Available online at www.sciencedirect.com
SCIENCE DIRECT®
Fisheries Research 73 (2005) 283–298
FISHERIES RESEARCH
www.elsevier.com/locate/fishres

Spatial variation in age and growth of the kingfish (*Scomberomorus commerson*) in the coastal waters of the Sultanate of Oman

J.L. McIlwain[a,*], M.R. Claereboudt[a], H.S. Al-Oufi[a], S. Zaki[b], J.S. Goddard[a]

[a] *Department of Marine Science and Fisheries, College of Agricultural and Marine Sciences, Sultan Qaboos University, PO Box 34, Al-Khod 123, Sultanate of Oman*
[b] *Marine Science and Fisheries Center, Ministry of Agriculture and Fisheries, PO Box 1700, Muscat 111, Sultanate of Oman*

Received 15 December 2003; received in revised form 15 September 2004; accepted 14 October 2004

Abstract

Age and growth parameters were determined for the kingfish (*Scomberomorus commerson*) at six locations in the Sultanate of Oman. During 2 years of sampling, 1244 kingfish were collected, from which 962 sagittal otoliths were sectioned and read. The fishery is characterized by a prevalence of 0+, 1+ and 2+ year classes, which made up approximately 90% of the total fish collected. Maximum fork lengths, weights and ages for all sexes combined were 166 cm, 40.4 kg and 20 years, respectively. Sex specific differences were evident in length, weight and growth. Growth parameters show that female *S. commerson* ($L_\infty = 140.44$, $K = 0.309$, $t_0 = -1.501$) grew at a slower rate but reached a greater asymptotic length than male fish ($L_\infty = 118.80$, $K = 0.595$, $t_0 = -0.730$). There were significant differences in growth between regions with Ash-Sharqiyah recording the greatest asymptotic length ($L_\infty = 172.82$) and Al-Wusta the lowest ($L_\infty = 122.596$). Fish from Al-Wusta also grew at a much greater rate ($K = 0.796$) than those from the other five regions. A comparison of VBGF values using length frequency data and age at length data at one region, Muscat, revealed differences in all three growth parameters. Catch curves reveal large differences in total mortality (Z) between geographic regions, with the highest recorded at Al-Batinah (1.321 year^{-1}) compared with 0.405 year^{-1} at Muscat. Large discrepancies in age structure, growth parameters and annual mortality between regions suggest overexploitation of this species may have already occurred in places like Al-Batinah and Dhofar. However we recommend that mortality estimates (Z, M and F) be used with caution until catch curve data for different fishing gear is made available.

Keywords: *Scomberomorus commerson*; Scombridae; Oman; Kingfish; Otoliths; Age; Growth; Narrow barred Spanish mackerel

1. Introduction

The kingfish, *Scomberomorus commerson* occurs along the entire coastline of the Sultanate of Oman, from the Musandam Peninsula in the north to the Yemeni border in the south. It is the most sought af-

* Corresponding author. Tel.: +968 2 441 3333x3699; fax: +968 2 441 3418.
E-mail address: mcilwain@squ.edu.om (J.L. McIlwain).

0165-7836/$ – see front matter
doi:10.1016/j.fishres.2004.10.020

ter table fish in the Arabian Peninsula region and its popularity and high market price has resulted in heavy exploitation of regional stocks in recent years (Dudley et al., 1992; Siddeek and Al-Hosni, 1998; Al-Hosni and Siddeek, 1999). This fishing pressure has seen a rapid decline in Oman's kingfish catches from a peak of 27,834 t in 1988 to 2559 t in 2001 (Anon., 2001). Kingfish are targeted by traditional fishermen, operating from small fibreglass boats (4–10 m length overall), or large wooden dhows (<25 m length overall)(Dudley et al., 1992; Al-Oufi et al., 2000). Five different types of fishing gear are used in the fishery, although drift gillnets and trolling lines are preferred (Dudley et al., 1992). Size of the mesh and length of the drift gillnets varies according to geographic location (Claereboudt et al., 2004). Presently there is no legislation regulating Oman's kingfish other than a general ban on the use of monofilament gillnets. Consequently, there are no restrictions on the numbers or size of *S. commerson* landed by traditional Omani fishermen.

Estimates of growth parameters for *S. commerson*, using either length or age-based information, vary greatly between geographic locations (see summary tables in Govender, 1994; Al-Hosni and Siddeek, 1999). In eastern Australia, where spawning lasts for 3 months, annuli are laid down from June to August, 3–4 months prior to the peaks in spawning, with evidence of a narrower, secondary increment laid down earlier in the year (McPherson, 1992). In South Africa, where spawning is protracted, it has been suggested that two annuli are laid down each year, although this assumption was based on a small sample size ($n = 2$) from a mark-recapture program (Govender, 1994). Despite the variation in estimates of growth between locations, age-based growth studies of *S. commerson* from Australia, South Africa and Oman all suggest rapid growth in juveniles (Dudley et al., 1992; McPherson, 1992; Govender, 1994, 1995).

Because of its economic importance in the Sultanate of Oman, *S. commerson* has been the focus of several fisheries studies (Dudley and Arundhati, 1989; Dudley et al., 1992; Bertignac and Yesaki, 1993; Siddeek and Al-Hosni, 1998; Al-Hosni and Siddeek, 1999). The earliest study calculated growth parameters using von Bertalanffy models fitted to monthly length frequency data collected over a 3-year period from 1987 to 1989 (Dudley and Arundhati, 1989). Their data suggested length at age to be 60 cm and 75–80 cm for fish 18 months and 2 years old, respectively. These estimates were reassessed in Dudley et al. (1992) who examined sectioned otoliths ($n = 37$) and found that growth of *S. commerson* was extremely rapid up until 2 years of age. Recalculated length was 70–80 cm and 100–110 cm for fish 1 and 2 years old, respectively. The most recent study fitted von Bertalanffy growth estimates to quarterly length frequency data collected over a longer period than previously reported (1987–1995) (Al-Hosni and Siddeek, 1999). Calculated seasonal rates of total mortality showed exploitation ratios to be indicative of over fishing.

Given that kingfish are found along the entire coastline of Oman, a major limitation of the previous studies in Oman was the collection of data from one landing site in Muscat. Most of these, with the exception of Dudley et al. (1992), included length frequency analysis to estimate population parameters. Therefore the major objectives of the present study were to analyse the patterns of growth for *S. commerson*, using age based techniques, from several key landing sites spread along the coast of Oman. A study examining age, growth and mortality rates of *S. commerson* over this spatial scale has not previously been attempted in the northwest Indian Ocean region. The specific aims of this study were (1) to describe and compare sex specific length/weight relationships for each of six regions, (2) to compare the age structure of *S. commerson* between these same regions, (3) to describe the region specific and sex specific growth curves, (4) to quantify mortality for each region using catch curves and (5) to construct age/length keys using length/frequency data of total catch at each landing site.

