

Age, growth and demographic characteristics of *Sillago flindersi* exploited in a multi-species trawl fishery

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Abstract This study investigated variability in the growth, length, and age compositions and the rates of mortality of Flinders' sillago *Sillago flindersi* exploited in a demersal trawl fishery in eastern Australia. Sampling was done over 2 years across three depth strata at two locations approximately 400 km apart. Ageing of sectioned sagittal otoliths indicated that the observed maximum age of females was 6 years and that of males 5 years, that growth was variable and that the von Bertalanffy growth parameters significantly differed according to gender and location. Females attained a greater L_{∞} than males, but males displayed greater k values. The L_{∞} values of both sexes and the mean length-at-age for fish aged 3–5 years were greater at the location of highest latitude. Length and age compositions differed according to depth, with smaller (<15 cm FL) and younger (<2 years) fish generally more

predominant in the shallow (<30 m) strata than in the deeper (>31 m) strata. *S. flindersi* appear to use the shallow strata as a juvenile habitat, moving to deeper waters as they grow. This depth stratification between cohorts may reduce intraspecific competition and could potentially be used as a spatial management tool to reduce any fishing-associated impacts on juveniles. Fish between 1 and 3 years old dominated the age compositions of populations combined across all depths, with estimated total mortality ranging between 2.24 and 2.40. Fishing mortality ranged between 1.54 and 1.70 and was more than twice the derived natural mortality. Exploitation rates were approximately 0.70, indicating that the species was heavily fished.

Keywords Australia · Commercial harvest · Demography · Fishery assessment · Mortality · Otolith · Sillaginidae

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Introduction

The teleost family Sillaginidae are primarily associated with sand, silt and mud substrates in nearshore coastal and estuarine waters throughout the Indian and western Pacific oceans [1]. The family contains approximately 35 species, many of which are exploited in commercial, recreational and artisanal fisheries [1–3]. Fundamental life-history information vital to fisheries management is available for several exploited species, including *Sillago sihama* [4, 5], *S. aeolus* [6, 7], *S. bassensis* [8], *S. robusta* [8, 9], *S. maculata* [10] and *Sillaginodes punctata* [11, 12]. Such studies have identified that sillaginids typically mature young (1–3 years), grow fast, have longevities of 4–16 years, and harvested populations of them are dominated by a few young age classes [10]. Such life

histories potentially make sillaginid populations susceptible to environmental fluctuations and overexploitation.

Sillago flindersi is endemic to coastal waters <100 m deep along the eastern and southern coasts of Australia between approximately 25 and 44°S [1, 9]. The species is commercially harvested in demersal otter trawl and Danish seine fisheries across five management jurisdictions (four state and one commonwealth), with reported total landings averaging around 1500 t per annum over the past 10 years (peaking at 2400 t in the mid-1990s) [13]. Depending on the jurisdiction, different input (limited entry, fishing gear and vessel restrictions, spatial and temporal closures) and output (minimum length limits and total allowable catches) controls are used as management tools for *S. flindersi*. Despite the extensive exploitation and importance of *S. flindersi* to various fisheries, there is little published information concerning essential aspects of its life history and how these may vary throughout its distribution. Aspects of the reproductive ecology of this species, including spawning periods and length at maturity, are known from its northern range [9], but there remains little in the primary scientific literature concerning its age and growth and length- and age-based demographic characteristics, even though global stock assessments over its entire distribution are undertaken on a periodic basis [14].

Age-based data such as length and age compositions of populations, longevity, and rates of growth and mortality, as well as the variations in these parameters in time and space, provide vital insights into population dynamics and fishery exploitation [15–18]. Here, we used sectioned sagittal otoliths to determine age-based parameters of populations of *S. flindersi* in a region on the east Australian coast where it is targeted and taken as byproduct in a state-based penaeid (prawn) trawl fishery [19, 20]. Most research in this fishery has focused on developing and evaluating more selective fishing gear to reduce unwanted bycatch whilst retaining market-sized prawns and byproduct, including *S. flindersi* [21, 22]. Studies on the population biology of the primary byproduct species have largely been ignored. Here, we redress this situation, as we specifically examined variability in growth, longevity, length and age compositions and mortality schedules among populations of *S. flindersi* across three depths at two separate locations (approximately 400 km apart). This study complements our understanding of the species reproductive ecology in this region, where it spawns year-round with individuals having multiple spawning events and, depending on the gender and location, 50 % of individuals attain sexual maturity at approximately 13–15 cm FL [9]. We discuss our findings relative to other sillaginid species and fishery exploitation.

