Age, growth and maturity of Southern Ocean skates (*Bathyraja* spp.) from the Kerguelen Plateau

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Abstract

Three species of Southern Ocean skates, *Bathyraja eatonii*, *Bathyraja irrasa* and *Bathyraja murrayi*, are commonly caught as incidental by-catch in fisheries around Heard Island and McDonald Islands of the Kerguelen Plateau. We used length-at-age data to present the species’ life history information (age, growth and maturity for the first-time). Length- and age-at-maturity analyses revealed that *B. irrasa* matured at > 6 years old and > 1000 mm total length (TL), which was older and larger than *B. murrayi* (> 5 years old and > 400 mm TL) but similar to *B. eatonii* (> 5 years old and > 900 mm). We fitted growth models using a multi-model Bayesian framework. Our findings support the assumption that *B. irrasa* is slow growing and late maturing compared to *B. eatonii* and *B. murrayi*, consequently putting it at greater risk to fishery-induced increases in mortality compared to other species (e.g., *B. murrayi*). This is the first-time age and growth has been estimated for these species, however sample sizes for *B. murrayi* and *B. eatonii* were small and hence growth models should be interpreted with caution. Our results represent vital information for population projection models and can therefore assist in the development and/or revision of current by-catch limits to inform ongoing management strategies and conservation efforts.

Keywords Antarctica · By-catch · Elasmobranch · Life history · Rajidae · Vertebral ageing

Introduction

Overfishing threatens over one-third of shark, skate and ray (class: Chondrichthyes, subclass Elasmobranchii) species with extinction and has profoundly altered their population dynamics (Dulvy et al. 2014, 2021). Global declines in elasmobranch populations have been attributed to targeted fishing and incidental capture as by-catch (Baraussse et al. 2014), raising concerns about their conservation status (Baje et al. 2018). Several elasmobranch species are particularly vulnerable to overfishing due to a combination of biological characteristics including slow growth, late maturity, and low fecundity (Baje et al. 2018; Caltabellotta et al. 2019). In many cases, such as for skates (superorder: Batoidae, order: Rajiformes), a lack of available life history information presents a problem for determining the vulnerability of a species to overfishing. Without this information, fishing may remain unsustainable and increases the risk of a population decline for a given species.

Commercial longline and trawl fishing occurs on the Kerguelen Plateau in the Southern Ocean. In the Australian Exclusive Economic Zone (EEZ) surrounding Heard Island...
and McDonald Islands (HIMI), Patagonian toothfish, Dis-sostichus eleginoides, is targeted in both demersal longline and trawl fisheries and mackerel icefish, Champsosophalus gunnari, is targeted by trawl only (Nowara et al. 2017). Since the Australian fishery first started in 1997, there has been 100% scientific observer coverage on all fishing trips. The fisheries are managed by the Australian Fisheries Management Authority (AFMA), in accordance with decisions by the Commission for the Conservation of Antarctic Living Resources (CCAMLR; Nowara et al. 2017). Stock assessment and population models provide the basis for determining annual target catch quotas and by-catch limits (Nowara et al. 2017). Other marine animals are often caught as incidental by-catch in the HIMI fisheries, including macrourids, other icefish species and skates (Nowara et al. 2017). Life history traits can vary greatly between skate species (Barnett et al. 2013). As such, species-specific life history information is central to the development of evidence-based management strategies. This includes species-specific by-catch mitigation approaches and catch limits, which can reduce the risk of overexploitation of skate species like that witnessed with the common skate (Dipturus batis) in the Irish Sea (Brander 1981; Dulvy et al. 2000).

