less productive regions (offshore) (Newsome et al. 2010). Using stomach content analyses, Meynier et al. (2008b) found that *D. delphis* in New Zealand fed on both oceanic and neritic prey, suggesting daily movements between inshore and offshore regions. In this study, $\delta^{13}\text{C}$ values showed a steep decrease from 2004–2016, which could indicate either a decline in net primary productivity in this system over this period and/or a shift in foraging behaviour towards more offshore prey. A drop in net primary productivity would, in turn, lessen the abundance of small schooling fish such as mackerel and anchovy through bottom-up trophic links between phytoplankton, zooplankton, and fish (Ware & Thomson 2005) and could help explain the observed decrease in mean *D. del-*

phis group size throughout the study period (48 in 2001–2005, Stockin et al. 2008b; 26 in 2010–2012, Dwyer et al. 2016). In energetically demanding animals such as *D. delphis*, who have been shown to depend on prey with high energy density (Spitz et al. 2010), large groups only form when prey availability or predator avoidance outweighs intra-specific competition (Perrin et al. 2009). A decrease in available prey increases intra-specific competition, rendering large groups unsustainable. Likewise, a depletion of prey stocks through increased commercial fishing could have similar effects. In the Hauraki Gulf, commercial catch has increased over the last 2 decades, and now contains comparatively more small schooling fish than in 2000 (Hauraki Gulf Forum 2020). Furthermore, the stock status of several *D. delphis* prey species, including jack mackerel *Trachurus* sp., grey mullet *Mugil cephalus*, and pilchard *Sardinops neopilchardus*, in the Hauraki Gulf is currently unknown (Hauraki Gulf Forum 2020). Stable isotopes can be used to assess temporal variability in resource use, as seasonal changes in isotopic values could suggest shifts in prey species or seasonal movements (Quillfeldt et al. 2005). Seasonal differences in foraging ecology have been observed in several other species of marine mammals, particularly pinnipeds, e.g. Steller sea lions *Eumetopias jubatus* (Sinclair & Zeppelin 2002) and grey seals *Halichoerus grypus* (Breed et al. 2006). However, unlike delphinids, pinnipeds usually have distinct reproductive seasons which can influence their foraging patterns (Perrin et al. 2009). In this study, dolphin $\delta^{15}\text{N}$ values and their variances were higher in austral autumn/winter compared to spring/summer. Although the differences are small, this could potentially indicate a wider foraging niche during the autumn/winter months, as has been observed in different species of penguins and seals (Cherel et al. 2007).

4.2. Mixing models

One of the necessary conditions which need to be fulfilled for Bayesian mixing models to work is that all isotopic consumer data fall within the minimum bounding polygon of their sources (Phillips et al. 2014). When testing our data for suitability of using a mixing polygon, we found that 21 % of our consumer data fell outside of the 95 % mixing region (Fig. 4b), which indicated that we were most likely missing one or more important food sources. As mentioned earlier, we were unable to obtain samples for *Epigonus* sp., a species which Meynier et al. (2008b) had

identified to make up 12.6% of stomach contents of *D. delphis* stranded in the Hauraki Gulf. It is likely that *Epigonus* is the source missing from our study, since our validation improved drastically when we included isotopic values for *Epigonus crassicaudus* obtained from Sepúlveda et al. (2018) (Fig. S3). However, these values are derived from samples collected in Chile, and we do not know if they are similar to those of *Epigonus* species in New Zealand, which is why we decided against including these values in our analysis.

Furthermore, *D. delphis* are well known for their dietary flexibility, and given that we selected prey species based on their prevalence in dolphin stomachs between 1997 and 2006 (Meynier et al. 2008b), there is a possibility that dolphins have since shifted to prey species that were not their main focus at the time, and hence were not included in our analysis. Additionally, samples of dolphin tissue were collected between 2004 and 2016, but all our prey samples are from 2018 only and might therefore not be representative for the entire study period. In particular, if a general change in primary production occurred during the study period as GAM results suggest, this would not have been captured in our prey data.

4.3. Implications for conservation

Our results have implications for species conservation management of *D. delphis* in the Hauraki Gulf. The abundance of the entire North Island *D. delphis* population is unknown, but seasonal abundance estimates for the Hauraki Gulf range from 732 (CI = 460–1177) individuals in autumn 2010 to 5304 (CI = 4745–5930) individuals in spring 2013 (Hupman et al. 2018). Recent analyses show that individuals in the Gulf belong to a genomically and geographically distinct population of New Zealand's east coast, with moderate migration into the population on New Zealand's west coast and Tasmania (Möller et al. 2020). Limited information is available on genetic population structure (Stockin et al. 2014); nevertheless, the region is considered an important area for the species, especially with regard to feeding activities (Stockin et al. 2009a, Dwyer et al. 2020). As discussed above, the observed shift in carbon isotope values could indicate changes in the food web. Opportunistic predators such as *D. delphis* exhibit high foraging plasticity and can therefore adapt to changes in prey abundance by exploiting various species of small schooling fish (Silva 1999, Meynier et al. 2008a,b), serving as an indicator species for ecosystem changes. Furthermore,

changes in *D. delphis* carbon isotope values may reflect a shift to offshore feeding due to depleted fish stocks in the Hauraki Gulf, forcing the dolphins to forage further offshore. Ecosystem changes, such as shifts in isotopic values, exacerbated by fisheries resource exploitation, likely also impact other apex predators in the region such as Bryde's whales *Balaenoptera edeni* (Wiseman et al. 2011) and Australasian gannets *Morus serrator* (Machovsky-Capuska et al. 2011). Spatial and temporal isotopic studies of other apex predators in this region would inform conservation and management decisions. This study has provided valuable new information on the foraging ecology of the *D. delphis* population in the Hauraki Gulf and has generated a baseline for detecting future changes in this important coastal ecosystem.