Materials and methods

Study area and sampling procedures

Samples of *Sillago flindersi* were collected from three depth ranges 11–30, 31–60 and 61–90 m (hereafter termed “shallow”, “mid” and “deep” depths, respectively), over inner continental shelf waters adjacent to Yamba (29°26'S, 153°20'E) and Newcastle (32°55'S, 151°45'E) off eastern Australia. A chartered ocean prawn-trawl vessel from each port made two replicate 60-min tows in each depth strata at night every 4 weeks (within 1 week of the new moon). This was done between November 2005 and November 2007 at Yamba and October 2006 and November 2007 at Newcastle [9].

The total number and weight of *S. flindersi* captured in each replicate tow (sample) was determined onboard the vessel, and either the whole catch or a random subsample (100–200 individuals) of the catch from each tow was measured for fork length (FL, nearest 0.1 cm) for length composition analyses. A subsample of 60 individuals (when caught) from each depth was retained for processing in the laboratory, where the fish were measured for FL, weighed (0.1 g), sexed and had their sagittal otoliths removed for age analyses. Fish categorized as juvenile could not be sexed due to a lack of gonad development.

Age estimation

Sectioned sagittal otoliths were used to estimate the age of *S. flindersi*. Otoliths were embedded in blocks of clear cast polyester resin and 3–4 serial transverse sections (approx. 0.7 mm) were cut through the otolith core using a Gemmaster diamond saw. The resulting sections were mounted on a microscope slide and polished using a Labopol polishing wheel fitted with 500-grit silicon carbide polishing paper until the growth zones on the sections became clear. The resulting sections were viewed against a black background under a compound microscope fitted with a digital camera. Otolith sections displayed a pattern of narrow opaque and broad translucent zones, and assignment of age was based on counts of completed opaque zones along the dorsal sulcal groove. Although growth zones were sometimes difficult to interpret due to deposition of aragonitic material, opaque zone interpretation could always be confirmed elsewhere on the otolith (Fig. 1). Each opaque zone was marked, and the distance between successive opaque zones was measured using the digital image analysis program Image J (<http://rsb.info.nih.gov/ij/>, accessed 29 Jan 2008), after which digital images of each section were recorded. Sections were interpreted without knowing the length or

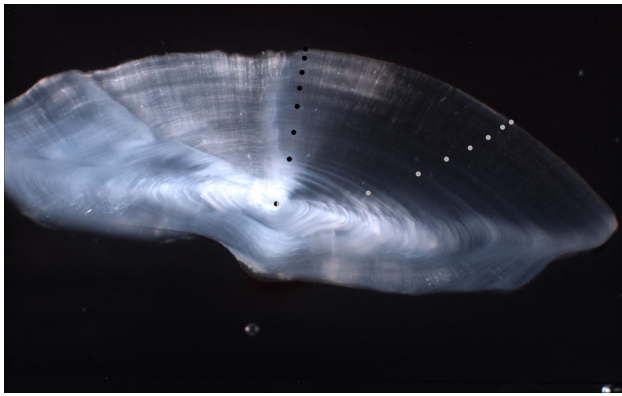


Fig. 1 Image viewed under reflected light of a sectioned otolith of a 6-year-old *Sillago flindersi*. The image displays dots on the six opaque growth zones plus one on the core and the otolith edge. Sectioned otoliths were aged along the sulcal groove (black dots), with identification of opaque zone structure confirmed on other, less-obscured parts of the otolith (grey dots)

sex of the fish or the date and location of capture, and all sections were read twice without knowledge of the first interpretation. In cases where the two readings differed, the sections were examined a third time to assign a final age. Because *S. flindersi* spawns year-round with no distinct seasonality in peak spawning activity [9], a universal birthdate could not be assigned to each fish. Thus, even though fish were aged from samples taken across different months, they could not be correctly assigned a digital (monthly) age. All ageing analyses were therefore performed at the level of age class.

Marginal increment analysis was used to determine the periodicity of formation of opaque zones. Sections were examined under a microscope (as described above) and assigned an age and an otolith margin condition of either opaque or translucent. As above, all sections were interpreted twice. A marginal ring was deemed to have formed where an opaque zone appeared on the edge with no translucent zone following. An image processor was used to measure the distance from the otolith core to each successive opaque zone and to the otolith edge. All measurements were made along the dorsal edge of the sulcus to the nearest 0.05 mm. The marginal increment ratio (MIR) was expressed as follows: (1) for fish with one opaque zone, the distance from the first opaque zone to the otolith edge as a proportion of the distance from the focus to the first opaque zone; (2) for fish with two or more opaque zones, the distance from the most recently completed opaque zone to the otolith edge as a proportion of the distance of the previous fully completed growth zone. Mean MIR (\pm standard error; SE) was calculated for all ages combined for each month.