Three species of Southern Ocean skates are commonly caught in HIMI fisheries: Kerguelen sandpaper skate (Bathyraja irrasa), Eaton’s skate (Bathyraja eatonii) and Murray’s skate (Bathyraja murrayi; Nowara et al. 2017). Amongst them, B. eatonii is the most frequently caught species in the icefish trawl fishery (Nowara et al. 2017). This species grows to over 1200 mm total length (TL) and may be found in depths up to 1100 m (Nowara et al. 2017). Bathyraja irrasa reaches a maximum length of ~ 120 mm TL and is found at 300–1700 m depth, whereas the smaller B. murrayi reaches a maximum length of ~ 70 mm TL and is found in shallower depths of 30–650 m (Nowara et al. 2017). The International Union for Conservation of Nature (IUCN) has listed B. eatonii and B. murrayi as ‘Least Concern’ on the IUCN Red List of Threatened Species, while B. irrasa is listed as ‘Near Threatened’ (Dulvy et al. 2020). Two of the species appear to have a limited distribution (Smith et al. 2008; Nowara et al. 2017). Bathyraja irrasa and B. murrayi are only found on the Kerguelen Plateau, while B. eatonii occurs on the Kerguelen Plateau, in Antarctic shelf waters in the South Indian sector of the Southern Ocean, the South Atlantic Ocean, and the Ross Sea (Smith et al. 2008). The skates at HIMI have limited movement based on mark-recapture tagging experiments between 2001 and 2013, which revealed that they were, on average, recaptured up to 7.5 km from their initial release point (Nowara et al. 2013). This indicates limited movement for all three species (Nowara et al. 2017).

Species-specific biological parameters, including age-based characteristics, along with accompanying growth rates, are key for reliable population assessments and the development of sustainable fisheries management strategies (Caltabellotta et al. 2019; James 2019). Researchers most commonly use a frequentist approach to estimate length-at-age growth models (Smart and Grammer 2021). However, Bayesian inference approaches may yield increased benefits to fisheries studies by having the ability of incorporating a priori knowledge about data distributions along with the data to be modelled (Doll and Jacquemin 2019). Age estimates are typically determined by examining hard structures such as otoliths in teleosts, or vertebral centra in elasmobranchs (James 2019). Growth zones are examined for characteristic band pairs consisting of alternating opaque and translucent bands, each pair assuming to correspond to a year of age (Cailliet et al. 2006). A preliminary population assessment of Bathyraja spp. at HIMI used a Generalised Yield Model to estimate a sustainable catch limit of 50–210 t (Constable et al. 1998), and subsequently an annual catch limit of 120 t for the HIMI fishery was set by CCAMLR. However, this assessment relied on growth estimates for Raja clavata from the North Sea, and estimates of maturity of the three Bathyraja spp. were pooled together (Brander and Palmer 1985; Constable et al. 1998). Age-related information for Southern Ocean skates is largely lacking due, in part, to a lack of biological specimens available for scientific research (Smith et al. 2008). Therefore, the aim of this study was to generate new life history information and present the first species-specific age, growth, and maturity estimates for the three Bathyraja spp. from HIMI.

### Methods

#### Sample collection

Fisheries observers on board commercial vessels operating within HIMI collected vertebrae samples from 249 B. irrasa, 22 B. eatonii and 21 B. murrayi between November 2013 and April 2018 (Fig. 1, S1 in Online Resource 1). Detailed sampling methodology followed the protocols described by Nowara et al. (2017). Biological measurements collected from each sample included the date of capture, total length (mm), sex, and maturity stage. Maturity was determined by examination of gonads and then categorisation according to the developmental stage of ovaries and uteri in females, and claspers in males (Table 1).

#### Age estimation

We collected, cleaned, and stored the vertebrae samples following standard protocols described by Cailliet and Goldman (2004). Vertebral sections were viewed using a charge-coupled device (CCD) digital camera mounted onto a Leica M80 dissecting microscope under transmitted light,
Operations were conducted at a magnification of ×10. Customised image analysis and ageing software were used to estimate age and derive annual growth measurements (Fig. 2). First, a birth band reflecting the time an individual hatched from their egg case was identified as the first distinct growth band after an angle change in the corpus calcareum. Next, the number of growth bands along a transect on the vertebrae section were counted, from the focus (time of birth) to the outer edge (time of death). Our samples did not span a wide enough range of months of capture to conduct a formal marginal increment analysis. We therefore assumed annual formation of growth bands, which is consistent with validated ageing protocols of several other closely related species (e.g., Cailliet and Goldman 2004; Okamura et al. 2013). Precision and bias were checked using average percent error (APE), Bowker’s test of symmetry, Chang’s coefficient of variation (CV) and age bias plots (Hoenig et al. 1995; Morison et al. 1998).