Acknowledgements. We are very grateful to Julie Brown, Josette Delgado, and Anna Kilimnik at NIWA for conducting the stable isotope analyses and all Department of Conservation staff and Tangata Whenua who facilitated the collection of tissue samples used in this study. We thank Théo Pinheiro and Odette Howarth for their dedicated help with lab work and Dr. Sarah Dwyer for the maps. We are grateful to 3 anonymous reviewers whose comments have substantially improved the manuscript. This project was completed under Department of Conservation permits 39239-MAR and Rnw/NO/2009/06 issued to Massey University. During part of this study, K.J.P. was supported by an Australia Awards Endeavour Research Fellowship. K.A.S. was supported by a Royal Society of New Zealand Te Aparangi Rutherford Discovery Fellowship.

LITERATURE CITED

- Amaral AR, Beheregaray LB, Bilgmann K, Boutov D and others (2012) Seascape genetics of a globally distributed, highly mobile marine mammal: the short-beaked common dolphin (genus *Delphinus*). PLOS ONE 7:e31482
- Barlow DR, Torres LG, Hodge KB, Steel D and others (2018) Documentation of a New Zealand blue whale population based on multiple lines of evidence. Endang Species Res 36:27–40
- Booth WE, Søndergaard M (1989) Picophytoplankton in the Hauraki Gulf, New Zealand. NZ J Mar Freshw Res 23: 69–78
- Borrell A, Saiz L, Víkingsson G, Gaufier P, Fernández AL, Aguilar A (2018) Fin whales as bioindicators of multi-decadal change in carbon and oxygen stable isotope shifts in the North Atlantic. Mar Environ Res 138:129–134
- Bowen W (1997) Role of marine mammals in aquatic ecosystems. Mar Ecol Prog Ser 158:267–274
- Brand D, Edelist D, Goffman O, Hadar N, Scheinin A, Kerem D (2019) Common dolphins, common in neritic waters off southern Israel, demonstrate uncommon dietary habits. Aquat Conserv: Mar Freshw Ecosyst 2019:1–7
- Breed GA, Bowen W, McMillan J, Leonard ML (2006) Sexual segregation of seasonal foraging habitats in a non-migratory marine mammal. Proc R Soc B 273:2319–2326
- Browning NE, McCulloch SD, Bossart GD, Worthy GJ (2014) Fine-scale population structure of estuarine bottlenose dolphins (*Tursiops truncatus*) assessed using stable isotope ratios and fatty acid signature analyses. Mar Biol 161:1307–1317
- Burnham KP, Anderson DR, Huyvaert KP (2011) AIC model selection and multimodel inference in behavioral ecology: some background, observations, and comparisons. Behav Ecol Sociobiol 65:23–35
- Cherel Y, Hobson KA, Guinet C, Vanpe C (2007) Stable isotopes document seasonal changes in trophic niches and winter foraging individual specialization in diving predators from the Southern Ocean. J Anim Ecol 76:826–836
- Coyle KO, Bluhm B, Konar B, Blanchard A, Highsmith RC (2007) Amphipod prey of gray whales in the northern Bering Sea: comparison of biomass and distribution between the 1980s and 2002–2003. Deep Sea Res II 54: 2906–2918
- Davenport SR, Bax NJ (2002) A trophic study of a marine ecosystem off southeastern Australia using stable isotopes of carbon and nitrogen. Can J Fish Aquat Sci 59:514–530
- DeMaster DP, Fowler CW, Perry SL, Richlen MF (2001) Predation and competition: the impact of fisheries on marine-mammal populations over the next one hundred years. J Mammal 82:641–651
- DeNiro MJ, Epstein S (1978) Influence of diet on the distribution of carbon isotopes in animals. Geochim Cosmochim Acta 42:495–506
- Dwyer SL, Kozmian-Ledward L, Stockin KA (2014) Short-term survival of severe propeller strike injuries and observations on wound progression in a bottlenose dolphin. NZ J Mar Freshw Res 48:294–302
- Dwyer S, Clement D, Pawley M, Stockin K (2016) Distribution and relative density of cetaceans in the Hauraki Gulf, New Zealand. NZ J Mar Freshw Res 50:457–480
- Dwyer SL, Pawley MD, Clement DM, Stockin KA (2020) Modelling habitat use suggests static spatial exclusion zones are a non-optimal management tool for a highly mobile marine mammal. Mar Biol 167:62
- Giménez J, Ramírez F, Almunia JG, Forero M, De Stephanis R (2016) From the pool to the sea: applicable isotope turnover rates and diet to skin discrimination factors for bottlenose dolphins (*Tursiops truncatus*). J Exp Mar Biol Ecol 475:54–61
- Giménez J, Cañadas A, Ramírez F, Afán I and others (2017a) Intra- and interspecific niche partitioning in striped and common dolphins inhabiting the southwestern Mediterranean Sea. Mar Ecol Prog Ser 567:199–210
- Giménez J, Marçalo A, Ramírez F, Verborgh P and others (2017b) Diet of bottlenose dolphins (*Tursiops truncatus*) from the Gulf of Cadiz: insights from stomach content and stable isotope analyses. PLOS ONE 12:e0184673
- Giménez J, Ramírez F, Forero MG, Almunia J, De Stephanis R, Navarro J (2017c) Lipid effects on isotopic values in bottlenose dolphins (*Tursiops truncatus*) and their prey with implications for diet assessment. Mar Biol 164:122
- Giménez J, Cañadas A, Ramírez F, Afán I and others (2018) Living apart together: niche partitioning among Alboran Sea cetaceans. Ecol Indic 95:32–40
- Hastie T, Tibshirani R (1990) Generalized additive models. Chapman & Hall/CRC, London
- Hauraki Gulf Forum (2020) State of our Gulf 2020. Auckland Council, Auckland
- Heithaus MR, Frid A, Wirsing AJ, Worm B (2008) Predicting ecological consequences of marine top predator declines. Trends Ecol Evol 23:202–210