2. Materials and methods

2.1. Sampling

A total of 1245 fish were randomly purchased from fishermen between January 2000 and December 2001. This was done on a bi-monthly basis at several landing sites within six regions (Musandam, Al-Batinah, Muscat, Al-Sharqiyah, Al-Wusta and Dhofar) encompassing the entire coastline of Oman (Fig. 1). Total (TL), fork (FL) and standard lengths (SL) were taken to the nearest cm and total weight (TW) to the nearest 0.1 kg was measured for all fish purchased. The

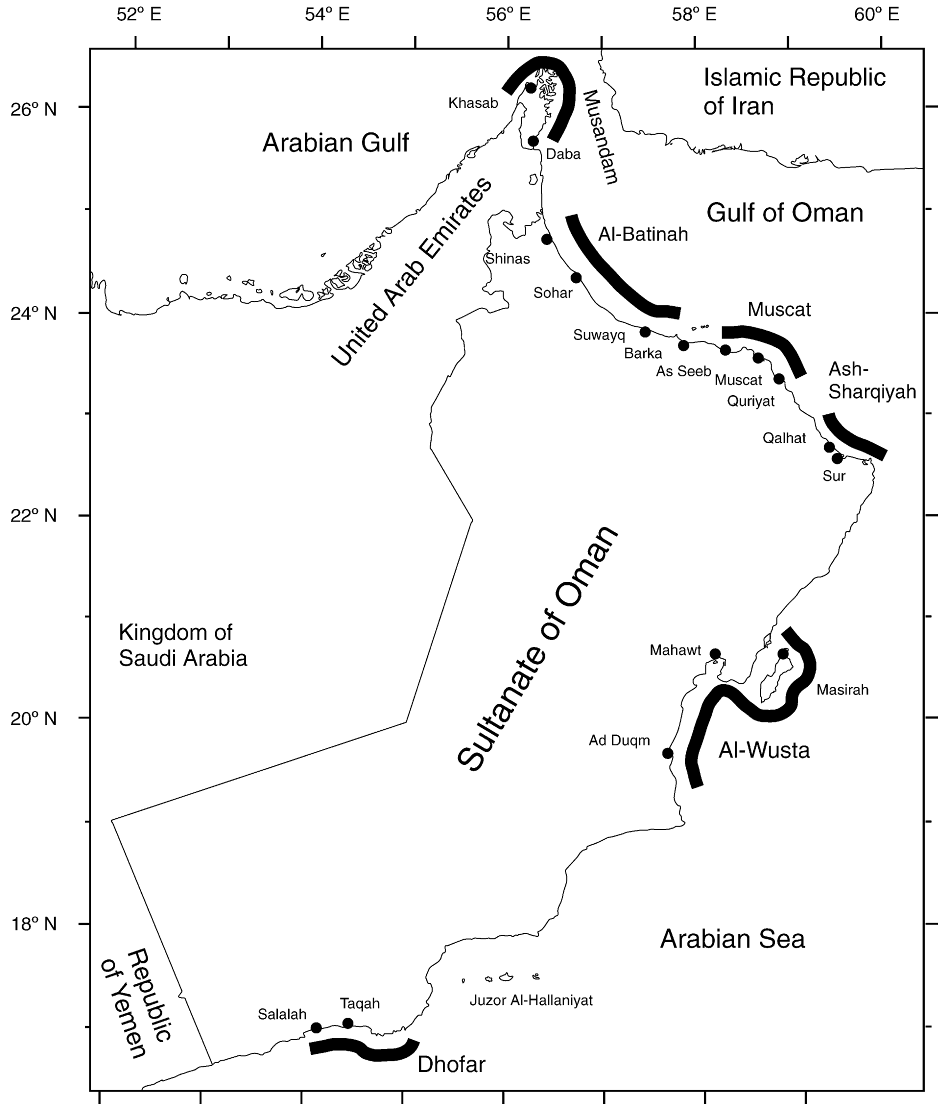

Fig. 1. Location of the six regions where *S. commerson* were sampled. Black areas indicate the extent of the fishing grounds for each region.

sex was initially determined for each individual macroscopically and then confirmed with histological preparations (Claereboudt et al., 2005). The sagittal otoliths were also removed from each fish, cleaned with alcohol and stored in a cool dry place in preparation for processing. In addition to the biological data collected from purchased fish, length (FL) and weight (TW) data were also collected from every fish ($n = 3800$) landed during each visit to the landing site. This resulted in a total of 5045 fish being measured from the six regions during the 2-year study.

2.2. Otolith processing

Prior to grinding, weights were taken (to the nearest 0.001 mg) only of intact whole otoliths. One sagittal otolith from each fish was then embedded in epoxy resin and a thin transverse section (300 μm) taken using a Low Speed Isomet saw and incorporating the core of the otolith. A grinding wheel fitted with silicon carbide paper was used to remove excess resin on the face of the section and to provide a polished face for viewing. The section was then mounted on a glass slide for reading.

All otolith processing and reading was conducted at the Marine Science and Fisheries Center, Muscat.

For fish older than 1 year, the annual opaque zones were counted using a compound microscope on low power with transmitted light. For fish with no obvious first annuli, daily rings were counted (see Brothers, 1987) using the same microscope on a higher power (400–1000× magnification) with transmitted light under oil immersion. Annuli and daily increments were counted along the same transect from the nucleus to the outer edge of the otolith. Two independent readers counted the annual and daily increments separately and without knowledge of the other reading or length data. The relative precision of age estimates between readers was calculated used an index of the average percentage error (IAPE) (Beamish and Fournier, 1981). Readings that did not agree on the number of annuli were removed from the database leaving a final total of 962 otoliths for analysis.

2.3. Validation of otolith increments

Marginal Zone or Edge Analysis was used to validate the annual deposition of the opaque zone on the otoliths of *S. commerson* purchased at Muscat during the 2-year sampling period. The growth zones on the outer edge of the otolith were recorded as either hyaline or opaque (Radebe et al., 2002). The frequency of the opaque zones was then plotted against the month of the year to determine the period when the opaque zone was deposited.

2.4. Data analysis

For each region, the relationship between length (FL) and weight (TW) was estimated for 3979 of the purchased and landed fish using linear regression analysis. To linearize the power curve ($W = aL^b$) that best described this relationship, both variables were transformed using $\log_e x$. The line of best fit for the linear relationship was described by $\log_e \mathrm{TW} = \log_e a + \log_e \mathrm{FL}$. Analysis of covariance (ANCOVA) was used to compare the relationship between transformed FL and TW among regions with weight as the dependent variable, length as the covariate and region as the categorical variable (Zar, 1996). ANCOVA was also used to compare the relationship between otolith weight and age between sexes with age as the dependent variable, otolith weight as the covariate and sex as the categorical variable.

Von Bertalanffy growth function (VBGF) curves $L_t = L_\infty(1 - e^{-K(t-t_0)})$ were fitted to length at age data for each region and individual sexes using the Maximum Loglikelihood function in Poptools, an add-in software to Excel (CSIRO, Canberra, Australia). The likelihood profile estimation function was used to calculate the 95% C.I. for each curve. The VBGF curves for region and sex were compared using the analysis of residual sums of squares (ARSS) method (Chen et al., 1992).

A VBGF curve was also fitted to the monthly length frequency data collected from the Muscat landing site over a 2-year period using the ELEFAN routine in the FiSAT computer package (Gayanilo et al., 1995). ELEFAN uses a non-parametric method of curve-fitting that passes through the most number of modes, giving estimates of L_∞ and K (Al-Hosni and Siddeek, 1999).

The annual instantaneous rate of mortality (Z) was estimated for each region and sex using age-based catch curves (Beverton and Holt, 1957; Ricker, 1975). The slope of the regression provided an estimate of Z. The natural logarithm of the number of fish per age class was plotted against age with the slope of the line of best fit, b equal to the annual instantaneous rate of total mortality or Z. The first age classes, which represented fish not fully vulnerable to the fishing gear, were not included in the analysis, given that different fishing gears are used in the different regions. Similarly because the older year classes (>10 years) were often poorly represented, they were not included in the curve fitting. Natural mortality (M) was calculated using the equation of Pauly (1980), which incorporates water temperature and the VBGF growth parameters L_∞ and K. The mean annual water temperature for the Gulf of Oman is 28.3 °C (including Musandam, Al-Batinah, Muscat and Ash-Sharqiyah), and 27.2 °C for Arabian Sea (Al-Wusta and Dhofar) (Claereboudt, unpublished data).

