Length–weight and otolith size to standard length relationships in 12 species of Southern Ocean Myctophidae: A tool for predator diet studies

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Abstract
Fish morphometric relationships are key tools for fisheries science and studies of food web dynamics and predator foraging behaviour, but parameterisations are limited for Southern Ocean myctophids (Family Myctophidae). New standard length ($L_s$) to total mass ($M_T$) relationships are therefore described for the 12 biomass-dominant myctophid fish species living in the Scotia Sea, Southern Ocean, using the most comprehensive data collected in the region to date. New linear regressions for otolith size (length; $O_L$ and width; $O_W$) and $L_s$ are also described. Significant ($p < .01$) $L_s-M_T$ relationships were established for all species using simple non-linear regression. Significant ($p < .01$) relationships between $L_s$ and both $O_L$ and $O_W$ were also determined for all species, with $O_W$ being the best predictor of $L_s$ in all but one species. Our study provides a comprehensive tool for reconstructing the myctophid component of marine predator diets that will improve future food web, predator behaviour and ecosystem studies in the Scotia Sea.

KEYWORDS
length–mass relationship, Myctophidae, otolith–body size relationship, otoliths, Southern Ocean

1 | INTRODUCTION

Myctophid fish (Family Myctophidae) are the most successful clade of mesopelagic fish in the Southern Ocean, with ~ 35 species and an estimated biomass that may substantially exceed 70–200 million tonnes (Hulley, 1981; Lubimova et al., 1987). Myctophids are crucial in Southern Ocean food webs, but there remains a need to evaluate their role in this system to resolve the impacts that ongoing environmental change will have on the local marine ecosystem (Atkinson et al., 2019; Murphy et al., 2007). Against this backdrop, recent studies have focussed upon the role of myctophids as consumers in Southern Ocean food webs (Saunders et al., 2019). However, their trophic role as prey for the many pelagic predators that inhabit the region is lesser understood, which has limited the assessment of Southern Ocean food web structure and resilience (Xavier et al., 2016).

The analysis of myctophid sagittal otoliths retrieved from predators can provide important information on their species, size, mass, and energetic content, which is a prerequisite for understanding predator trophodynamics. However, useful information can only be obtained from the otoliths if the species-specific relationship between otolith size (or mass) and fish size is established robustly.
Existing information on otolith size to fish size relationships are available for some Southern Ocean myctophids, but they are limited by relatively small samples sizes collected predominantly over limited spatial and temporal scales (Adams & Klages, 1987; Cherel et al., 1997; Reid, 1996; Williams & McEldowney, 1990). The available body length–mass relationships are similarly limited. Here, we examine the relationships between otolith size and standard length, and standard length and mass, for the biomass-dominant myctophids in the Scotia Sea to improve the accuracy of their parameterisation for Southern Ocean food web and ecosystem studies.

2 | MATERIALS AND METHODS

Mesopelagic fish were collected across the Scotia Sea (southwest Atlantic: 57.57°S, 40.07°W) during four multidisciplinary research cruises onboard RRS *James Clark Ross* in Mar–Apr 2004, Oct–Dec 2006, Jan–Feb 2008 and Mar–Apr 2009 (see Collins et al., 2008; 2012 for further details). Specimens were collected from discrete depth horizons (at ~200 or 300 m intervals) between 0 and 1,000 m using a 25 m$^2$ rectangular mid-water trawl net (RMT25, with 3 mm cod end mesh; Piatkowski et al., 1994). Net samples were sorted onboard to the lowest taxonomic level possible (Hulley, 1990). Standard length (L$_S$) and total mass (M$_T$) of each specimen was recorded to the nearest 0.1 cm and 0.01 g, respectively, and a random sub-sample of up to 10–25 specimens per haul was frozen at −20°C for subsequent otolith analysis. Additional samples of the rarer species *Gymnoscopelus bolini* and *Gymnoscopelus hintonoides* were obtained by a commercial sized demersal trawl (FP-120) deployed to ~200–500 m during a scientific survey around the South Georgia shelf-break onboard the fishing vessel *Dorada* in Jan 2003 (see Collins et al., 2004).