- Hobson KA, Gibbs HL, Gloutney ML (1997a) Preservation of blood and tissue samples for stable-carbon and stable-nitrogen isotope analysis. *Can J Zool* 75:1720–1723
- Hobson KA, Sease JL, Merrick RL, Piatt JF (1997b) Investigating trophic relationships of pinnipeds in Alaska and Washington using stable isotope ratios of nitrogen and carbon. *Mar Mamm Sci* 13:114–132
- Hupman KE (2016) Photo-identification and its application to gregarious delphinids: common dolphins (*Delphinus* sp.) in the Hauraki Gulf, New Zealand. PhD thesis, Massey University, Albany
- Hupman K, Visser I, Martinez E, Stockin K (2015) Using platforms of opportunity to determine the occurrence and group characteristics of orca (*Orcinus orca*) in the Hauraki Gulf, New Zealand. *NZ J Mar Freshw Res* 49: 132–149
- Hupman K, Stockin KA, Pollock K, Pawley MDM, Dwyer SL, Lea C, Tezanos-Pinto G (2018) Challenges of implementing mark–recapture studies on poorly marked gregarious delphinids. *PLOS ONE* 13:e0198167
- Irwin LJ (2005) Marine toxins: adverse health effects and biomonitoring with resident coastal dolphins. *Aquat Mamm* 31:195–225
- Jackson AL, Inger R, Parnell AC, Bearhop S (2011) Comparing isotopic niche widths among and within communities: SIBER—Stable Isotope Bayesian Ellipses in R. *J Anim Ecol* 80:595–602
- Jackson MC, Donohue I, Jackson AL, Britton JR, Harper DM, Grey J (2012) Population-level metrics of trophic structure based on stable isotopes and their application to invasion ecology. *PLOS ONE* 7:e31757
- Jennings S, Pinnegar JK, Polunin NV, Warr KJ (2002) Linking size-based and trophic analyses of benthic community structure. *Mar Ecol Prog Ser* 226:77–85
- Keeling CD, Mook WG, Tans PP (1979) Recent trends in the $^{13}\text{C}/^{12}\text{C}$ ratio of atmospheric carbon dioxide. *Nature* 277: 121–123
- Kiszka JJ, Heithaus MR, Wirsing AJ (2015) Behavioural drivers of the ecological roles and importance of marine mammals. *Mar Ecol Prog Ser* 523:267–281
- Knoff A, Hohn A, Macko S (2008) Ontogenetic diet changes in bottlenose dolphins (*Tursiops truncatus*) reflected through stable isotopes. *Mar Mamm Sci* 24:128–137
- Lesage V, Morin Y, Rioux È, Pomerleau C, Ferguson SH, Pelletier È (2010) Stable isotopes and trace elements as indicators of diet and habitat use in cetaceans: predicting errors related to preservation, lipid extraction, and lipid normalization. *Mar Ecol Prog Ser* 419: 249–265
- Loizaga de Castro R, Saporiti F, Vales DG, García NA, Cardona L, Crespo EA (2016) Feeding ecology of dusky dolphins *Lagenorhynchus obscurus*: evidence from stable isotopes. *J Mammal* 97:310–320
- Machovsky-Capuska GE, Dwyer SL, Alley MR, Stockin KA, Raubenheimer D (2011) Evidence for fatal collisions and kleptoparasitism while plunge-diving in Gannets. *Ibis* 153:631–635
- Mackay KA, Mackay EJ, Neil HL, Mitchell JS, Bardsley SA (2012) Hauraki Gulf. NIWA Chart, Miscellaneous Series 91. National Institute of Water & Atmospheric Research Ltd.
- Manly BFJ (1997) Randomization, bootstrap and Monte Carlo methods in biology. Chapman & Hall, London
- Marçalo A, Nicolau L, Giménez J, Ferreira M and others (2018) Feeding ecology of the common dolphin (*Delphinus delphis*) in Western Iberian waters: Has the decline in sardine (*Sardina pilchardus*) affected dolphin diet? *Mar Biol* 165:44
- Martinez E, Stockin K (2013) Blunt trauma observed in a common dolphin *Delphinus* sp. likely caused by a vessel collision in the Hauraki Gulf, New Zealand. *Pac Conserv Biol* 19:19–27
- McClelland JW, Valiela I, Michener RH (1997) Nitrogen-stable isotope signatures in estuarine food webs: a record of increasing urbanization in coastal watersheds. *Limnol Oceanogr* 42:930–937
- McCullagh P, Nelder JA (1989) Generalized linear models. Chapman & Hall, New York, NY
- Meissner AM, MacLeod CD, Richard P, Ridoux V, Pierce G (2012) Feeding ecology of striped dolphins, *Stenella coeruleoalba*, in the north-western Mediterranean Sea based on stable isotope analyses. *J Mar Biol Assoc UK* 92:1677–1687
- Méndez-Fernandez P, Pierce GJ, Bustamante P, Chouvelon T and others (2013) Ecological niche segregation among five toothed whale species off the NW Iberian Peninsula using ecological tracers as multi-approach. *Mar Biol* 160: 2825–2840
- Meynier L, Pusineri C, Spitz J, Santos MB, Pierce GJ, Ridoux V (2008a) Intraspecific dietary variation in the short-beaked common dolphin *Delphinus delphis* in the Bay of Biscay: importance of fat fish. *Mar Ecol Prog Ser* 354: 277–287
- Meynier L, Stockin KA, Bando MKH, Duignan PJ (2008b) Stomach contents of common dolphin (*Delphinus* sp.) from New Zealand waters. *NZ J Mar Freshw Res* 42: 257–268
- Minagawa M, Wada E (1984) Stepwise enrichment of ^{15}N along food chains: further evidence and the relation between $\delta^{15}\text{N}$ and animal age. *Geochim Cosmochim Acta* 48:1135–1140
- Möller L, Barcelo A, Sandoval-Castillo J, Beheregaray L, Hupman K, Betty E, Stockin KA (2020) Population structure and size of New Zealand common dolphins. Ministry for Primary Industries, Wellington
- Natoli A, Cañadas A, Peddemors VM, Aguilar A, Vaquero C, Fernández-Piqueras P, Hoelzel AR (2006) Phylogeography and alpha taxonomy of the common dolphin (*Delphinus* sp.). *J Evol Biol* 19:943–954
- Neumann DR (2001) Seasonal movements of short-beaked common dolphins (*Delphinus delphis*) in the north-western Bay of Plenty, New Zealand: influence of sea surface temperature and El Niño/La Niña. *NZ J Mar Freshw Res* 35:371–374
- Neumann DR, Leitenberger A, Orams MB (2002a) Photo-identification of short-beaked common dolphins (*Delphinus delphis*) in north-east New Zealand: a photo-catalogue of recognisable individuals. *NZ J Mar Freshw Res* 36:593–604
- Neumann DR, Russell K, Orams MB, Baker CS, Duignan P (2002b) Identifying sexually mature, male short-beaked common dolphins (*Delphinus delphis*) at sea, based on the presence of a postanal hump. *Aquat Mamm* 28: 181–187
- Newsome SD, Clementz MT, Koch PL (2010) Using stable isotope biogeochemistry to study marine mammal ecology. *Mar Mamm Sci* 26:509–572
- Niño-Torres CA, Gallo-Reynoso JP, Galván-Magaña F, Escobar-Briones E, Macko SA (2006) Isotopic analysis of $\delta^{13}\text{C}$, $\delta^{15}\text{N}$, and $\delta^{34}\text{S}$ ‘a feeding tale’ in teeth of the longbeaked