3. Results

3.1. Length weight relationships

The slopes of the length-weight regressions differed significantly among regions (ANCOVA; $F_{5,3972} = 38.22$; $P < 0.05$) and between sexes (AN-

Table 1
Results of the linear regression analysis describing the length-weight relationships for each of the six regions

Parameter	n	a	b	r^2	$FL_{min-max}$	$TW_{min-max}$	Av FL (s.e.)	Av TW (s.e.)
Region								
Musandam	601	6.18×10^{-6}	3.049	0.975	37.9–152.0	0.49–29.00	96.29 (0.72)	7.68 (0.16)
Al-Batinah	748	1.56×10^{-5}	2.841	0.941	49.5–157.0	0.96–27.30	73.51 (0.54)	3.56 (0.11)
Muscat	1479	9.74×10^{-6}	2.961	0.960	47.0–165.0	0.80–40.40	83.52 (0.66)	6.40 (0.20)
Ash-Sharqiyah	384	1.277×10^{-5}	2.889	0.956	50.5–162.0	1.30–28.00	94.60 (1.07)	7.50 (0.26)
Al-Wusta	501	1.25×10^{-5}	2.911	0.982	42.0–150.0	0.71–27.01	87.75 (1.10)	6.98 (0.23)
Dhofar	266	6.16×10^{-6}	3.051	0.978	50.8–166.0	1.17–38.20	84.96 (3.88)	5.69 (0.98)
Sex								
Females	690	9.41×10^{-6}	2.950	0.981	39.6–153.5	0.49–27.49	81.75 (0.76)	4.95 (0.61)
Males	555	1.15×10^{-5}	2.909	0.984	37.9–146.2	0.51–26.01	79.93 (0.81)	4.64 (0.14)

FL = fork Length, TW = total weight. Measurements are cm for length and kg for weight.

COVA; $F_{1,1244} = 14.72$; $^{**}P < 0.01$). Al-Batinah recorded the smallest average length of 73.51 cm compared to the largest average in Musandam at 96.29 cm (Table 1). For all individuals measured, the minimum and maximum FL recorded was 37.9 cm and 166.0 cm at Musandam and Dhofar, respectively. The average weight of *S. commerson* was smallest in Al-Batinah at 3.56 kg, almost half that of Musandam, which recorded the highest average weight of 7.68 kg. The remaining regions had average weights of between 5.69 kg (Dhofar) and 7.50 kg (Ash-Sharqiyah). The minimum and maximum TW was 0.49 kg and 40.40 kg from Musandam and Muscat, respectively. For purchased fish, on average females were longer and heavier than males (Table 1). The longest female fish recorded was 153.5 cm FL compared to the largest male at 146.2 cm FL. The heaviest individual fish was also a female at 27.5 kg compared to the heaviest male at 26 kg.

3.2. *Otolith interpretation and relationship with age*

The sagittae of *S. commerson* are the largest of the three pairs, has two elongated rostra, one longer than the other, and a slightly rounded posterior end. When viewed under transmitted light, sectioned otoliths clearly showed annuli as opaque zones that appeared darker than the adjacent hyaline or translucent zones. The first of these opaque zones or annuli was usually much wider than the remainder and more difficult to define. The IAPE value was 2.8%, representing good reproducibility between readings. Of the 962 readings included in the analysis, ages ranged between 0 and 20 years. Daily growth increments were counted on 256 fish with no annuli, representing the 0+ age class. Age at length data included in the VBGF models incorporated both the annuli and daily increments.

The Edge Analysis revealed strong seasonality to the deposition of the annuli as indicated by the presence of an opaque zone at the otolith margin (Fig. 2). From early fall to late winter (September to February) approximately 80% of fish landed in Muscat had opaque margins. Deposition of the hyaline zone occurred predominately during the spring and summer months (March to July). There appears to be no relationship between the timing of either the opaque or hyaline zone and seawater temperature.

The slopes of otolith weight and age were not significantly different between sexes (ANCOVA; $F_{1,633}$ =

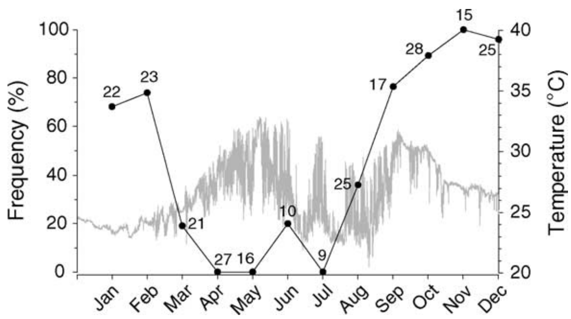

Fig. 2. The percentage frequency of *S. commerson* from Muscat with an opaque zone at the otolith margin. Grey line is seawater temperature measured during 2001 at Muscat using a Vemco® Minithermograph 12 bit, at 9 m, with a reading every 20 min. Numbers represent sample size for each month.

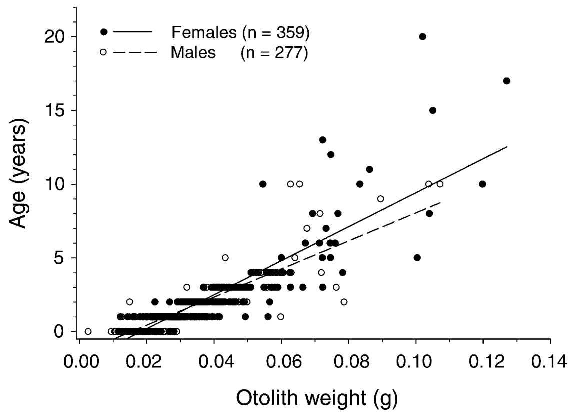

Fig. 3. Relationship between otolith weight (g) and age (years) for each sex. All regions have been combined.

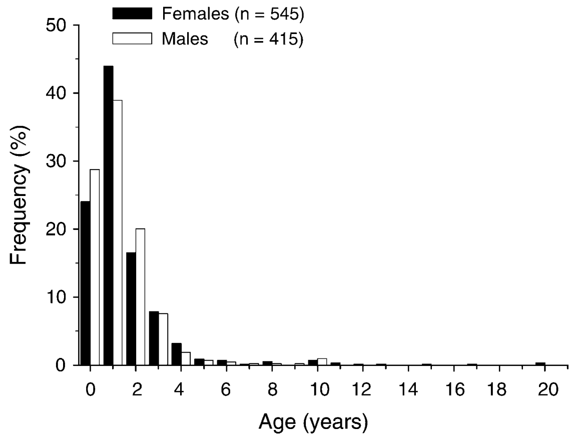

Fig. 4. Age frequency distributions of *S. commerson* based on sex. All regions have been combined.

0.004; n.s.) (Fig. 3). Approximately 75% of the variability in otolith weight could be attributed to age for both female and male *S. commerson*, and when all data were combined (Table 2).

3.3. Age and length distributions

The sex ratio of *S. commerson* in all age classes was not significantly different ($\chi^2 = 0.2431$, d.f. = 7; $^{*}P < 0.05$)(Fig. 4). However, there was a clear female bias in the older age classes, with no male fish older than 10 years. The oldest fish sampled was a 20-year-old female. In the first 5-year classes, which dominated the sample, there were more males in the 0+ and 2+ year classes, and more females in the 1+ and 3+ year classes.

The five youngest age classes dominated in all six regions sampled, with 96% of all fish between the 0+ and 5+ classes (Fig. 5). This is confirmed by the results of the age-length keys of both the observed age at length data from otoliths and the estimated age at length for the entire landing (Table 3a and b). Within these five dominant classes, there were clear differences in the age structure amongst regions. Approximately 95

Table 2
The relationship between age (year) and otolith weight (g) for male and female *S. commerson*

Sex	*n*	Equation	r^2
Female	359	Age = 115.31OtoWt − 2.11	0.751
Male	277	Age = 95.23OtoWt − 1.47	0.746
Total	636	Age = 107.93OtoWt − 1.86	0.745

and 90% of fish from Al-Batinah and Al-Wusta were found in the 0+, 1+ or 2+ classes, respectively (Fig. 5b and e). These two regions were also characterized by a dominance of the smaller length classes, particularly fish 60–70 cm FL (Fig. 6b and e). Musandam and Ash-Sharqiyah recorded the lowest frequency of these 3-year classes with 83 and 64%, respectively (Fig. 5a and d) and a greater number of fish 90–110 cm FL (Fig. 6a and d). The greatest number of fish over 5 years old occurred in Ash-Sharqiyah (7%) followed by Al-Wusta (6.6%) and Muscat (4.7%).