Length-at-age and growth

A three-factor ANOVA was used to test for differences in the mean length-at-age (combined across years) of *S. flindersi* between locations, sexes and age classes. The length-at-age data for each sex and location (combined across years for Yamba) were separately fitted to the von Bertalanffy growth function (VBGF): $L_t = L_\infty [1 - e^{-k(t-t_0)}]$, where t is age (years), t_0 is the theoretical age of the fish when they had zero length (years), L_t is the FL at age t (cm), L_∞ is the asymptotic FL (cm) and k is the rate at which the curve approaches L_∞ (year^{-1}) [15]. Because data were binned into actual age classes (as opposed to digital ages), the data were analysed and graphically presented in the middle of each age class. Differences in growth between sexes and locations were tested by comparing the VBGF fitted across equal ages using the analysis of residual sums of squares (ARSS) method of Chen et al. [23].

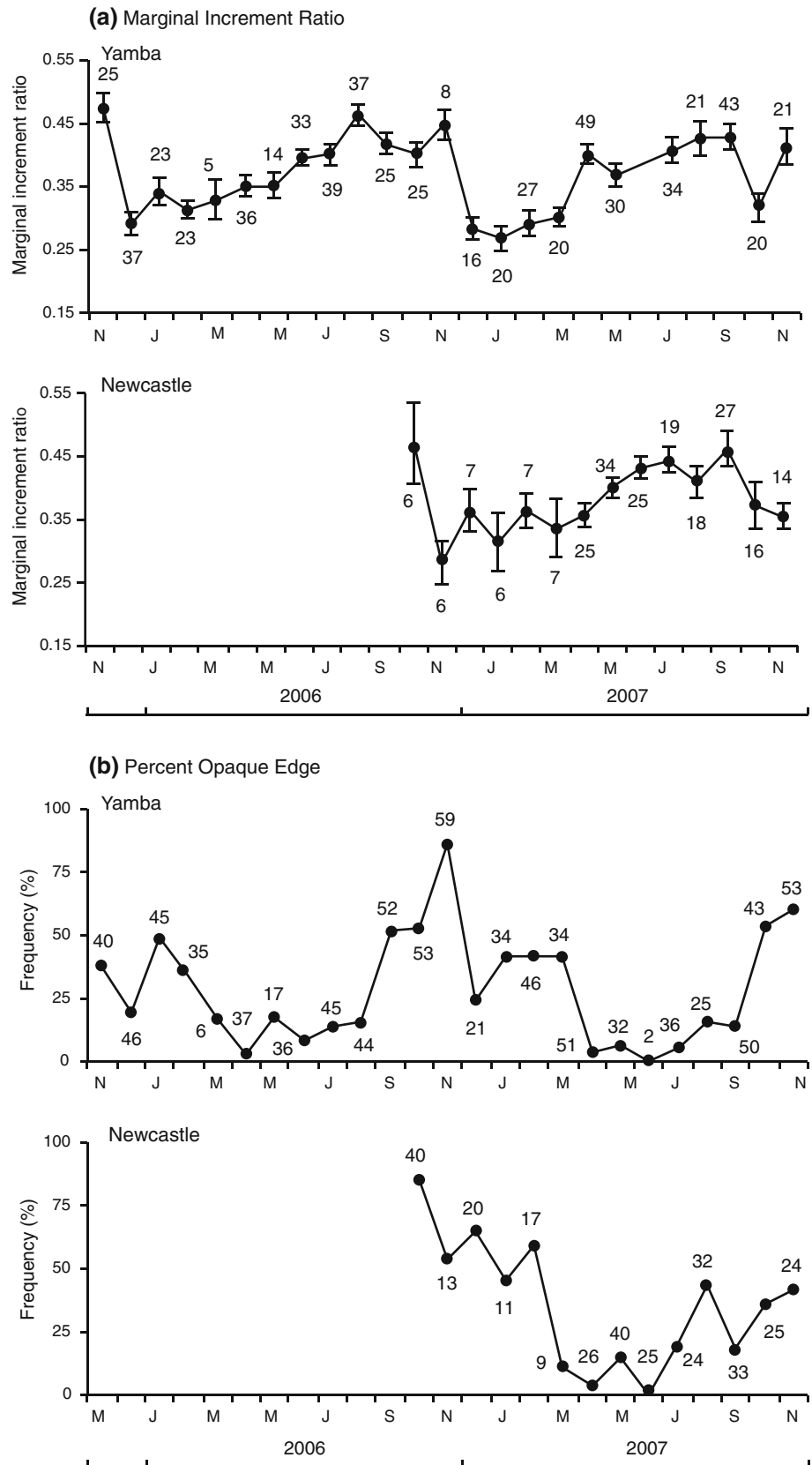
Length and age compositions

Annual length–frequency histograms of *S. flindersi* at each depth and for all depths combined (weighted by monthly catch) were generated for both locations. The corresponding age compositions of populations were calculated by applying separate age–length keys for each location to the relevant length–frequency data. Multiple Kolmogorov–Smirnov (K–S) tests were used to determine whether the length and age compositions differed among depths at each location.