**Maturity**

Maturity stage was expressed as a binary maturity category (immature/maturing = 0 or mature = 1) for use in statistical analyses.
analyses (Table 1). Length and maturity information was collected from 37,612 B. irrasa, 19,186 B. eatonii and 5922 B. murrayi between October 1998 and July 2020.

To estimate the length at 50% maturity ($L_{50}$) and 95% maturity ($L_{95}$), a three-parameter logistic model was fitted:

$$y = \frac{a}{1 + \left(\frac{L}{L_{50}}\right)^b}$$

where $L_t$ is length as a function of time, $y$ is the percent-age of mature animals, $a$ the asymptotic value, $b$ the shape parameter. A single logistic regression model (FSA’ R package version 0.8.30; Ogle 2016) was applied with the natural logarithm of the odds of an individual being mature (i.e., logit link) as a linear function of the explanatory variable, lengths, where maturity was assumed to follow a Bernoulli distribution. Age-at-maturity was estimated by converting length-at-maturity estimates with the formula:

$$y = \frac{a}{1 + \left(\frac{L_t}{L_0}\right)^b}$$

where $L_t$ is length as a function of time, $L_0$ the length at birth, $L_a$ the asymptotic length and $k/g$ the growth-completion coefficient.

Growth model fitting and statistical analyses

Due to the small sample sizes for both B. eatonii and B. murrayi, we used two model-fitting approaches for each of the three species, (1) multi-model frequentist and (2) multi-model Bayesian. In both approaches, we fitted three candidate growth models to observed length-at-age data following the recommendations in Smart et al. (2016): (1) a von Bertalanffy growth model (VBGM); (2) a Gompertz growth function; and (3) a logistic growth model (Table 2).

### Frequentist approach

We modelled the growth of each Bathyraja spp. using a frequentist multi-model approach, which used the Akaike Information Criterion (AIC) to select the best model fit based on the lowest AICc value (Akaica 1974). We fitted the growth models using the ‘Estimate Growth’ function within the ‘AquaticLifeHistory’ R package (Smart 2019).

### Bayesian approach

The informative priors specified for Bayesian models included $L_{50}$ and $L_0$ as normal distributions with means and standard errors. Growth coefficients and sigma values were uniform priors with an upper and lower bound, and the growth curve had a normal error structure (Smart and Grammer 2021). Priors were set based on the observed species-specific length and maturity data and a review of growth parameters for deep water skates from the scientific literature (S2 in Online Resource 1). The priors for $L_{50}$ were determined as the largest TL measured amongst all samples caught (1452 mm ± 132 SE for B. irrasa, $L_{50} = 1322$ mm ± 132 SE for B. eatonii and 477 mm ± 132 SE for B. murrayi) while that of $L_0$ was set using a presumed length-at-birth based on the smallest TL measured from age zero individuals (117 mm ± 29.25 SE for B. irrasa and 209 mm ± 30 SE for B. murrayi). However, as no age zero samples were obtained for B. eatonii, $L_0$ for this species was based on a hypothetical value (209 mm ± 30 SE) derived from averaging $L_0$ values of similarly sized Antarctic skate species (i.e., B. irrasa and Amblyraja georgiana; Francis and Maolagáin 2005). Standard error for $L_{50}$ was consistent across all species at 132 mm, while the standard error for $L_0$ was set at 25% of the corresponding $L_0$ value. The $L_0$ standard error for B. eatonii was set at 50% of the $L_0$ value (55 mm) to account for...
for uncertainties due to using a hypothetical TL value. Additionally, sensible upper bounds for non-informative priors $k$ and $\sigma$ were set at 3 and 300, respectively, while the lower bounds were set at zero (Smart and Grammer 2021). We also performed age adjustments of 0.5 years to the observed age classes for the Bayesian models to account for assumed asynchronous reproduction patterns for growth model fitting (Harry et al. 2010).