3.4. Growth models

The analysis of residual sums of squares (ARSS) indicated that male and female *S. commerson* had significantly different VBGF growth curves ($F_{3,96} = 5.739$; $^{***}P < 0.001$). Overall, males attained a smaller length than females but had faster growth towards L_∞ (Table 4, Fig. 7a and b). Growth was rapid in male fish until 4 years when it slowed considerably, compared with females, who continued relatively rapid growth until 7–8 years then slowed.

The VBGF curves fitted to length-at-age data varied significantly between regions (ARSS; $F_{15,943} = 14.556$; $^{***}P < 0.001$). Overall, the total sample comprised only eight individuals greater than 10 years, resulting in underestimates of L_∞. This was clearly the case in four of the six regions (Musandam, Muscat, Al-Wusta and Dhofar) where estimates of L_∞ were less than the maximum FL (Tables 1 and 4). In two of these regions,

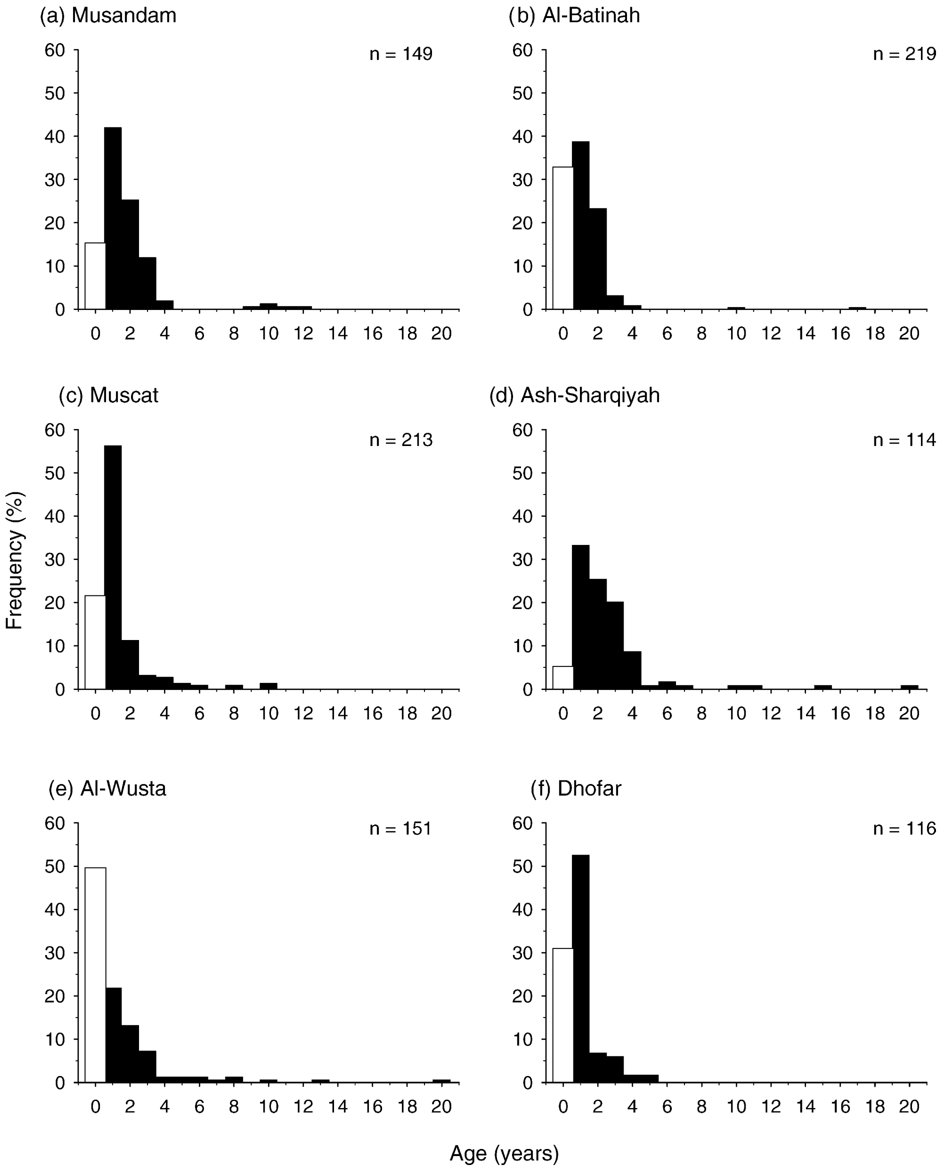

Fig. 5. Age frequency distributions of *S. commerson* by region.

Muscat and Dhofar, no fish older than 10 and 5 years respectively were sampled (Fig. 8c and f). Fish landed in Ash-Sharqiyah had the lowest growth coefficient (K) but reached a larger asymptotic length than other regions (Table 4; Fig. 8d). In contrast, fish caught in Al-Wusta had a smaller asymptotic length compared to other regions ($L_\infty = 122.596$), but recorded the greatest growth coefficient (0.796), reaching L_∞ by 4 years after which growth slowed considerably (Fig. 8e).

Monthly length frequency data from Muscat show distinct modes during the 2 years of sampling with a clear progression of these modes over this time period (Fig. 9). The smallest year class appeared in September 2000 at 45 cm and was distinct until October/November

Table 3
The observed age-length key for *S. commerson* from (a) the otolith study and (b) the estimated age distribution of the entire landing

Length (cm)	Age (years)																					Total
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
(a) The otolith study																						
40	20																					20
50	84	9																				93
60	89	63																				152
70	55	139	19	1																		214
80	8	130	61	14																		213
90	1	52	46	21	2																	121
100		5	32	19	7	1																64
110		1	13	15	7	1		1		1	2			1								42
120				2	8	3	4		2		1		1									21
130				1	1	3	2	1			2	1										11
140									2		2					1					1	6
150											1	1						1				3
160																					1	1
Total	257	399	171	73	25	8	6	2	4	1	8	2	1	1	0	1	0	1	0	0	2	962
(b) The estimated age distribution of the entire landing																						
40	33																					33
50	341	37																				378
60	518	367																				885
70	118	297	41																			456
80	19	302	141	32																		494
90	5	236	204	95	9																	548
100		33	212	126	46	7																424
110		5	71	82	38	5		5		5	11			5								230
120				13	51	19	26		13		6		6									134
130				12	12	36	24	12			24	12										131
140									24		24					12					12	72
150											5	5						5				15
160																					5	5
170																						0
Total	1033	1276	669	360	157	67	49	17	37	5	70	17	6	5		12		5			17	3805

The lengths are the lower limits of each 10 cm length class.

2001 at 70–95 cm. The growth parameters described by the VBGF in ELEFAN differed to those described by the VBGF estimated using the non-linear least squares method applied to length at age data (Table 4). The former method estimated a greater L_∞, a slightly larger K value and larger t_0.

3.5. Mortality estimates

Al-Wusta was the only region whose 0+ age classes were fully recruited to the fishery and included in the instantaneous rates of total mortality (Z) estimated from the catch curves (Fig. 10). Estimates of Z varied significantly between regions, from 0.373 year^{-1} ($r^2 = 0.637$) in Muscat to 1.321 year^{-1} ($r^2 = 0.960$) in Al-Batinah (Table 5). Estimates of natural mortality (M) from Pauly's (1980) regression equation were greater than those of the total annual mortality in Musandam, similar in Muscat and lower in Al-Batinah, Ash-Sharqiyah, Al-Wusta and Dhofar (Table 5). The estimates of fishing mortality (F) reveal that the Al-Batinah population was fished at a higher rate, 0.878 year^{-1}, than other regions. Estimates of Z for females and males were relatively similar (0.901 and 0.892 year^{-1}). However (F) estimates for each sex reveal females are fished more intensely than males.