Mortality and exploitation

Estimates of the instantaneous rate of total mortality (Z) were made using the age-based catch curve method [15] for data (weighted by catch) combined across all depths for each year at Yamba and Newcastle. The natural logarithm of the proportion of fish in each age class (N_t) was plotted against their corresponding age class (t), and a linear regression was fitted and Z determined as the slope of the descending regression. Standard error (SE) and r^2 values were calculated for each regression. For these analyses, we assumed that the most abundant age class (2 years; see “Results”) in each sample was fully recruited to the sampled population and that the selectivity, recruitment and growth of fish were constant across years and that growth was asymptotic [15]. The instantaneous rate of natural mortality (M) was estimated using the equation [$\ln(M) = 1.46 - 1.01 \ln(t_m)$, where t_m is the maximum age in years] of Hoenig [24], based on a maximum age of *S. flindersi* of 6 years (see “Results”). Fishing mortality

Fig. 2 a The mean (SE) marginal increment ratio for all ages of *Sillago flindersi* combined for each calendar month at Yamba and Newcastle, and **b** the proportion of sectioned otoliths that had opaque edges each month. Sample sizes are also shown for each month as *numbers on the plots*



(F) was determined by subtracting M from each estimate of Z , which also provided a corresponding rate of exploitation (E) ($E = F/Z$).

Results

A total of 44,398 *S. flindersi* were captured (18,581 at Yamba and 25,817 at Newcastle) and 2115 sectioned otoliths examined. This included 633 females, 648 males and 45 juveniles at Yamba and 407 females, 301 males and 81 juveniles at Newcastle. Sampled fish ranged from 4.6 to 27.8 cm FL and 0 to 6 years of age, but less than 1 % of captured fish were smaller than 10 cm FL due to the selectivity of the trawl gears. The overall agreement between the re-read of otolith sections was 81 % and for a variation of ± 1 year it was 99 %. Nearly all discrepancies were for fish aged 2 and 3 years and concerned differences in the interpretation of the first growth zone.

Age determination

The MIR for *S. flindersi* displayed a cyclical pattern that was consistent across the two years at Yamba, with the MIR being greatest in November and decreasing to a low in December/January, after which it increased (Fig. 2a). A slight temporal shift in this pattern was displayed at Newcastle, with the MIR being greatest in September/

October and least in November. These data indicated that the opaque growth zone was deposited once per annum between September and January. A cyclical trend in the proportion of otoliths with opaque edges was also evident, with the highest percentages occurring mostly between September/October and March at Yamba and August to February at Newcastle, and least between April and July (Fig. 2b).

Length-at-age and growth

Length-at-age was variable among individual *S. flindersi*, with considerable overlap seen between sexes (Fig. 3). ANOVA identified that the mean length-at-age differed significantly according to the interactive effects of location and sex ($df = 1, 1968, F = 4.46, P < 0.05$), location and age ($df = 4, 1968, F = 7.64, P < 0.0001$) and sex and age ($df = 4, 1968, F = 7.40, P < 0.001$). For ages 1 and 2, the mean length at age (pooled across sexes) did not differ between locations, whereas for age classes 3–5 it was greater at Newcastle than Yamba (Table 1). Mean length-at-age (pooled across locations) did not differ between sexes for ages 1–3, but was greater in females than males for ages 4 and 5 (Table 1).

The VBGF differed significantly between sexes at each location (ARSS tests: Yamba $F_{3,1364} = 14.761, P < 0.001$; Newcastle $F_{3,864} = 4.578, P < 0.01$) and also

Fig. 3 Length-at-age of female and male *Sillago flindersi* at Yamba and Newcastle, and resulting von Bertalanffy growth curves. n denotes sample size