All Bayesian models were evaluated with the ‘Estimate_MCMC_Growth’ function within the ‘BayesGrowth’ R package version 0.3.1 (Smart 2020). We used 1000 iterations to determine parameter posterior distributions, after which convergence and auto-correlation of the models were checked using the Gelman-Rubin test ($R = 1$ for all models) and diagnostic plots, respectively (S3, S4 and S5 in Online Resource 1; Emmons et al. 2020.). The best fitting Bayesian model was identified using the leave-one-out cross validation information criterion (LOOIC) and selected as the model resulting in the lowest LOOIC value.

Results

Age estimation

For B. irrasa, corresponding values of APE and CV for the inter- and intra-reader variability were 4.21 and 5.96 and 2.83 and 4.01 (S6 in Online Resource 1), respectively, indicating a high degree of precision observed between reader 1 and reader 2. No systematic bias was detected between both readers by Bowker’s test of symmetry (Bowker; $df = 16$, $x^2 = 25.30$, $P = 0.065$) and between the first read and second read (Bowker; $df = 11$, $x^2 = 18.00$, $P = 0.082$). Corresponding values of APE and CV for the intra-reader variability was 11.91 and 16.85 respectively for B. eatonii (S7a in Online Resource 1). These values are comparable to other elasmobranch age and growth studies despite being high relative to teleost ageing studies (Campana 2001; Cailliet et al. 2006; D’Alberto et al. 2016). For B. murrayi, corresponding values of APE and CV for the intra-reader variability was 6.32 and 8.94, respectively (S7b in Online Resource 1). Estimating the ages of B. eatonii and B. murrayi in this study proved to be difficult due to the small sizes of the collected samples, posing challenges in both preparation and interpretation of the vertebrae which resulted in inconsistencies in the age estimates.

Maturity

Length-at-maturity

We conducted length-at-maturity analysis based on a dataset of 62,720 individuals (37,612 B. irrasa; 19,186 B. eatonii; 5922 B. murrayi; S8 in Online Resource 1). Females were found to mature at greater lengths compared to males across all three species (Table 3; Fig. 3). There were 13,626 (36.22%) mature B. irrasa in the length samples (Table 4).

Mean estimates of $L_{50}$ and $L_{95}$ for males were 1096 (1093–1098; 95% CI) mm TL and 1254 (1249–1259; 95% CI) mm TL, respectively (Table 3; Fig. 3a), while the mean

| Table 3 | Summary of length-at-maturity analysis for Bathyraja irrasa, Bathyraja eatonii and Bathyraja murrayi from the Heard and McDonald Islands |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| **Species**     | **Sex**         | $L_{10}$        | $L_{50}$        | $L_{90}$        | $L_{95}$        |
| B. irrasa       | Combined        | 969.96          | 1118.99         | 1268.02         | 1318.70         |
|                 | $n = 37,612$    |                 |                 |                 |                 |
|                 | Male            | 977.33          | 1095.54         | 1213.75         | 1253.95         |
|                 | $n = 24,206$    |                 |                 |                 |                 |
|                 | Female          | 1003.93         | 1165.39         | 1326.85         | 1381.75         |
|                 | $n = 13,406$    |                 |                 |                 |                 |
| B. eatonii      | Combined        | 899.42          | 1020.37         | 1141.31         | 1182.44         |
|                 | $n = 19,186$    |                 |                 |                 |                 |
|                 | Male            | 894.60          | 997.32          | 1100.05         | 1134.98         |
|                 | $n = 13,295$    |                 |                 |                 |                 |
|                 | Female          | 942.25          | 1084.48         | 1226.72         | 1275.09         |
|                 | $n = 5891$      |                 |                 |                 |                 |
| B. murrayi      | Combined        | 394.12          | 461.38          | 528.64          | 551.51          |
|                 | $n = 5922$      |                 |                 |                 |                 |
|                 | Male            | 391.42          | 455.29          | 519.17          | 540.89          |
|                 | $n = 3768$      |                 |                 |                 |                 |
|                 | Female          | 388.78          | 485.83          | 582.87          | 615.87          |
|                 | $n = 2154$      |                 |                 |                 |                 |