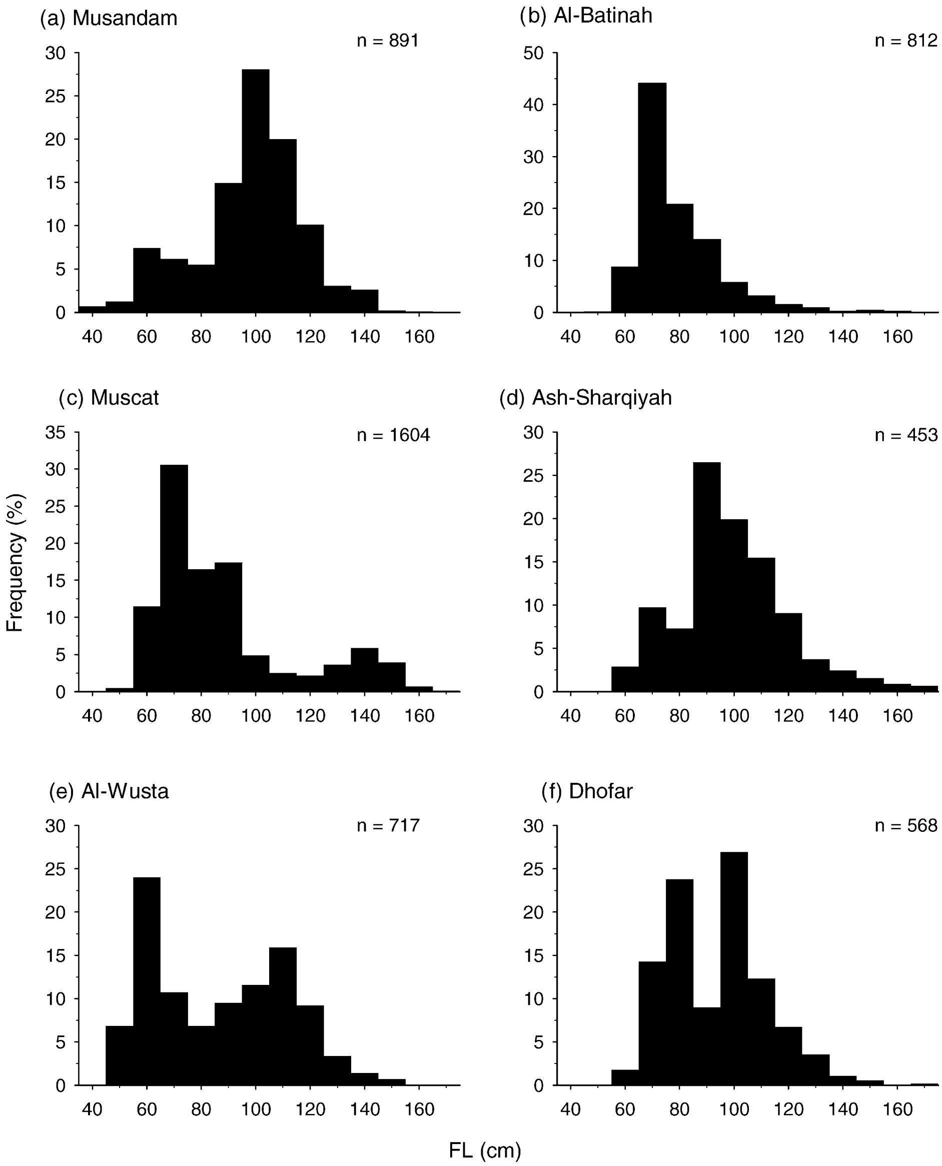

Fig. 6. Size frequency distributions of *S. commerson* by region.

4. Discussion

In the past, *Scomberomorus* species have been aged using whole rather than sectioned otoliths (Manooch et al., 1987; Sturm and Salter, 1990; McPherson, 1992; Govender, 1994; Begg and Sellin, 1998; but see Schmidt et al., 1993; DeVries and Grimes, 1997). However in this study, we chose to section the otoliths of *S. commerson* for greater precision. These sections produced clearly identifiable, opaque increments that were validated as annuli using Edge Analysis. Growth curves constructed for each of six locations revealed a significantly different age structure for kingfish along the coastline of Oman. In Dhofar and Muscat, we did not find individuals older than 5 and 10 years, respectively. Along the Al-Batinah coast, 95% of the catch was comprised of 0+ to 2+ age classes whereas in Ash-Sharqiyah these same age classes made up only 64%

Table 4
Growth parameters (±95% C.I.) calculated separately for each region from VBGF, using length-at-age data

Parameter	L_∞ (cm)	CI (cm)	K (year^{-1})	CI (year^{-1})	t_0 (year^{-1})	CI (year^{-1})	r^2
Region							
Musandam	118.11	108, 129	0.514	0.33, 0.83	−1.152	−0.54, −1.99	0.585
Al-Batinah	163.08	145, 186	0.184	0.13, 0.25	−2.205	−1.69, −2.89	0.634
Muscat	140.62	128, 159	0.286	0.19, 0.41	−1.740	−1.75, −2.55	0.667
Muscat (ELEFAN)	173.25	na	0.310	na			na
Ash-Sharqiyah	172.82	154, 203	0.127	0.08, 0.18	−4.211	−3.05, −5.99	0.716
Al-Wusta	122.59	118, 128	0.796	0.67, 0.94	−0.315	−0.22, −0.44	0.897
Dhofar	150.31	124, 302	0.261	0.07, 0.48	−1.726	−0.99, −3.24	0.779
Sex							
Females	140.44	143, 160	0.309	0.16, 0.23	−1.501	−2.49, −3.19	0.718
Males	118.80	126, 146	0.595	0.22, 0.34	−0.730	−1.94, −2.62	0.696
Combined	146.4	140, 153	0.216	0.19. 0.25	−2.618	−2.38, −2.88	0.654

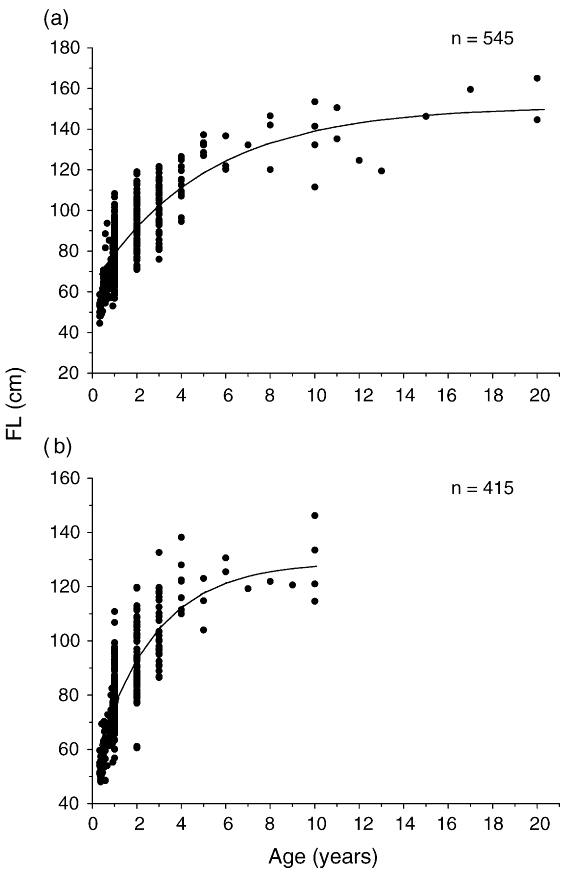

Fig. 7. von Bertalanffy growth curves fitted to *S. commerson* length-at-age data for (a) females and (b) males.

of the catch. These differences could have come about through regional differences in gear type use, overexploitation at the local scale resulting in extinction of the older year classes or a combination of both.