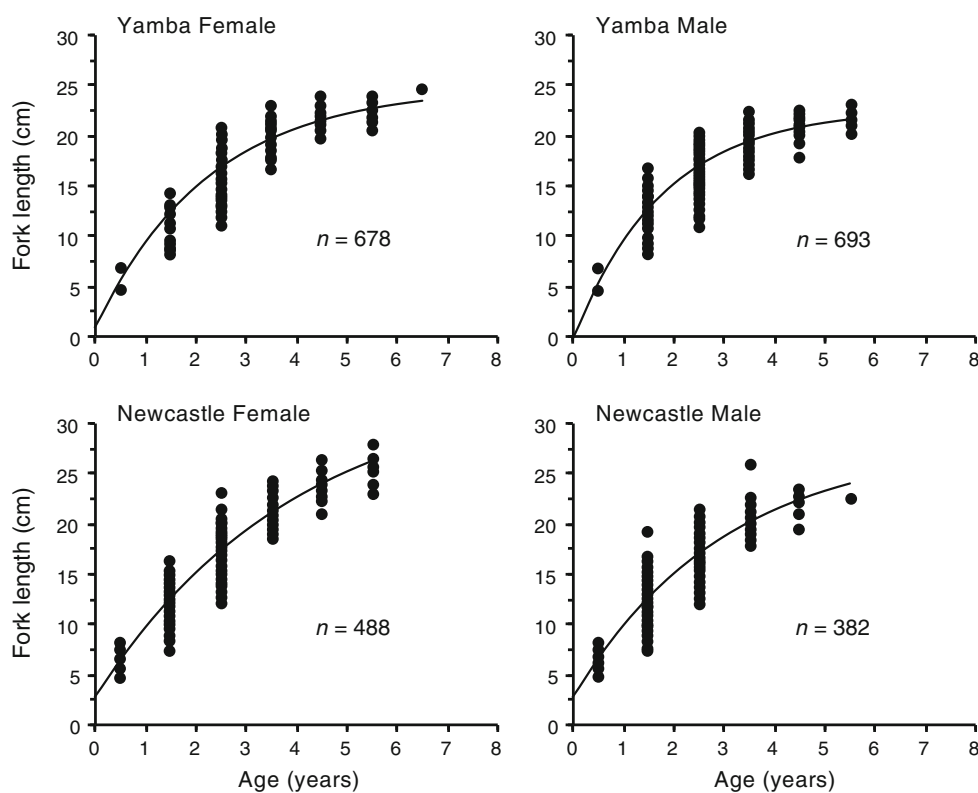


Table 1 Mean fork length (cm) (SE) for each age class of female and male *Sillago flindersi* at Yamba and Newcastle

Age (years)	Yamba		Newcastle	
	Female (SE)	Male (SE)	Female (SE)	Male (SE)
0	5.70 (1.00)	5.70 (1.00)	6.91 (0.17)	6.91 (0.17)
1	12.86 (0.17)	13.06 (0.13)	13.17 (0.14)	13.73 (0.17)
2	16.94 (0.13)	17.22 (0.10)	17.50 (0.17)	17.20 (0.14)
3	19.98 (0.07)	19.48 (0.08)	21.47 (0.21)	20.44 (0.33)
4	21.33 (0.15)	20.66 (0.17)	23.85 (0.25)	21.93 (0.30)
5	22.09 (0.25)	21.88 (0.24)	25.36 (0.59)	22.50
6	24.50	–	–	–

Age 0 fish were unsexed juveniles and attributed to both female and male

Table 2 Summary of von Bertalanffy growth function parameters for female and male *Sillago flindersi* at Yamba and Newcastle

Location	Sex	L_{∞} (SE)	k (SE)	t_0 (SE)
Yamba	Female	24.84 (0.75)	0.44 (0.04)	−0.08 (0.01)
	Male	22.68 (0.50)	0.56 (0.05)	−0.02 (0.01)
Newcastle	Female	34.15 (2.23)	0.25 (0.03)	−0.34 (0.09)
	Male	28.07 (1.75)	0.33 (0.04)	−0.31 (0.09)

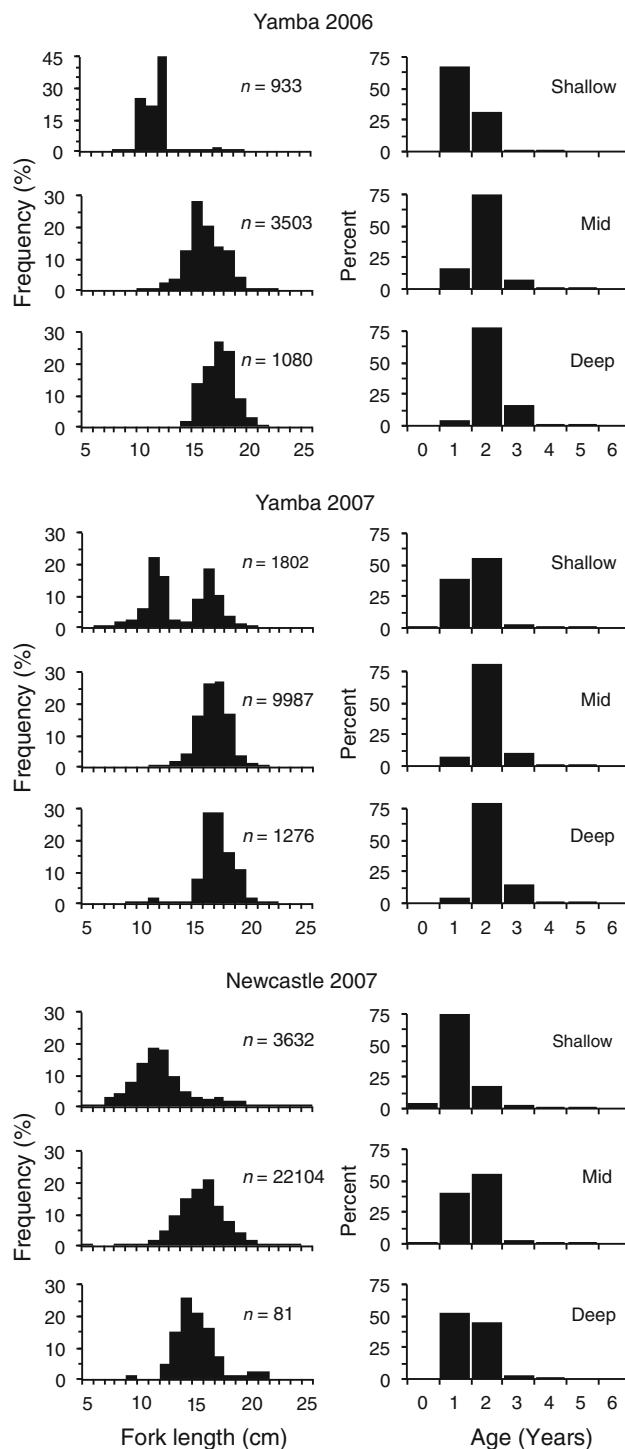
L_{∞} and t_0 refer to fork length (FL) in cm