### TABLE 1

| Species | Location | n | L$_S$ range (cm) | M$_T$ range (g) | a | ±95% C.I. $a$ | b | ±95% C.I. $b$ | $r^2$ |
|---------|----------|---|-----------------|-----------------|---|----------------|---|----------------|------|
| Electrona carlsbergi (Tåning, 1932) | Northern Scotia Sea | 377 | 6.5–9.0 | 3.77–9.27 | 0.0183 | ±0.00451 | 2.88 | ±0.121 | 0.856 |
| Electrona antarctica (Günther, 1878) | All Scotia Sea | 1,459 | 2.5–11.3 | 0.16–22.12 | 0.00510 | ±0.000392 | 3.45 | ±0.0339 | 0.975 |
| Gymnoscopelus bolini Andriashev, 1962 | South Georgia | 111 | 14.9–25.5 | 44.00–198.00 | 0.00560 | ±0.00235 | 3.23 | ±0.140 | 0.954 |
| Gymnoscopelus braueri (Lönnberg, 1905) | All Scotia Sea | 884 | 3.4–16.2 | 0.24–19.49 | 0.00510 | ±0.00059 | 3.21 | ±0.0441 | 0.976 |
| Gymnoscopelus fraseri (Fraser-Brunner, 1931) | Northern Scotia Sea | 100 | 3.9–11.5 | 0.34–11.75 | 0.00690 | ±0.00157 | 3.22 | ±0.104 | 0.979 |
| Gymnoscopelus hintonoides Hulley, 1981 | South Georgia | 20 | 10.2–14.5 | 12.00–38.00 | 0.0200 | ±0.0192 | 2.80 | ±0.368 | 0.951 |
| Gymnoscopelus nicholsi (Gilbert, 1911) | All Scotia Sea | 53 | 3.4–16.0 | 0.27–48.17 | 0.00890 | ±0.00627 | 3.06 | ±0.261 | 0.963 |
| Gymnoscopelus opisthopterus Fraser-Brunner, 1949 | All Scotia Sea | 38 | 5.6–17.0 | 1.00–50.00 | 0.0777 | ±0.0735 | 2.25 | ±0.353 | 0.964 |
| Krefftichthys anderssoni (Lönnberg, 1905) | Northern Scotia Sea | 605 | 2.7–7.4 | 0.14–4.16 | 0.0113 | ±0.00137 | 2.97 | ±0.0682 | 0.963 |
| Protomyctophum tenisoni (Norman, 1930) | Northern Scotia Sea | 157 | 2.8–5.5 | 0.22–1.84 | 0.0193 | ±0.00274 | 2.69 | ±0.0933 | 0.973 |
| Protomyctophum bolini (Fraser-Brunner, 1949) | All Scotia Sea | 376 | 2.5–6.6 | 0.19–3.58 | 0.144 | ±0.00176 | 2.95 | ±0.0774 | 0.951 |
| Protomyctophum choriodon Hulley, 1981 | Northern Scotia Sea | 48 | 5.6–8.4 | 1.69–6.61 | 0.0206 | ±0.00745 | 2.75 | ±0.188 | 0.957 |

Note: The Northern Scotia Sea was defined as waters north of the South Antarctic Circumpolar Current Front, which occurs generally in the region at ~56°S.