Drift and set gillnets account for approximately 75% of the gear types used to exploit Oman's kingfish (Claereboudt et al., 2004). The frequency distribution of gillnet mesh sizes varied significantly between the six locations (Fig. 11). Mesh sizes (defined here as stretched mesh size) were smallest in Al-Batinah and Muscat, where nets with a mesh size less than 12 cm accounted for approximately 75% of the total nets deployed by fishermen. The observed differences in mesh sizes among locations probably contributed to the differences in age and size classes, as frequent use of small mesh nets by fishermen in Al-Batinah and Muscat would result in a bias towards younger, smaller fish.

Unfortunately, the observed variation in selectivity of the different gear types and sizes among locations

Table 5
Estimates of instantaneous rates of total mortality (Z), natural mortality (M) and fishing mortality (F) for each of the six regions

Region	Z (year^{-1})	S.E. (Z)	M year^{-1} (Pauly)	F (year^{-1})
Musandam	0.407	0.099	0.661	–
Al-Batinah	1.321	0.190	0.443	0.878
Muscat	0.373	0.151	0.397	0.007
Ash-Sharqiyah	0.693	0.122	0.488	0.204
Al-Wusta	0.522	0.082	0.305	0.217
Dhofar	0.822	0.189	0.407	0.414
Females	0.901	0.092	0.376	0.525
Males	0.892	0.319	0.490	0.402

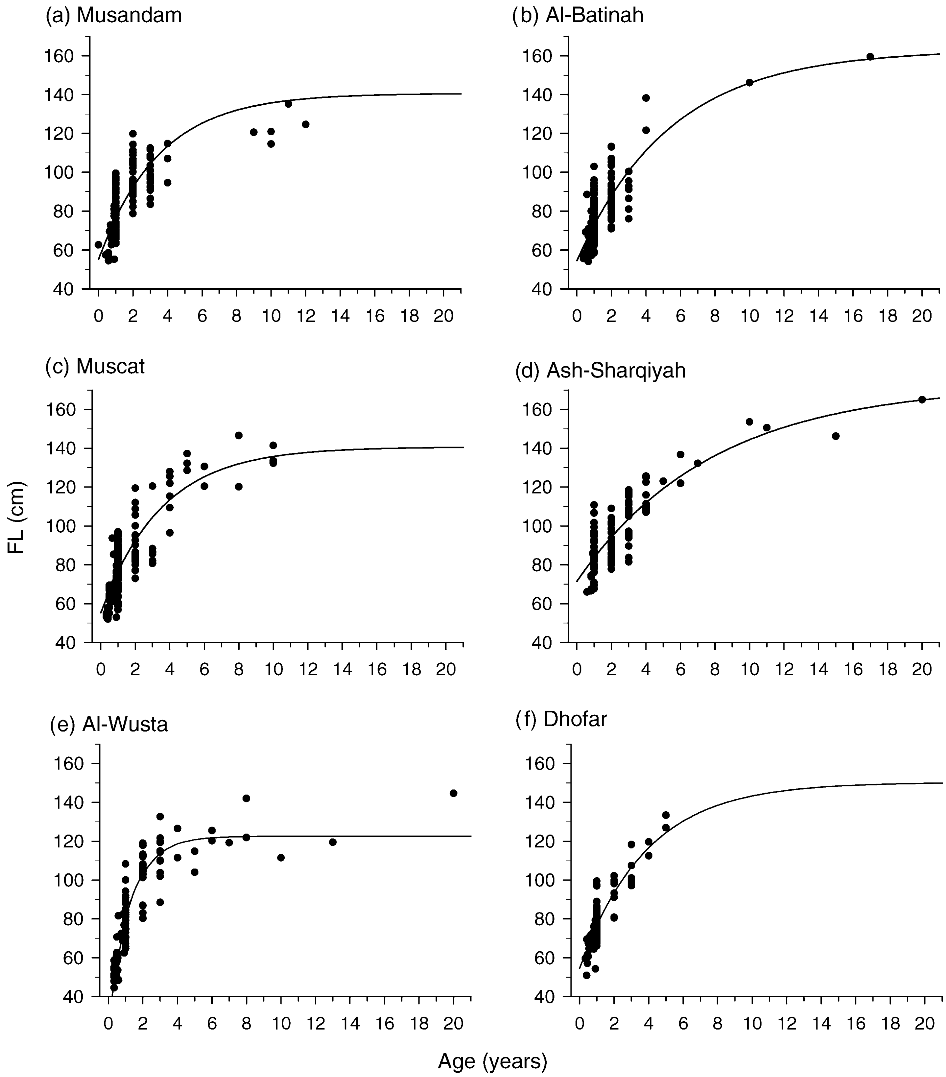

Fig. 8. von Bertalanffy growth curves fitted to *S. commerson* length-at-age data for each of the six regions.

give biased parameter estimates of the VBGF growth curves and confounds a comparison of growth curves between locations. In Al-Batinah and Dhofar, where older age classes were rare, estimates of L_∞ were probably too low and K values over-inflated. However, by eliminating selectivity as a confounding factor, a direct comparison of growth rates among locations might be possible. For this and other *Scomberomorus* species, differences in growth rates between regions has indicated stock separation (Fable et al., 1987; Sutter et al., 1991; McPherson, 1992; DeVries and Grimes, 1997), which has, in some cases, supported a genetic difference (Begg and Sellin, 1998). Follow-up ageing studies for the Oman kingfish fishery should incorporate data collection that records how individual fish were caught, enabling a direct and meaningful comparison of growth rates among locations. Doing so may offer some insight into the stock structure of this species, if differences in growth rates among locations were detected.

Differences in selectivity between regions would also influence estimates of instantaneous total mortality because the catch curve method, using single

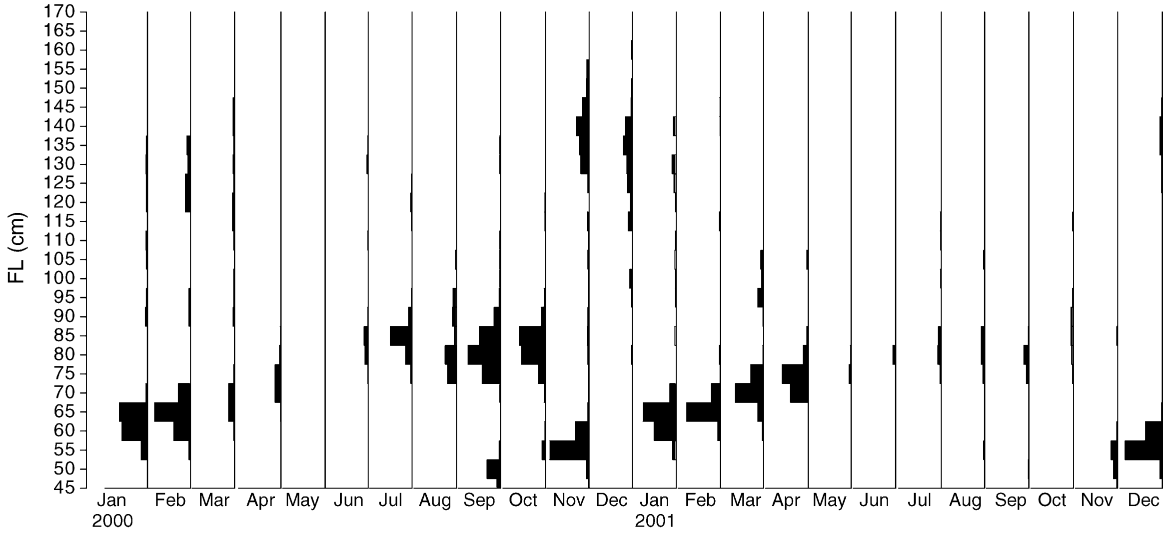

Fig. 9. Monthly length frequency data collected from Muscat between January 2000 and December 2001. Maximum frequency on horizontal axis for each month is 60.

age-frequency distributions, assumes that catchability is equal across all age classes (Hilborn and Walters, 1992; Russ et al., 1998). In addition to problems with gear selectivity, mortality estimates in king mackerel (*Scomberomorus cavalla*) from the Gulf of Mexico were compromised by the migratory nature of the species and like *S. commerson*, the females live longer and grow bigger than males (Manooch et al., 1987). It is therefore recommended that mortality estimates (Z, M and (F)) given here be used with caution until catch curve data for different fishing gear is made available.