between locations for each sex (ARSS tests: female $F_{3,1159} = 8.564$, $P < 0.01$; male $F_{3,1069} = 6.158$, $P < 0.01$). The VBGF parameters for each growth curve varied; L_{∞} ranged between 22.68 and 34.15 cm FL, k ranged between 0.25 and 0.56, and t_0 ranged between −0.34 and −0.02 (Table 2). The estimated L_{∞} was greater for females than for males at both locations. Further, the L_{∞} for both sexes was significantly greater (9.31 cm FL for females and 5.39 cm FL for males) at Newcastle than at Yamba (Table 2). The growth parameter k was greater for males than females at both locations and was greater for both sexes at Yamba than at Newcastle.

Observed maximum age was similar for both sexes and both locations, with the oldest female and male being 6 (Fig. 1) and 5 years, respectively, at Yamba, and 5 years for both sexes at Newcastle. The largest female and male sampled was 27.8 and 24.5 cm FL, respectively, and both came from Newcastle.

Length and age compositions

The length compositions of *S. flindersi* differed significantly among depths at each location in each year (multiple

**Fig. 4** Length and age compositions of *Sillago flindersi* by depth and year at Yamba and Newcastle. n denotes sample size

K–S tests, $P < 0.05$ in all cases). A smaller length class (7–12 cm FL) was caught in the shallow depth compared to mid and deep strata (Fig. 4). The mid and deep strata primarily contained fish 12–20 cm FL. Both length cohorts were present, however, in the shallow strata at Yamba in