$L_{10}$ total length (TL) at 10% maturity, $L_{50}$ TL at 50% maturity, $L_{90}$ TL at 90% maturity, $L_{95}$ TL at 95% maturity, CI confidence interval
estimates of \( L_{50} \) and \( L_{95} \) for females were 1165 (1162–1169; 95% CI) mm TL and 1382 (1372–1391; 95% CI) mm TL, respectively (Table 3; Fig. 3b). There were 3670 (19.13%) mature \( B. \) eatonii in the length samples (Table 4). Mean estimates of \( L_{50} \) and \( L_{95} \) for males were 997 (994–1000; 95% CI) mm TL and 1135 (1127–1143; 95% CI) mm TL, respectively (Table 3; Fig. 3c), while the mean estimates of \( L_{50} \) and \( L_{95} \) for females were 1084 (1076–1093; 95% CI) mm TL and 1275 (1256–1295; 95% CI) mm TL, respectively (Table 3; Fig. 3d). There were 1939 (32.74%) mature \( B. \) murrayi in the length samples (Table 4). Mean estimates of \( L_{50} \) and \( L_{95} \) for males were 455 (453–458; 95% CI) mm TL and 541 (534–548; 95% CI) mm TL, respectively (Table 3; Fig. 3e), while the mean estimates of \( L_{50} \) and \( L_{95} \) for females were 486 (479–494; 95% CI) mm TL and 616 (595–640; 95% CI) mm TL, respectively (Table 3; Fig. 3f).

**Age-at-maturity**

Mean estimates of \( A_{50} \) and \( A_{95} \) for male \( B. \) irrasa were 6.29 (6.05–6.54; 95% CI) and 11.80 (10.16–14.33; 95% CI) years, respectively (Table 5), while the mean estimates of \( A_{50} \) for females were 7.83 (7.48–8.20; 95% CI). \( A_{95} \) for female \( B. \) irrasa could not be determined due to
Table 5 Summary of age-at-maturity analysis for Bathyraja irrasa, Bathyraja eatonii and Bathyraja murrayi from Heard and McDonald Islands

| Species      | Sex          | \(A_{50}\)  | \(A_{95}\)  | \(A_{50}\) CI        |
|--------------|--------------|--------------|--------------|----------------------|
|              |              | 2.5%         | 97.5%        |                      |
| B. irrasa    | Combined     | 6.76         | 19.17        | 6.40 7.16            |
|              | Male         | 6.29         | 11.80        | 6.05 6.54            |
|              | Female       | 7.83         | –            | 7.48 8.20            |
| B. eatonii   | Combined     | 5.32         | 8.70         | 5.09 5.56            |
|              | Male         | 5.02         | 7.50         | 4.87 5.17            |
|              | Female       | 6.30         | 13.61        | 6.02 6.61            |
| B. murrayi   | Combined     | 5.28         | 10.55        | 4.94 5.64            |
|              | Male         | 4.79         | 8.54         | 4.40 5.21            |
|              | Female       | 5.63         | 10.20        | 5.31 5.98            |

\(A_{50}\) age (years) at 50% maturity, \(A_{95}\) age (years) at 95% maturity, CI confidence interval