In countries where minimum size and bag limits have been implemented, 0+ *S. commerson* are often under sampled, resulting in poor predictions of growth for this age class using techniques such as the VBGF (McPherson, 1992). However, the absence of minimum size limits on kingfish in Oman gave us a unique opportunity to sample large numbers of fish less than 1 year old. VBGF curves fitted through data which included counts of daily increments for fish less than 1 year old suggested the life history of *S. commerson* stocks in Oman is comprised of two distinct phases. The first phase is distinguished by extremely rapid growth from the larval stage to 18 months of age. The second phase can be described as the period when growth slows considerably. The start of the second phase coincides with the time at which kingfish reach age at first reproduction (Claereboudt et al., 2005). This fast-growth strategy during the early stages most vulnerable to predation is typical of large-prey species like *Scomberomorus* (Jenkins et al., 1985; Begg and Sellin, 1998). Our results are in general agreement with other studies from the region. In Kuwait, *S. commerson* grew to between 44.5 and 52 cm in the first 5 months and in Oman size at age was found to be 50–60 cm for 6-month-old fish (Brothers and Mathews, 1987; Dudley et al., 1992).

Sex specific differences in length, weight, growth and longevity were evident during this study. At most landing sites, there was a female bias in the catch, which may be attributed to gear selectivity (Claereboudt et al., 2004). Growth parameters revealed females grew at a slower rate but reached a greater asymptotic length than male fish. Greater representation in the older year classes (>10 years) suggested females also lived longer than males. Rapid initial growth in male kingfish supports reproductive data collected on the same individuals, where males reached size at first maturity faster than females (Claereboudt et al., 2005). In the only other growth study of *S. commerson* where sex was also differentiated, the results obtained were similar to ours. Female *S. commerson* from eastern Australia were also found to reach a higher L_∞ and displayed smaller K values than male fish from the same region

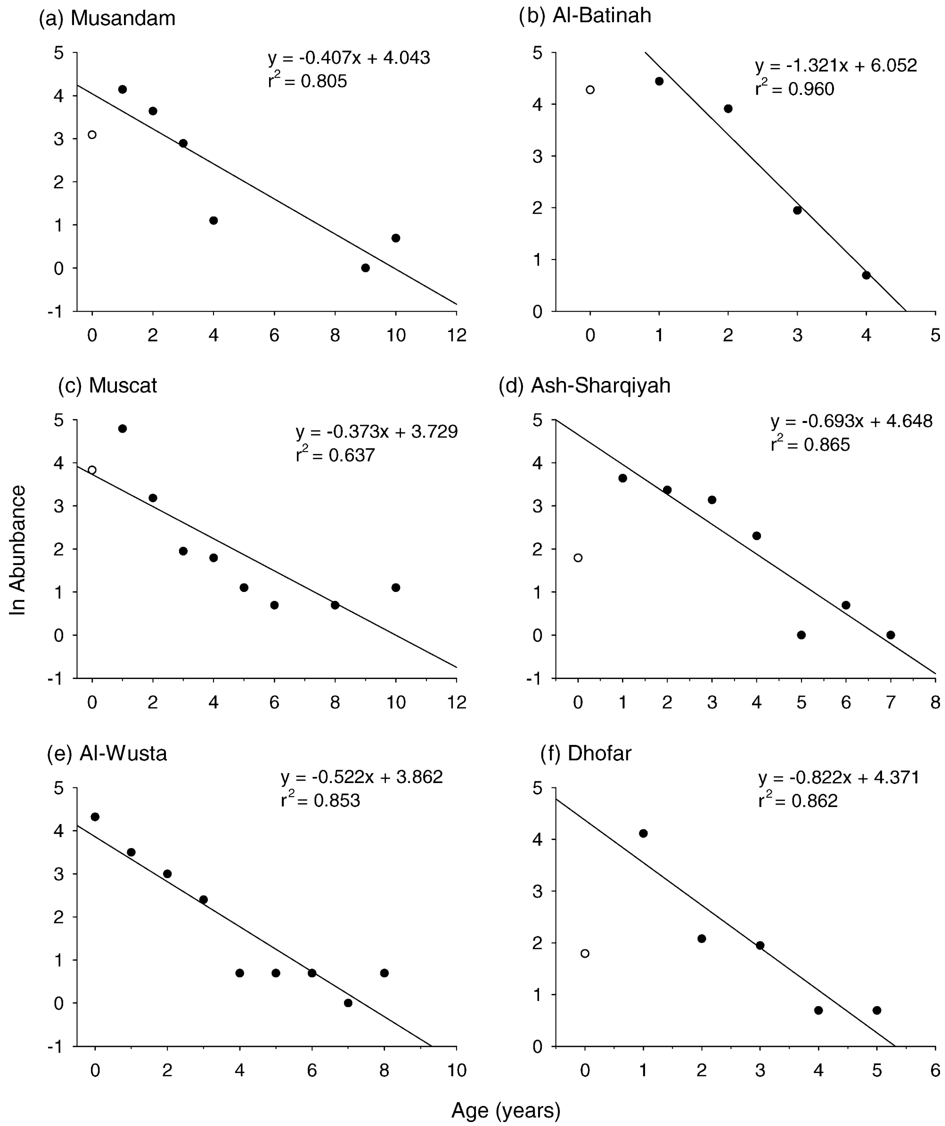

Fig. 10. Age-based catch curves for each of the six regions using annuli counts of otoliths. ((●) Points used in the regression; (○) points not used in the regression).

(McPherson, 1992). These observed sex-specific differences in growth are probably related to differing investment in gametogenesis by the two sexes.

Like Oman, South Africa's *S. commerson* fishery is comprised primarily of young fish. From a large sample size ($n = 637$) no individuals were recorded older than 5 years of age (Govender, 1994). Govender suggested the observed growth rates for this fishery were underestimates as they were based on the assumption of opaque bands being laid down annually. Instead, he proposed that for this South African population, which displayed a protracted spawning season, opaque bands are probably laid down twice a year. This is unlikely to be the case in Oman, where spawning occurs over a relatively short period from April to May in both the Gulf of Oman and the Arabian Sea (Claereboudt et al., 2005). Furthermore, visual inspection of the otolith margins from fish sampled at Muscat reveals a large