- common dolphin, *Delphinus capensis*. Mar Mamm Sci 22: 831–846
- ✦ Paul D, Skrzypek G, Fórizs I (2007) Normalization of measured stable isotopic compositions to isotope reference scales — a review. Rapid Commun Mass Spectrom 21:3006–3014
- Perrin WF (2009) Common dolphins. In: Perrin WF, Würsig B, Thewissen JGM (eds) Encyclopedia of marine mammals. Academic Press, San Diego, CA
- Perrin WF, Würsig B, Thewissen J (2009) Encyclopedia of marine mammals. Academic Press, San Diego, CA
- ✦ Peterson BJ, Fry B (1987) Stable isotopes in ecosystem studies. Annu Rev Ecol Syst 18:293–320
- ✦ Phillips DL, Gregg JW (2003) Source partitioning using stable isotopes: coping with too many sources. Oecologia 136:261–269
- ✦ Phillips DL, Inger R, Bearhop S, Jackson AL and others (2014) Best practices for use of stable isotope mixing models in food-web studies. Can J Zool 92:823–835
- Pierce GJ, Boyle PR (1991) A review of methods for diet analysis in piscivorous marine mammals. Oceanogr Mar Biol Annu Rev 29:409–486
- ✦ Post DM (2002) Using stable isotopes to estimate trophic position: models, methods, and assumptions. Ecology 83: 703–718
- ✦ Post DM, Layman CA, Arrington DA, Takimoto G, Quattrochi J, Montaña CG (2007) Getting to the fat of the matter: models, methods and assumptions for dealing with lipids in stable isotope analyses. Oecologia 152:179–189
- ✦ Pusineri C, Magnin V, Meynier L, Spitz J, Hassani S, Ridoux V (2007) Food and feeding ecology of the common dolphin (*Delphinus delphis*) in the oceanic northeast Atlantic and comparison with its diet in neritic areas. Mar Mamm Sci 23:30–47
- ✦ Quay P, Sonnerup R, Westby T, Stutsman J, McNichol A (2003) Changes in the $^{13}\text{C}/^{12}\text{C}$ of dissolved inorganic carbon in the ocean as a tracer of anthropogenic CO_2 uptake. Global Biogeochem Cycles 17:4-1–4-20
- ✦ Quillfeldt P, McGill RA, Furness RW (2005) Diet and foraging areas of Southern Ocean seabirds and their prey inferred from stable isotopes: review and case study of Wilson's storm-petrel. Mar Ecol Prog Ser 295:295–304
- R Core Team (2020) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna
- ✦ Read AJ, Drinker P, Northridge S (2006) Bycatch of marine mammals in US and global fisheries. Conserv Biol 20: 163–169
- ✦ Rubenstein DR, Hobson KA (2004) From birds to butterflies: animal movement patterns and stable isotopes. Trends Ecol Evol 19:256–263
- ✦ Ruiz-Cooley R, Villa EC, Gould WR (2010) Ontogenetic variation of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ recorded in the gladius of the jumbo squid *Dosidicus gigas*: geographic differences. Mar Ecol Prog Ser 399:187–198
- ✦ Ryan C, McHugh B, Trueman CN, Harrod C, Berrow SD, O'Connor I (2012) Accounting for the effects of lipids in stable isotope ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values) analysis of skin and blubber of balaenopterid whales. Rapid Commun Mass Spectrom 26:2745–2754
- ✦ Santos M, Clarke M, Pierce GJ (2001) Assessing the importance of cephalopods in the diets of marine mammals and other top predators: problems and solutions. Fish Res 52:121–139
- ✦ Schoener TW (1974) Resource partitioning in ecological communities. Science 185:27–39
- ✦ Sepúlveda F, Gálvez P, Molina-Burgos BE, Klarian SA (2018) Hábitos alimentarios del besugo *Epigonus crassicaudus* combinando contenido estomacal e isótopos estables. Rev Biol Mar Oceanogr 53:31–37
- ✦ Silva M (1999) Diet of common dolphins, *Delphinus delphis*, off the Portuguese continental coast. J Mar Biol Assoc UK 79:531–540
- ✦ Sinclair EH, Zeppelin TK (2002) Seasonal and spatial differences in diet in the western stock of Steller sea lions (*Eumetopias jubatus*). J Mammal 83:973–990
- ✦ Skinner MM, Martin AA, Moore BC (2016) Is lipid correction necessary in the stable isotope analysis of fish tissues? Rapid Commun Mass Spectrom 30:881–889
- ✦ Slooten E, Dawson SM (1995) Conservation of marine mammals in New Zealand. Pac Conserv Biol 2:64–76
- ✦ Smith JA, Mazumder D, Suthers IM, Taylor MD (2013) To fit or not to fit: evaluating stable isotope mixing models using simulated mixing polygons. Methods Ecol Evol 4: 612–618
- ✦ Spitz J, Mouroucq E, Leauté JP, Quérou JC, Ridoux V (2010) Prey selection by the common dolphin: fulfilling high energy requirements with high quality food. J Exp Mar Biol Ecol 390:73–77
- ✦ Stock BC, Jackson AL, Ward EJ, Parnell AC, Phillips DL, Semmens BX (2018) Analyzing mixing systems using a new generation of Bayesian tracer mixing models. PeerJ 6:e5096
- Stockin KA, Orams M (2009) The status of common dolphins (*Delphinus delphis*) within New Zealand waters. J Cetacean Res Manag SC/61/SM20
- ✦ Stockin KA, Law RJ, Duignan PJ, Jones GW and others (2007) Trace elements, PCBs and organochlorine pesticides in New Zealand common dolphins (*Delphinus* sp.). Sci Total Environ 387:333–345
- ✦ Stockin KA, Lusseau D, Binedell V, Wiseman N, Orams MB (2008a) Tourism affects the behavioural budget of the common dolphin *Delphinus* sp. in the Hauraki Gulf, New Zealand. Mar Ecol Prog Ser 355:287–295
- ✦ Stockin KA, Pierce GJ, Binedell V, Wiseman N, Orams MB (2008b) Factors affecting the occurrence and demographics of common dolphins (*Delphinus* sp.) in the Hauraki Gulf, New Zealand. Aquat Mamm 34:200–211
- ✦ Stockin KA, Binedell V, Wiseman N, Brunton DH, Orams MB (2009a) Behavior of free-ranging common dolphins (*Delphinus* sp.) in the Hauraki Gulf, New Zealand. Mar Mamm Sci 25:283–301
- ✦ Stockin KA, Duignan PJ, Roe WD, Meynier L, Alley M, Fettermann T (2009b) Causes of mortality in stranded common dolphins (*Delphinus* sp.) from New Zealand waters between 1998 and 2008. Pac Conserv Biol 15:217–227
- ✦ Stockin KA, Law RJ, Roe WD, Meynier L and others (2010) PCBs and organochlorine pesticides in Hector's (*Cephalorhynchus hectori hectori*) and Maui's (*Cephalorhynchus hectori mauui*) dolphins. Mar Pollut Bull 60:834–842
- ✦ Stockin KA, Amaral AR, Latimer J, Lambert DM, Natoli A (2014) Population genetic structure and taxonomy of the common dolphin (*Delphinus* sp.) at its southernmost range limit: New Zealand waters. Mar Mamm Sci 30:44–63
- ✦ Straley JM, Moran JR, Boswell KM, Vollenweider JJ and others (2018) Seasonal presence and potential influence of humpback whales on wintering Pacific herring populations in the Gulf of Alaska. Deep Sea Res II 147: 173–186
- ✦ Tezanos-Pinto G, Hupman K, Wiseman N, Dwyer SL and others (2017) Local abundance, apparent survival and