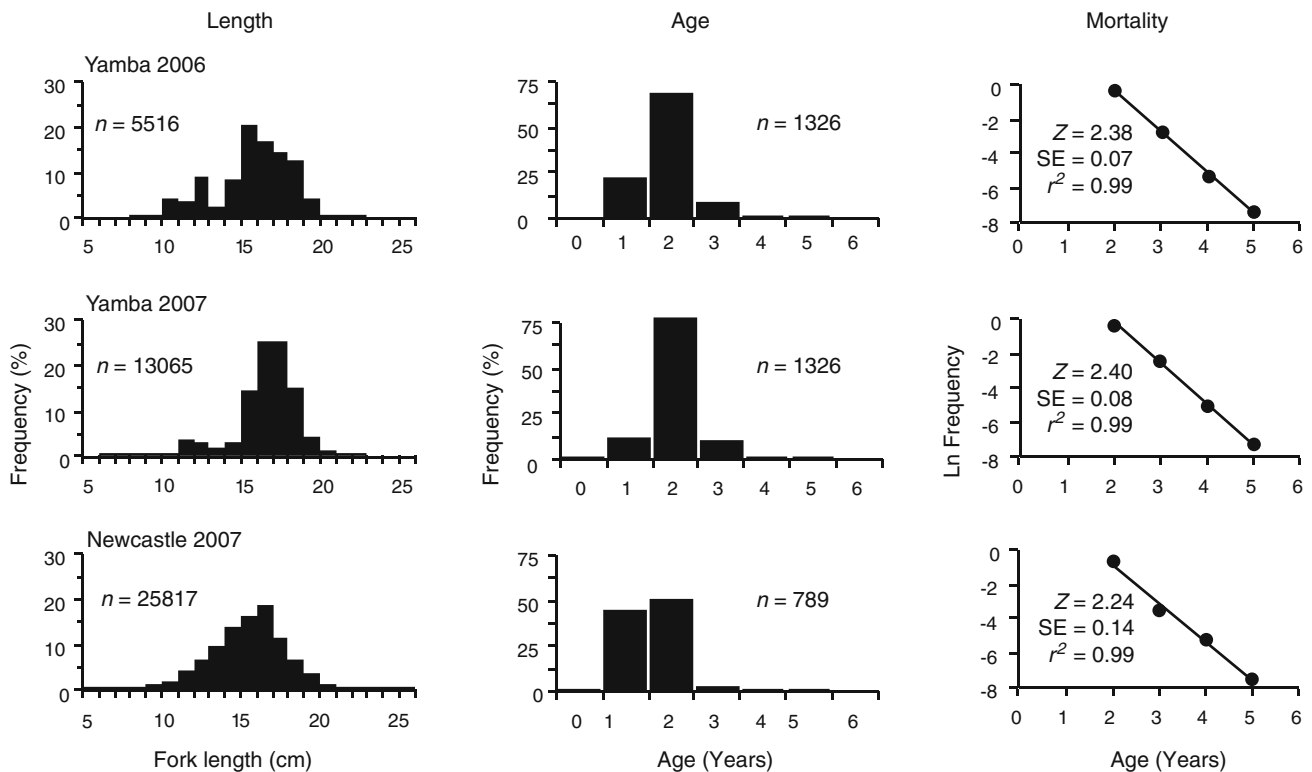


Fig. 5 Length and age compositions of *Sillago flindersi* combined across depths and associated catch curves at Yamba and Newcastle. n denotes sample size for length composition, and the number of samples used in the age–length key for age composition, for each location

2007. The corresponding age compositions of samples also differed significantly among depths at both locations (multiple K–S tests, $P < 0.05$ in all cases). Despite this, at Yamba 1- and 2-year-old fish dominated samples in the shallow strata, whereas 2 year olds were most prevalent in the mid and deep strata (Fig. 4). At Newcastle, 1 year olds dominated the shallow strata, whereas 1- and 2-year-old fish were most prevalent in the mid and deep strata (Fig. 4). Few fish >3 years old were present in samples from any depth strata at either location.

Mortality and exploitation

Z was determined as 2.38 and 2.40 at Yamba in 2006 and 2007, respectively, and 2.24 at Newcastle for samples pooled across depths and including age classes 2–5 (Fig. 5). Because only one fish aged 6 years was observed in the study, age 5 was used as the terminal age class in the catch curve analyses to facilitate consistency of comparisons across years and locations. M was determined as 0.70, providing values of $F = 1.68$ and 1.70 at Yamba in 2006 and 2007, respectively, and 1.54 at Newcastle. The corresponding rates of E were 0.70 and 0.71 at Yamba in 2006 and 2007 and 0.69 at Newcastle.

Discussion

Age and growth

Counts of opaque zones on sectioned otoliths of *S. flindersi* were validated as annuli by the marginal increment analyses. This concurs with reports for other sillaginid species [7, 10] and fish in general [25]. Our data indicate that there was a small temporal shift in the timing of completion of opaque zone deposition between our two study locations, with the lowest values occurring about 1 month later at Yamba than Newcastle. Latitudinal shifts in the timing of deposition of growth zones on otoliths are common and generally occur later at higher latitudes [26, 27], contrasting with our findings. Similar to our findings, it was reported that otolith growth zone deposition occurred about 1 month earlier in southern compared to northern populations (separated by about 100 km) of *Lethrinus miniatus* on the Great Barrier Reef [28]. The opaque zones on otoliths of *S. flindersi* potentially started forming during late winter and early spring (August to November), but were not observed as complete (i.e. counted) on some individuals until late summer (February). The spring–summer timing of completion of opaque zone formation is the same as that observed in other east Australian sillaginid species, *S. maculata* [10], *S.*

robusta (Gray et al. [9], unpubl. data) and *S. ciliata* [29], as well as a diverse range of other coastal and estuarine fish within the region, including *Mugil cephalus* [30], *Girella tricuspidata* [31], *Scorpaena cardinalis* [32], *Platycephalus longispinis* and *P. richardsoni* [33].