Abbreviations: ±95% CI, 95% confidence intervals for $a$ and $b$; $a$, intercept; $b$, slope; $n$, total number of specimens collected; $r^2$, coefficient of determination.
| Species                     | n     | $L_S$ range (mm) | $O_L$ range (mm) | $O_W$ range (mm) | $L_S$ to $O_L$ | $L_S$ to $O_W$ |
|-----------------------------|-------|------------------|------------------|------------------|----------------|----------------|
| $a$                         | $b$   | $\pm 95\%$ CI   | $r^2$            | $a$              | $b$            | $\pm 95\%$ CI |
| Electrona carlsbergi         | 134   | 65–90            | 2.96–3.92        | 2.63–3.50        | 17.0           | 4.69           | 20.2 | 1.57 | .614 | 5.86 | 5.99 | 21.0 | 1.76 | .577 |
| Electrona antarctica         | 173   | 36–109           | 0.88–2.32        | 1.64–2.68        | −4.23          | 2.78           | 48.8 | 1.58 | .876 | −8.57 | 2.39 | 42.1 | 1.12 | .913 |
| Gymnoscopelus bolini         | 50    | 174–255          | 6.00–9.20        | 3.33–5.25        | 49.2           | 17.8           | 37.5 | 4.16 | .682 | 33.5  | 14.4  | 23.9 | 1.95 | .799 |
| Gymnoscopelus braueri       | 164   | 42–139           | 0.80–2.62        | 0.88–2.42        | 2.25           | 3.39           | 49.8  | 1.82 | .684 | −17.7 | 3.60  | 59.6  | 1.91  | .884 |
| Gymnoscopelus fraseri       | 42    | 45–85            | 1.64–3.70        | 1.08–2.44        | −9.74          | 8.07           | 39.8  | 3.90 | .763 | −0.0460 | 6.65  | 22.9 | 2.10  | .787 |
| Gymnoscopelus hintonoides   | 15    | 118–145          | 4.13–5.50        | 2.50–3.17        | 25.6           | 27.0           | 38.2  | 9.37 | .615 | 57.9  | 13.1  | 16.0  | 2.69  | .773 |
| Hulley, 1981                |       |                  |                  |                  |                |                |       |      |      |       |       |       |       |      |
| Gymnoscopelus nicholsi      | 97    | 39–159           | 1.70–6.29        | 1.14–3.67        | −25.8          | 3.54           | 50.8  | 1.21 | .959 | −17.5 | 3.29  | 28.2  | 0.66  | .960 |
| Gymnoscopelus opisthopterus | 20    | 82–166           | 1.68–3.52        | 1.28–2.84        | 17.3           | 11.4           | 53.6  | 5.72 | .901 | −0.600 | 9.01  | 58.5  | 4.24  | .952 |
| Fraser-Brunner, 1949        |       |                  |                  |                  |                |                |       |      |      |       |       |       |       |      |
| Gymnoscopelus choriodon     | 24    | 59–98            | 1.85–2.25        | 1.63–2.18        | 0.482          | 28.5           | 34.0  | 13.8 | .501 | 6.29  | 24.1  | 34.1  | 12.7  | .532 |
| Hulley, 1981                |       |                  |                  |                  |                |                |       |      |      |       |       |       |       |      |

Abbreviations: 95% CI, 95% confidence intervals for $a$ and $b$; $a$, intercept; $b$, slope; $F$, significance level of the ANOVA $F$ test (*$p < .01$); $n$, total number of specimens collected; $r^2$, coefficient of determination.
Sagittal otoliths were removed by dissection, cleaned and dried. For each otolith, the maximum otolith length ($L$) and width ($O$) were measured to the nearest 0.001 mm using a microscope and a calibrated eyepiece graticule, recording the greatest distance from the anterior tip to the posterior edge ($O$), and the greatest distance between the otolith dorsal and ventral margins ($O$). Standard length–mass relationships were calculated for each species, using the simple non-linear regression model: $M = aL^n$, where the coefficients $a$ and $b$ are constants of the regression. Linear regression was used to relate $L$ to $O$ and $O$. These equations were first calculated for both left and right otoliths for each species and a $t$ test was used to compare regression coefficients; when significant differences ($p < 0.05$) were not found, the $H_0$ hypothesis ($b_{left} = b_{right}$) was accepted. Where these equations did not differ statistically, a single linear regression was reported for each variable ($O$ and $O$) and species.