Table 6 Total length (mm) estimates for Bathyraja irrasa, Bathyraja eatonii and Bathyraja murrayi from Heard and McDonald Islands

| Species      | Model    | \(L_0\) (± SE) | \(L_\infty\) (± SE) | \(k/g\) (± SE) | LOOIC (± SE) |
|--------------|----------|----------------|---------------------|---------------|--------------|
| B. irrasa    | Gompertz | 367.25 ± 21.09 | 1201.19 ± 27.39     | 0.34 ± 0.03   | 2608.71 ± 25.86 |
|              | VBF      | 317.39 ± 24.53 | 1241.03 ± 33.75     | 0.24 ± 0.02   | 2610.60 ± 25.30 |
|              | Logistic | 397.99 ± 19.29 | 1177.05 ± 23.32     | 0.45 ± 0.04   | 2608.89 ± 25.30 |
| B. eatonii   | Gompertz | 134.25 ± 53.29 | 861.42 ± 43.26      | 1.30 ± 0.35   | 273.42 ± 8.81  |
|              | VBF      | 126.43 ± 53.92 | 907.49 ± 75.97      | 0.74 ± 0.26   | 273.93 ± 11.23 |
|              | Logistic | 142.30 ± 50.20 | 846.32 ± 36.40      | 1.95 ± 0.45   | 273.51 ± 7.32  |
| B. murrayi   | Gompertz | 162.33 ± 22.04 | 586.99 ± 63.49      | 0.26 ± 0.06   | 195.96 ± 7.71  |
|              | VBF      | 155.40 ± 23.54 | 642.33 ± 74.66      | 0.15 ± 0.04   | 196.18 ± 7.94  |
|              | Logistic | 168.84 ± 21.49 | 546.68 ± 55.66      | 0.38 ± 0.08   | 196.57 ± 7.79  |

Total length estimates were for combined sexes and generated by three Bayesian growth models: Gompertz, von Bertalanffy (VBF) and Logistic. Priors were set at \(L_0 = 117\) mm ± 29.25 SE and \(L_\infty = 1452\) mm ± 132 SE for B. irrasa, \(L_0 = 110\) mm ± 55 SE and \(L_\infty = 1322\) mm ± 132 SE for B. eatonii and \(L_0 = 209\) mm ± 30 SE and \(L_\infty = 477\) mm ± 132 SE for B. murrayi. \(L_0\) length-at-birth, \(L_\infty\) asymptotic length, \(k/g\) growth coefficient, LOOIC leave-one-out cross-validation information criterion.
be the best fitting frequentist model (Table 7). The Bayesian growth curve displayed an improved fit for younger and older individuals (Fig. 4d). This would largely be due to the absence of age zero samples which were accounted for in the Bayesian models but not the frequentist models.

The Bayesian models for *B. murrayi* displayed similar trends, with differences only noticeable for older ages (Fig. 4e). The models differed in both length-at-birth and asymptotic length, ranging from 155.40 mm TL to 168.84 mm TL; and 546.68 mm TL to 642.33 mm TL, respectively (Table 6). The frequentist von Bertalanffy growth model for *B. murrayi* was the best fitting frequentist model (Table 7). The Bayesian growth curve displayed an improved fit for younger and older individuals (Fig. 4f), similarly due to the absence of age zero samples accounted for in the Bayesian models.

**Discussion**

This study provides the first species-specific life history information for *B. irrasa, B. eatonii* and *B. murrayi*. All three species exhibit a physical growth-limiting characteristic of being late-maturing relative to other skate species (Dulvy et al. 2000; Stevens et al. 2000; Nowara et al. 2017). Based on this life history characteristic, the three species...
have a high probability of being susceptible to overexploitation, even when taken as by-catch (Dulvy et al. 2000; Stevens et al. 2000; Nowara et al. 2017).