- site fidelity of Bryde's whales in the Hauraki Gulf (New Zealand) inferred from long-term photo-identification. *Endang Species Res* 34:61–73
- ✦ Thompson FN, Abraham ER, Berkenbusch K (2013) Common dolphin (*Delphinus delphis*) bycatch in New Zealand commercial trawl fisheries. *PLOS ONE* 8:e64438
- ✦ Walker JL, Macko SA (1999) Dietary studies of marine mammals using stable carbon and nitrogen isotopic ratios of teeth. *Mar Mamm Sci* 15:314–334
- ✦ Ware DM, Thomson RE (2005) Bottom-up ecosystem trophic dynamics determine fish production in the Northeast Pacific. *Science* 308:1280–1284
- ✦ Wiseman N, Parsons S, Stockin KA, Baker CS (2011) Seasonal occurrence and distribution of Bryde's whales in the Hauraki Gulf, New Zealand. *Mar Mamm Sci* 27:E253–E267
- Wood SN (2001) mgcv: GAMs and generalized ridge regression for R. *R News* 1:20–25
- Wood SN (2017) *Generalized additive models: an introduction with R*. CRC Press, Boca Raton, FL
- ✦ Young DD, Cockcroft V (1994) Diet of common dolphins (*Delphinus delphis*) off the south-east coast of southern Africa: opportunism or specialization? *J Zool (Lond)* 234: 41–53
- ✦ Yurkowski DJ, Hussey NE, Semeniuk C, Ferguson SH, Fisk AT (2015) Effects of lipid extraction and the utility of lipid normalization models on $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values in Arctic marine mammal tissues. *Polar Biol* 38:131–143
- ✦ Zaeschmar JR, Tezanos-Pinto G, Dwyer SL, Peters C and others (2020) Occurrence, site-fidelity and associations of oceanic common bottlenose dolphins (*Tursiops truncatus*) off northeastern New Zealand. *Mar Mamm Sci* 36: 1180–1195
- ✦ Zeldis JR, Swaney DP (2018) Balance of catchment and offshore nutrient loading and biogeochemical response in four New Zealand coastal systems: implications for resource management. *Estuar Coast* 41:2240–2259
- ✦ Zeldis JR, Walters RA, Greig MJ, Image K (2004) Circulation over the northeastern New Zealand continental slope, shelf and adjacent Hauraki Gulf, during spring and summer. *Cont Shelf Res* 24:543–561

*Editorial responsibility: Peter Corkeron,
Woods Hole, Massachusetts, USA*

*Submitted: March 20, 2020; Accepted: August 31, 2020
Proofs received from author(s): October 12, 2020*

Supplementary material

Foraging ecology of the common dolphin *Delphinus delphis* revealed by stable isotope analysis

Katharina J. Peters^{*1,2}, Sarah J. Bury³, Emma Betty¹, Guido J. Parra⁴, Gabriela Tezanos-Pinto^{1,5} & Karen A. Stockin¹

Author affiliations:

¹Cetacean Ecology Research Group, School of Natural and Computational Sciences, Massey University, Auckland 0745, New Zealand

²Global Ecology, College of Science and Engineering, Flinders University, Adelaide 5001, South Australia

³National Institute of Water and Atmospheric Research, Greta Point, 301 Evans Bay Parade, Hataitai, Wellington 6021, New Zealand

⁴Cetacean Ecology, Behaviour and Evolution Lab, College of Science and Engineering, Flinders University, Adelaide 5001, South Australia

⁵Molecular Ecology of Aquatic Vertebrates Lab (LEMVA), Los Andes University, Bogota 11711, Colombia