3 | RESULTS

Significant ($p < 0.01$) length–mass relationships ($L$ to $M$) and length–otolith size regressions ($L$ to $O$ and $L$ to $O$) were established for 12 species and the model parameters are given in Tables 1 and 2. The $t$ tests on the relationship between $L$ and $O$ and $O$ did not show significant differences ($p > 0.05$) between left and right sagittae, so a single regression was used for each species. Based on the coefficient of determination ($r^2$), $O$ was the best predictor of $L$ for all species except *Electrona carlsbergi*.

4 | DISCUSSION

Our data represent a large proportion of the Southern Ocean myctophid fish assemblage and encompass the biomass-dominant species that reside in waters south of the Antarctic Polar Front (APF; Hulley, 1981). They also cover the species found most frequently in predator diets in the region (Reid et al., 2006). Myctophids are challenging to sample adequately at appropriate spatio-temporal scales in the remote Southern Ocean, which has hindered adequate parameterisation of their morphometric relationships. We examined data from greater sample sizes and more resolve spatio-temporal scales than previously available in the region, making our study the most accurate tool available to date for reconstructing the myctophid component of Southern Ocean predator diets. We also provide the most comprehensive standard length–mass relationships for myctophids that occur south of the APF, which are of high importance for many applications in a fisheries science, food web and marine ecosystem research context.

With respect to the standard length–otolith size relationships, our data are broadly characteristic of the size ranges caught in the Scotia Sea for each species. In general, few specimens <40 mm of any species have been found in the region across multiple years and seasons, using a range of different sampling gear (Saunders et al., 2019). The lack of data at smaller size classes is likely to be a prime contributor to the negative intercepts of the relationships for some species (Table 2), which indicates that data from waters north of the APF, where the smaller size classes probably occur (Hulley, 1981), may be needed to constrain the relationships more robustly. This is also true for the predominately expatriate species *E. carlsbergi*, where more data across its full size range are needed to establish a more accurate length–weight relationship (Table 1). Indeed, this is a problem common to previous studies in the Southern Ocean. We maintain that it is advisable to use the $O$–$L$ and $O$–$L$ linear regressions and the $L$–$M$ equation within the fish size range limits reported in order to avoid errors in mass and size estimation, particularly when extrapolating to other regions of the Southern Ocean. Clearly, further studies are required throughout the Southern Ocean to put our parameterisations into context and facilitate regional comparisons in growth and morphometry. Other limitations to the use of this methodology include the rate at which the otolith increases in length may slow down, with otoliths increasing only in thickness at the maximum body size (Williams & Bedford, 1974), and a change in the otolith size and fish size relationship may be observed in larval and juvenile specimens (Bystydzienska et al., 2010).

ACKNOWLEDGEMENTS

This work was undertaken as part of the British Antarctic Survey’s Ecosystems Programme, funded by the Natural Environment Research Council, a part of UK Research and Innovation. R. P. Vieira and S. Lourenço were supported by the Caixa Geral de Depósitos Grant Programme “Nova Geração de Cientistas Polares”, under the Portuguese Polar Program PROPOLAR. J. Xavier and S. Lourenço received financial support from Fundação para a Ciência e Tecnologia (FCT, Portugal), with the research being part of the strategic project UIDB/04292/2020 granted to MARE-Marine and Environmental Sciences Centre. We are grateful to C. Assis for assistance and guidance during the otolith analysis and C. Reiss for constructive comments on the manuscript.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Saunders RA, Lourenço S, Vieira RP, Collins MA, Xavier JC. Length–weight and otolith size to standard length relationships in 12 species of Southern Ocean Myctophidae: A tool for predator diet studies. J Appl Ichthyol. 2020;00:1–5. https://doi.org/10.1111/jai.14126