The VBGF for *S. flindersi* differed between sexes with females attaining a greater maximum length and for ages 4 and 5 having a greater mean length-at-age than males. This sex-related divergence in growth is concordant with many other sillaginid species [10], including *S. sihama* [4], *S. japonica* [34], *S. aeolus* [7], *S. analis* and *S. schomburgkii* [35], and is generally attributed to a life-history tactic to maximize the potential fecundity of females [10, 36]. *S. flindersi* attains sexual maturation at 1–2 years of age (13.27–14.87 cm FL, [9]). In contrast, some sillaginid species, including *S. robusta* [8], *S. burrus* and *S. vittata* [37], display no consistent gender-related differences in growth. Latitudinal differences in the growth of *S. flindersi* were also obvious, with both sexes having a greater mean length-at-age for ages 3–5 and displaying a greater L_{∞} but a lower k (rate of attainment of asymptotic length) value at Newcastle, the location of highest latitude. Intraspecific latitude-related differences in VBGF parameters are commonly observed among fish species [38–40] and can be due to a plethora of interacting biotic and abiotic factors such as food availability, water temperatures and tradeoffs with reproductive investment [41–43]. Fishing can also impact patterns of growth and other life-history characteristics of fish [44]. Although we could not determine the mechanisms that caused the observed latitudinal differences in growth of *S. flindersi* here, our data demonstrate that *S. flindersi* has spatially flexible growth dynamics, an important consideration in fisheries assessment models [16].

Our observed maximum age of 6 years for *S. flindersi* was similar to that reported for the species at higher latitudes [14], which is in the low to mid range compared to other sillaginid species (4–16 years; see [10]). The largest *S. flindersi* female (28 cm FL) and male (24 cm FL) sampled (both at Newcastle) in our study was less than the predicted L_{∞} in the corresponding VBGFs and less than the maximum reported length in McKay [1]. It is not uncommon for harvested populations of fish to display truncated length and age compositions [45]. Indeed, very few *S. flindersi* >3 years of age occurred in our samples. This was not a consequence of gear selectivity, as these trawl gears retained larger organisms (e.g. *Platycephalidae*, *Mullidae*, *Triglidae* [22, 33]) than the largest sillaginids sampled.

Fishery exploitation

Smaller, younger and immature *S. flindersi* were most prominent in the shallow strata compared to the mid and

deep strata [9], indicating that *S. flindersi* use the shallow strata as a nursery habitat and move to deeper waters as they grow and attain sexual maturation [9]. An anomaly in this pattern was evident in Yamba in 2007, when a cohort of larger fish was captured in the shallow strata. Nevertheless, this hypothesised general depth-related distributional pattern of *S. flindersi* is the same as the reported life history of other sillaginid species, including *S. bassensis* [8], *S. vittata* [37] and *Sillaginodes punctata* [11, 12]. Many species of fish utilize different depths of water during particular life-history stages [46–48], which is a potential mechanism to reduce intraspecific competition for resources among different length and age cohorts [49, 50]. Such depth stratification between different cohorts of *S. flindersi* could be utilized as a management mechanism to provide refuge and reduce any potential trawl-associated mortality of juvenile *S. flindersi* by closing inshore waters (e.g. <30 m) to demersal trawling. The impacts of any such spatial closure on other species as well as the social and economic implications for the fishery would need to be considered.

Our age-based determinations of mortality indicated that fishing at both study locations has impacted populations of *S. flindersi*. One- and two-year-old fish dominated populations, with a greater proportion of 1-year-olds occurring at Newcastle. This predominance of young fish is similar to that reported for other harvested coastal sillaginids, including *S. japonica* [34], *S. aeolus* [7] and *S. robusta* (Gray CA et al., unpubl. data, 2014). Our estimates of Z , F and E were similarly high across both locations and years, with F more than double M . These relatively high values were most likely due to the sustained regional fishing pressure of the East Coast Prawn Trawl Fishery, in which annual reported total harvests of *S. flindersi* have fluctuated around 500 t over the past 20 years [20]. We acknowledge that temporal and spatial fluctuations in year-class strength can impact instantaneous mortality schedules [15], and thus a longer time series of data is required for more rigorous population assessments of *S. flindersi* and associated fishery impacts in our particular study area. Estimates of F and E were dependent on M , which is hard to determine in exploited fish stocks [15]. Elsewhere, sensitivity analyses determined $M = 0.6$ for *S. flindersi* taken at higher latitudes [14]. If we adopted this value of M , our estimates of F and E would be greater than reported here. This highlights the complexities of assessing the exploitation statuses of fish populations, particularly those that display variable demographic characteristics and are subjected to differing fishery conditions across large distributional ranges.

Current levels of exploitation of *S. flindersi* across its entire range are reported to be sustainable [13] and are controlled using TACs in the Southern and Eastern Scalefish and Shark Fishery [14]. In our study area and

fishery, no output controls are imposed on *S. flindersi* and targeting practices, byproduct retention rates and total catch levels are primarily market-driven [14, 20]. The potential impacts of such harvesting strategies on fish populations can therefore occur at a regional scale and be fishery- and time-specific. It is therefore imperative to understand regional variations in population demographics in combination with fishery dynamics. The data reported here and in Gray et al. [9] can be used as a basis to evaluate potential future changes in demographic characteristics of *S. flindersi* associated with shifts in harvesting strategies in this fishery.

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