*Corresponding author: k.peters@massey.ac.nz

Extended methods

Details on stable isotope analysis

Carbon isotope data were corrected via a 2-point normalisation process (Paul et al. 2007) using NIST 8573 (USGS40 L-glutamic acid; certified $\delta^{13}\text{C} = -26.39 \pm 0.09$ ‰) and NIST 8542 (IAEA-CH-6 Sucrose; certified $\delta^{13}\text{C} = -10.45 \pm 0.07$ ‰). A 2-point normalisation process using NIST 8573 (USGS40 L-glutamic acid; certified $\delta^{15}\text{N} = -4.52 \pm 0.12$ ‰) and IAEA-N-2 (ammonium sulphate; certified $\delta^{15}\text{N} = +20.41 \pm 0.2$ ‰) was applied to $\delta^{15}\text{N}$ data. DL-Leucine (DL-2-Amino-4-methylpentanoic acid, $\text{C}_6\text{H}_{13}\text{NO}_2$, Lot 127H1084, Sigma, Australia) was run every ten samples to check analytical precision and enable drift corrections to be made if necessary. NIST 8547 (IAEA-N1 ammonium sulphate; certified $\delta^{15}\text{N} = +0.43 \pm 0.04$ ‰) and USGS65 Glycine (certified $\delta^{13}\text{C} = -20.29 \pm 0.04$ ‰; certified $\delta^{15}\text{N} = 20.68 \pm 0.06$ ‰) were run daily to check isotopic accuracy with 2 laboratory standards L Proline and homogenized squid run as an additional check precision.

Lipid correction formulae

We calculated a $\delta^{13}\text{C}$ lipid-correction factor using linear regression analysis of the $\delta^{13}\text{C}$ values of the original whole (non lipid-extracted) and lipid-extracted samples.

Common dolphins (*Delphinus delphis*): Corrected $\delta^{13}\text{C}$ value = $(-7.4674 + 0.5409 \times \text{uncorrected } \delta^{13}\text{C value})$

Prey: Corrected $\delta^{13}\text{C}$ value = $(-2.6526 + 0.7781 \times \text{uncorrected } \delta^{13}\text{C value})$

Details on Layman metrics

We used 6 different Layman metrics (Layman et al. 2007, Jackson et al. 2011) to measure niche variation between males and female *D. delphis*.

- 1) **$\delta^{15}\text{N}$ range:** distance between the highest and lowest $\delta^{15}\text{N}$ values (i.e. $\max \delta^{15}\text{N} - \min \delta^{15}\text{N}$). Measure of trophic length of the community.
- 2) **$\delta^{13}\text{C}$ range:** distance between the highest and lowest $\delta^{13}\text{C}$ values (i.e., $\max \delta^{13}\text{C} - \min \delta^{13}\text{C}$). Estimates the diversity of basal resources.
- 3) **Total area (TA):** total area of the convex hull comprising all data points. Measure of the total amount of niche space occupied and indication of niche width.
- 4) **Mean distance to centroid (CD):** average Euclidean distance of each sample to the centroid. Measure of niche width and sample spacing.
- 5) **Mean nearest neighbour distance (MNND):** mean of the Euclidean distances to each sample's nearest neighbor. Measure of density and clustering of individuals.
- 6) **Standard deviation of nearest neighbour distance (SDNND):** measure of the evenness of spatial density and packing of individuals. Low SDNND values indicate more even distribution of trophic niches.

Supplementary tables

Table S1 Raw data of *Delphinus delphis* recovered from the Hauraki Gulf, New Zealand, between 2004 and 2016. Season refers to the austral season (austral spring/summer = September–February; and austral autumn/winter = March–August).

ID	Year	Sex	Season	$\delta^{15}\text{N}$ (‰)	$\delta^{13}\text{C}$ (‰)	Body length (cm)
WS04-19Dd	2004	Male	Winter	14.18	-14.69	174
WS04-28Dd	2004	Female	Summer	13.36	-15.73	195
WS04-29Dd	2004	Female	Summer	13.09	-16.01	195
WS04-30Dd	2004	Male	Summer	13.1	-16.21	118
WS04-32Dd	2004	Female	Summer	14.19	-15.84	99
WS04-33Dd	2004	Female	Summer	12.99	-16.87	195
WS04-34Dd	2004	Female	Summer	13.43	-16.41	189
WS04-35Dd	2004	Female	Summer	13.38	-16.68	200
WS04-36Dd	2004	Female	Summer	12.56	-15.87	195
WS05-06Dd	2005	Male	Summer	14.76	-16.42	220
WS05-16Dd	2005	Female	Autumn	16.51	-14.94	207
WS05-18Dd	2005	Male	Summer	12.35	-17.73	213
WS05-19Dd	2005	Male	Summer	12.12	-17.24	207
WS05-20Dd	2005	Male	Summer	11.82	-17.28	211
WS05-24Dd	2005	Female	Autumn	16.18	-16.15	189
WS05-25Dd	2005	Female	Winter	14.68	-15.74	170
WS05-26Dd	2005	Male	Winter	14.66	-15.45	160
KS06-04Dd	2006	Female	Spring	15.19	-15.47	206
WS06-04Dd	2006	Female	Winter	15.44	-15.81	128
WS06-14Dd	2006	Female	Winter	14.95	-15.39	166
WS06-15Dd	2006	Male	Spring	15.78	-15.70	153
KS07-01Dd	2007	Female	Spring	17.04	-15.33	100
KS07-11Dd	2007	Female	Spring	15.32	-16.73	172
KS07-12Dd	2007	Female	Summer	16.18	-15.90	207
WS07-01Dd	2007	Female	Summer	15.68	-16.19	190
KS08-07Dd	2008	Male	Winter	14.37	-16.06	161
KS08-08Dd	2008	Male	Winter	16.76	-15.29	118
KS09-09Dd	2009	Female	Winter	14.88	-16.62	156
KS09-13Dd	2009	Male	Winter	15.11	-15.47	214
KS09-18Dd	2009	Female	Winter	14.56	-15.81	197
KS10-26Dd	2010	Male	Winter	14.3	-16.49	217