Several examples exist where skate populations have collapsed due to fishing mortality (Brander 1981; Dulvy et al. 2000), demonstrating the vulnerability of this taxon to overfishing. The three species in this study have previously been managed using a by-catch limit based on a population assessment without species-specific growth estimates. Instead, inferences from other closely related species were used (Nowara et al. 2017). This poses an undefined level of risk if their management is not sufficiently precautionary. Accurate stock assessments are built on a foundation of species-specific life history information, which is required to understand population productivity. This study has addressed this for *B. irrasa*, *B. murrayi* and *B. eatonii*, providing additional information to support evidenced-based decision-making by fisheries managers to help reduce the risk of overexploitation of these species.

In many species, vertebrae grow isometrically with respect to the rest of the body (Gburski et al. 2007), therefore age estimates obtained by observing the growth bands within the vertebral centra of *Bathyraja* spp. were assumed to be reliable. Similarity in the growth banding structures supported the assumption that a single growth band was produced each year (Perez et al. 2010). However, many species of elasmobranchs exhibit asynchronous reproduction throughout the year (Harry et al. 2010), with previous studies of skate reproduction supporting year-round egg deposition in *Bathyraja* species (Ainsley et al. 2011b). This assumption was made in this study for all three species as their reproductive patterns remain unknown. To maximise the accuracy of the results, the effects of asynchronous reproduction must be accounted for in the growth analyses, as the first growth increment could reflect any number of months growth, depending on when the individual was born. Age determination of most chondrichthyans, including skates, relies on counts of regularly deposited growth increments on the vertebrae that are regularly deposited, which has been validated for several other closely related species (e.g., Cailliet and Goldman 2004; Okamura et al. 2013). It is, however, important to acknowledge that no validation has previously been attempted for these species due to the lack of sample specimens. The age of asynchronously reproducing animals is uncertain (within 12 months) due to the unknown age at first increment formation (Harry et al. 2010). To account for this uncertainty, we performed age adjustments of 0.5 years to the observed age classes (Harry et al. 2010). The models for all three species should be reassessed should information regarding the reproductive biology, specifically those regarding their reproductive cycles, becomes known through future studies.

*Bathyraja irrasa* was found to mature at around 6 and 8 years of age for males and females, respectively. This is younger than that of the graytail skate, *B. griseocauda* (males 14 years, females 18 years), and the whitebrow skate, *B. minispinosa* (males 23 years, females 24 years; Arkhipkin et al. 2008; Ainsley et al. 2011a), which are species of similar size and occupy a similar habitat, although it should still be considered as a late maturing skate species when compared to species of other genera (S9 in Online Resource 1). *Bathyraja eatonii* matures at 5 and 6 years of age for males and females, respectively, while *B. murrayi* matures at 5 years for both males and females. Estimating the age of *B. eatonii* and *B. murrayi* also proved to be difficult due to the smaller size of the vertebrae. The challenges posed in preparation and interpretation of such small samples included inconsistent growth patterns and faint growth band pairs (Gburski et al. 2007). This resulted in inconsistencies in the age estimates as defined by the intra-reader variability having larger APE values. Coupled with the small sample sizes, the true age-at-maturity of these species remain elusive. While future studies could improve accuracy with a larger sample size, ideally a minimum of 200 (Smart et al. 2010), the comparison of life history parameters for these species with others may provide additional insight.
2013; Thorson and Simpfordorfer 2009), consisting of a wider spread of different age- and size-classes, this study still provides a useful advancement from the previously used proxy species.

*Bathyraja irrasa* was also found to mature at larger sizes compared to other skate species. In comparison, the Antarctic starry skate, *A. georgiana*, from the Ross Sea reaches sexual maturity at smaller sizes of 640 mm and 690 mm TL for males and females, respectively (Francis and Maolagáin 2005; S2 and S10 in Online Resource 1). Information from past studies show most other *Bathyraja* spp. reach sexual maturity at smaller sizes, except for the Aleutian skate, *B. aleutica*, which matures at 1210 mm and 1330 mm TL for males and females, respectively (S2 in Online Resource 1). Elasmobranch species with late maturity at larger sizes may be more susceptible to the effects of fishing as a larger proportion of those captured may be comprised of immature individuals (Ainsley et al. 2011a, b). This is even more problematic for skates, which were found to mature at 75–90% of their maximum TL (Ainsley et al. 2011a). With later maturity, such as that seen with *B. irrasa*, a high rate of survival is necessary for an individual to reach maturity and subsequently reproduce.