KS10-29Dd	2010	Male	Spring	16.42	-16.86	135
KS11-08Dd	2011	Male	Summer	15.41	-16.39	177
KS11-12Dd	2011	Male	Autumn	16.05	-16.32	171
KS11-13Dd	2011	Male	Autumn	14.43	-17.44	217
KS11-14Dd	2011	Female	Autumn	15.33	-17.22	195
KS11-39Dd	2011	Female	Winter	15.21	-17.44	152
KS11-40Dd	2011	Female	Winter	15.21	-17.43	149
KS11-50ADd	2011	Female	Spring	14.27	-16.43	73
KS11-50Dd	2011	Female	Spring	12.58	-17.64	195
KS12-13Dd	2012	Female	Winter	16.71	-16.46	189
KS12-14Dd	2012	Male	Winter	15.93	-17.22	185
KS12-15Dd	2012	Female	Winter	15.53	-16.36	190
KS12-17Dd	2012	Male	Winter	16.7	-16.40	156
KS12-23Dd	2012	Male	Summer	15.89	-16.70	146
KS13-07Dd	2013	Male	Winter	16.03	-17.33	130
KS13-08Dd	2013	Female	Winter	15.8	-17.74	155
KS13-09Dd	2013	Male	Winter	15.92	-17.53	172
KS14-38Dd	2014	Male	Winter	15.3	-17.12	207
KS14-39Dd	2014	Female	Winter	15.29	-17.98	150
KS14-42Dd	2014	Female	Spring	16.2	-17.31	123
KS15-01Dd	2015	Male	Summer	13.22	-17.60	220
KS15-19Dd	2015	Female	Winter	15.29	-17.19	195
KS15-20Dd	2015	Female	Winter	16.18	-16.99	98
KS15-21Dd	2015	Female	Winter	15.28	-17.23	162
KS16-29Dd	2016	Female	Spring	12.71	-17.35	160

Supplementary figures

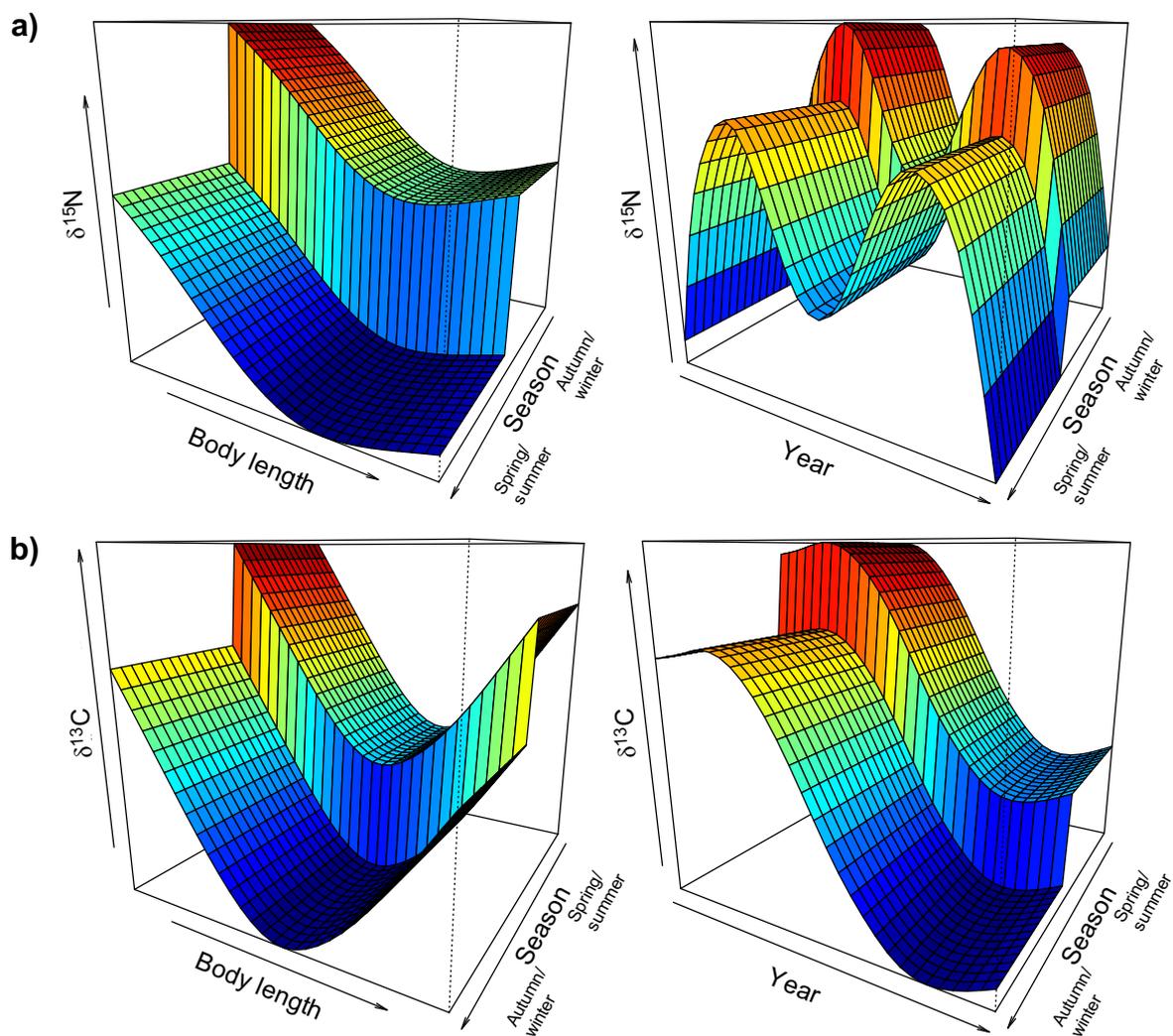


Figure S1 Visual representation of the categorical variable ‘season’ in GAMs, for **a)** nitrogen and **b)** carbon isotopic values. Graphs in **b)** have been rotated to show lower variable level in front.