Accuracy of the growth models applied relies on the inclusion of both the smallest and largest sizes of individuals in the population (Francis and Francis 1992). The absence of these size classes may result in problems with the estimation of growth parameters: missing smaller age groups will over-estimate *L*∞, while missing larger age groups will underestimate *K* (Francis and Francis 1992). This could happen for *B. eatonii* in this study, as the maximum size of an individual sampled was 958 mm TL, which is considerably smaller than the reported maximum size of 1100 mm TL (Francis 2006). No age zero individuals (i.e., below one year of age) were sampled, indicating the smallest size class of the population was absent. This resulted in the use of hypothetical *L*∞ values from similar-sized *Bathyraja* spp. for *B. eatonii* when setting the priors for the Bayesian growth models. Therefore, while the Bayesian modelling approach was able to better account for missing older individuals (Smart and Grammer 2021) and provided the best available information, further work is needed to improve the accuracy of these growth models, which can be achieved through inclusion of actual biological information obtained from age zero individuals.

The Bayesian growth model comparison resulted in the same growth function, the Gompertz growth model, being selected as the best fitting model for all three species, although all three models provide very similar quality of fit for the data. We chose the von Bertalanffy growth models for inferences in this study so that our findings are easier to be included in future analyses such as mortality estimation, especially since many current modelling software requires von Bertalanffy parameter inputs (Kenchington 2013). Using the von Bertalanffy growth curve combined for sexes, the asymptotic length is larger for *B. irrasa* (1241.03 mm) than *B. eatonii* (907.49 mm) and *B. murrayi* (642.33 mm), along with other similar Antarctic skate species such as *A. georgiana* (1013 mm; Francis and Maolagáin 2005) and other *Bathyraja* spp. with asymptotic lengths ranging from 597 to 3652 mm (S2 in Online Resource 1). *Bathyraja irrasa* can therefore be considered to mature at relatively large sizes.

The findings support the assumptions that *B. irrasa* have slow growth rates and mature late, indicating their increased vulnerability to exploitation. Although scientific surveys have suggested that populations of the three species have remained stable over time, with the exception of a substantial increase between 2009 and 2011, a risk of localised depletion exists (Nowara et al. 2017). Furthermore, the phasing out of trawl fishing in the HIMI Patagonian toothfish fishery and increase in longline effort at the HIMI fisheries may alter the impacts on skates, which would thereby require a timely review on their population status, especially for *B. irrasa* which forms the majority of longline by-catch and therefore may face an increased risk of overexploitation (Nowara et al. 2017). The estimates of age and growth parameters, will help improve the management of these species by providing more certainty in a fundamental component of future population assessments. Therefore, our results represent valuable information on these *Bathyraja* spp. and subsequently serve as a foundation to further refine and develop future management strategies and conservation efforts.

**Supplementary material**

The following supplementary material is made available in Online Resource 1:

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s00300-022-03062-z.

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Author contributions DW and JR conceived and designed the research. JC, PY and PZ advised on the study and provided all samples used. DW, JB and JR conducted sample processing and data collection. DW, JS and JR performed data analysis. DW wrote the first draft of the manuscript, and all authors edited/commented on previous versions of the manuscript. All authors read and approved the final manuscript. JR and JS supervised the study.

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Data availability The datasets generated and/or analyzed during the study are available from the corresponding author on reasonable request, if not already included in this published article and its supplementary information files.

Declarations

Conflict of interest All authors have no competing interests to declare that are relevant to the content of this article.

Ethical approval No approval of research ethics committees was required for this study as no live animals were used throughout.

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