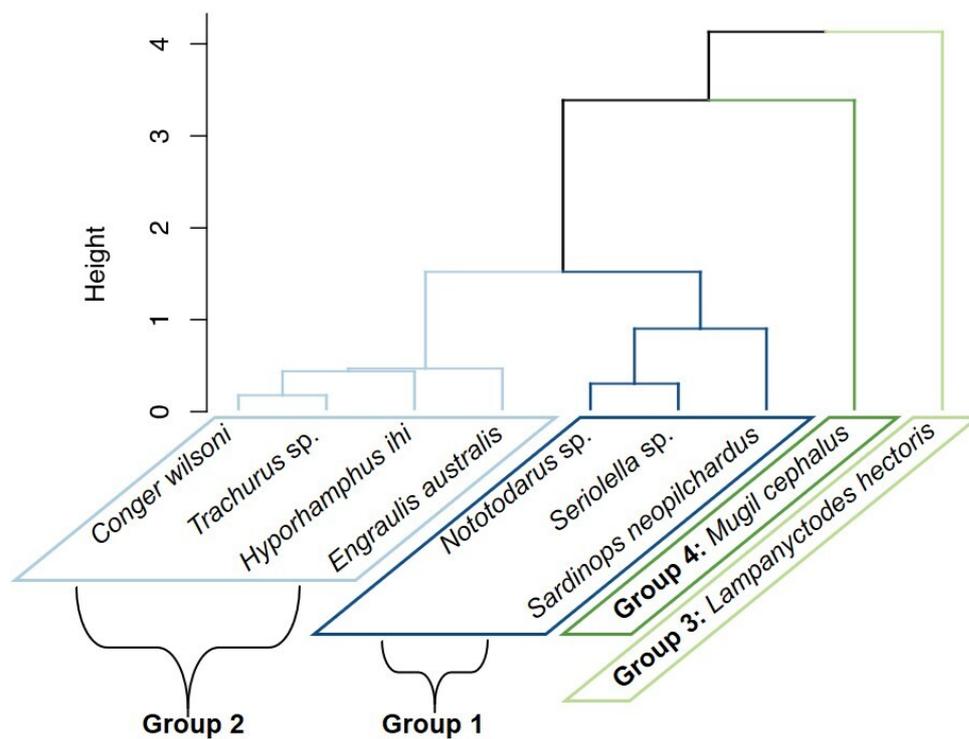


Figure S2 Dendrogram showing clustering of potential prey species. Ward's correlation coefficient = 0.728, height indicates the cophenetic distance between members.

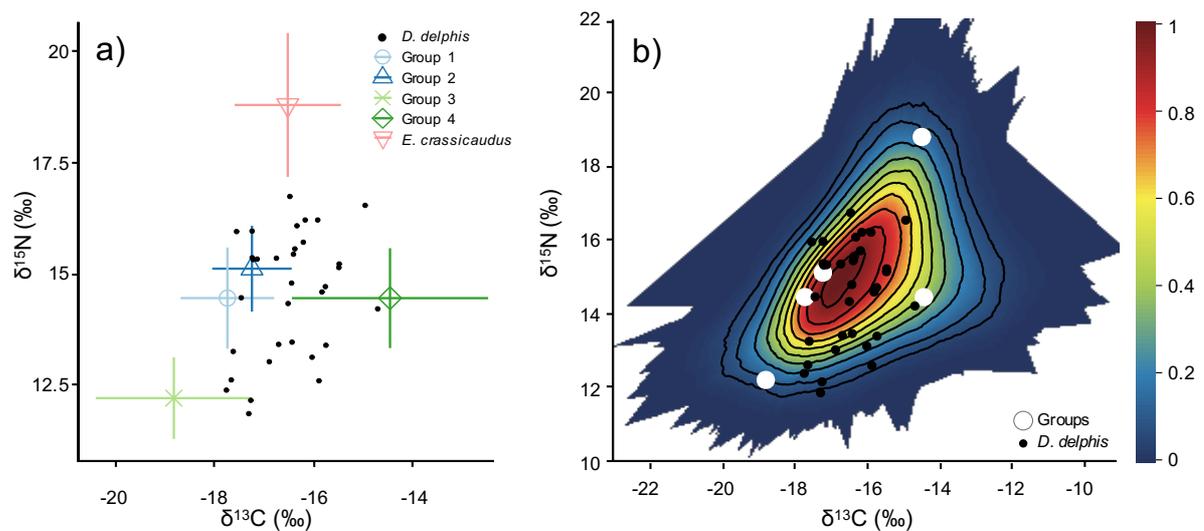


Figure S3 a) Isotopic values for weaned (≥ 170 cm body length) *Delphinus delphis*, individuals represented as black dots) and their potential dietary source groups (displayed as mean ± 1 SD, with incorporated diet-to-tissue discrimination factors: $1.01 \pm 0.37\text{‰}$ (mean \pm SD) for $\delta^{13}\text{C}$ and $1.57 \pm 0.52\text{‰}$ for $\delta^{15}\text{N}$) including *Epigonus crassicaudus* (values obtained from Sepúlveda et al. (2018)). **Group 1:** *Sardinops neopilchardus*, *Seriola* sp., *Nototodar* sp.; **Group 2:** *Hyporhamphus ihi*, *Trachurus* sp., *Conger wilsoni*, *Engraulis australis*; **Group 3:** *Lampanyctodes hectoris*; **Group 4:** *Mugil cephalus*. **b)** Mixing polygon for data presented in a), showing individual dolphins (black dots) and potential dietary source groups (white dots). Black lines represent probability contours at 10% levels. By including *E. crassicaudus*, validation improves drastically with only 1 individual dolphin falling outside of the 95% mixing space.

REFERENCES

- Jackson, A. L., Inger, R., Parnell, A. C. & Bearhop, S. 2011. Comparing isotopic niche widths among and within communities: SIBER – Stable Isotope Bayesian Ellipses in R. *J. Anim. Ecol.*, 80, 595-602.
- Layman, C. A., Arrington, D. A., Montaña, C. G. & Post, D. M. 2007. Can stable isotope ratios provide for community-wide measures of trophic structure? *Ecology*, 88, 42-48.
- Paul, D., Skrzypek, G. & Fórizs, I. 2007. Normalization of measured stable isotopic compositions to isotope reference scales—a review. *Rapid Commun. Mass Spectrom.*, 21, 3006-3014.
- Sepúlveda, F., Gálvez, P., Molina-Burgos, B. E. & Klarian, S. A. 2018. Hábitos alimentarios del besugo *Epigonus crassicaudus* combinando contenido estomacal e isótopos estables. *Rev. Biol. Mar. Oceanogr.*, 53, 31-37.