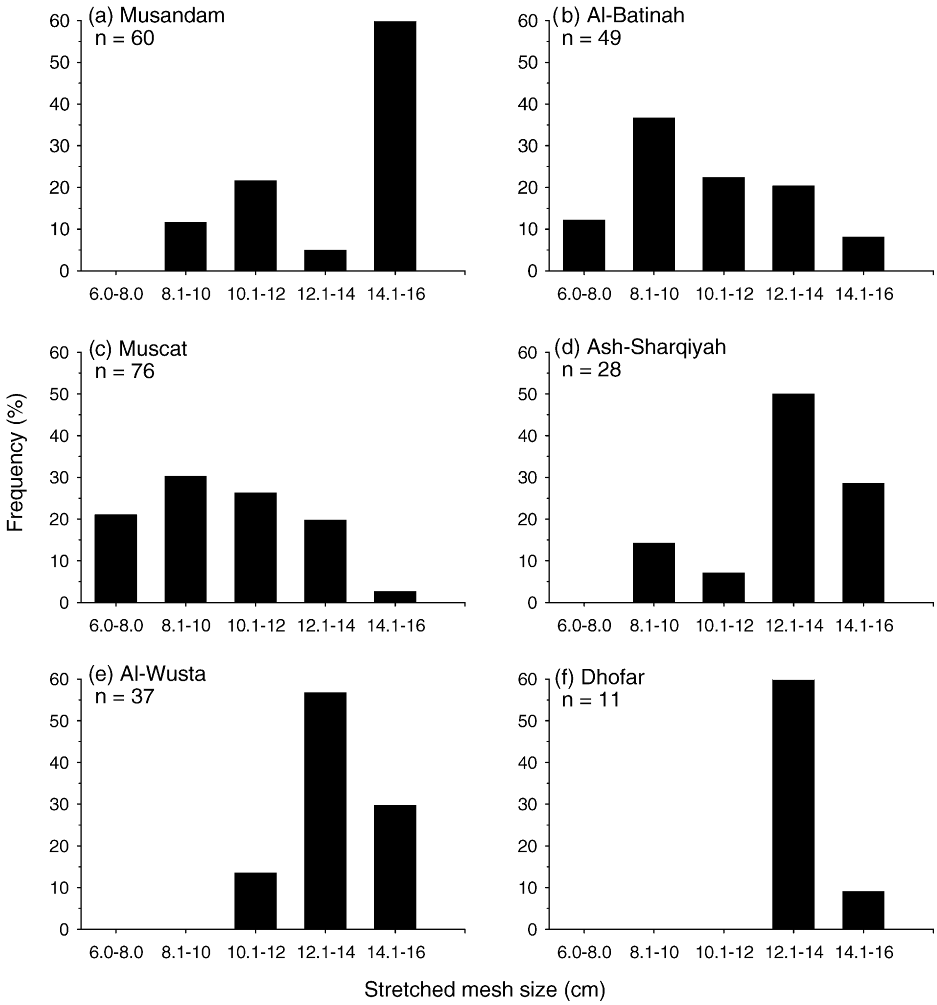

Fig. 11. A comparison of mesh size for drift and set nets used by kingfish fishermen in each of the six regions.

proportion of fish deposit the opaque zone once a year during the winter months.

Although the timing of the formation of the opaque zone in this study was similar to that recorded from other geographic regions, the length of time during which this formation took place was much greater than observed elsewhere. For 6 months (September to February) more than 75% of the fish were forming an opaque zone on their otolith edge. In eastern Australia, the opaque zone is apparent for 3 months (June, July, August) just prior to the onset of spawning in late spring (October, November) (McPherson, 1992). The timing appeared to be delayed by 2–3 months for fish in South Africa, with peaks in the formation of the opaque margins occurring in September (Govender, 1992). These observed differences in the timing and longevity of zone formation for *S. commerson* from these three locations probably came about through differences in classification between observers and differences in otolith preparation. Classification of the otolith edge can be affected by factors such as light conditions, magnification or variability in human interpretation (Beckman and Wilson, 1995). Similarly the timing of the opaque zone formation has been found to be different between whole and sectioned otoliths (Campana, 1984), and by as much as 2 months in another species, *S. cavalla* (Collins et al., 1989). We recommend a more detailed study that examines the timing of the deposition of opaque and translucent material for kingfish in Oman, preferably using a technique like marginal increment analysis (Campana, 2001).

Of the otoliths examined in this study, more than 80% had a translucent zone at the edge during late spring and summer (March–July). This coincides with the onset of a predictable summer weather pattern, when upwelling events are a common feature along the coast, driven by the southeast monsoon or khareef (Smith, 2001). Daily water temperatures during the monsoon can vary by as much as 5 °C (Fig. 2). It has been suggested that kingfish undertake a spawning migration out of local coastal waters during these summer months (Claereboudt et al., 2004). This is supported by evidence of seasonality in catch statistics, where kingfish landings decline dramatically during the reproductive season (see also April, May, June data from Muscat, Fig. 9). It is therefore possible that the formation of the translucent zone coincides with periods of low somatic growth, when energy is required to undertake a lengthy migration and to reproduce.

In light of the decline in kingfish landings in Oman over the past decade (Anon., 2001) and previous scientific evidence that stocks are currently over-exploited (Al-Hosni and Siddeek, 1999), an ongoing data collection program using life history parameters such as age must be initiated. However the type of data to be collected would need careful consideration given the problems highlighted in this study. Data on gear types used to catch individual fish would need to be collected, as would the continuation of sex differentiation given the differences in growth rates and longevity between males and females. We also recommend that future stock assessment of *S. commerson* in Oman use length-at age data, based on otolith analysis and techniques outlined in this manuscript.

Acknowledgements

The authors would like to thank the following technicians for help in collection of the samples; G. Hermosa, H. Al-Habsi, J. Villaneuva, K. Al-Riyami, Mohd. Alam, H. Al-Masroori, S. Al-Barwani, S. Al-Khusaibi, A. Al-Nabhani, and A. Al-Busaidi. We would also like to thank A. Govender and A. Halford for helpful comments on earlier versions of the manuscript. The comments of two anonymous reviewers helped improve the final draft. This project was fully funded by the Fisheries Research Fund of Oman.

References

Anon., 2001. Annual Statistic Report (2000) for the Sultanate of Oman. Department of Fisheries Statistics, Directorate General of Fisheries Resources, Ministry of Agriculture and Fisheries, Muscat, 210 pp.

Al-Hosni, A.H., Siddeek, S.M., 1999. Growth and mortality of the narrowbanded Spanish Mackerel, *Scomberomorus commerson* (Lacepede), in Omani waters. Fish. Man. Ecol. 6, 145–160.

Al-Oufi, H., McLean, E., Palfreman, A., 2000. Observations upon the Al-Batinah artisanal fishery, the Sultanate of Oman. Mar. Pol. 24, 423–429.

Beamish, R.J., Fournier, D.A., 1981. A method for comparing the precision of a set of age determinations. Can. J. Fish. Aquat. Sci. 38, 982–983.

Beckman, D.W., Wilson, C.A., 1995. Seasonal timing of opaque zone formation in fish otoliths. In: Secor, D.H., Dean, J.M., Campana, S.E. (Eds.), Recent Developments in Fish Otolith Research. University of South Carolina Press, Columbia, pp. 27–43.

Begg, G.A., Sellin, M.J., 1998. Age and growth of school mackerel (*Scomberomorus queenslandicus*) and spotted mackerel (*S. munroi*) in Queensland east-coast waters with implications for stock structure. Mar. Freshwater Res. 49, 109–120.

Bertignac, M., Yesaki, M., 1993. Preliminary assessment of the narrow-barred Spanish mackerel stock off Oman using length-frequency distributions by Bhattacharya's method. Rev. Stocks Tuna Biol. IPTP Collective Volumes 8, Part 2, 88–95.

Beverton, R.J.H., Holt, S.J., 1957. On the dynamics of exploited fish populations. Fishery Invest. (Ministry of Agriculture and Food (Great Britain) Series) 2 (19), 533.

Brothers, E.B., 1987. Methodological approaches to the examination of otoliths in aging studies. In: Summerfelt, R.C., Hall, G.E. (Eds.), Age and Growth of Fish. Iowa State University Press, Ames, pp. 319–330.

Brothers, E.B., Mathews, C.P., 1987. Application of otolith microstructural studies to age determination of some commercially valuable fish of the Arabian Gulf. Kuw. Bull. Mar. Sci. 9, 127–157.

Campana, S.E., 1984. Comparison of age determination methods for the starry flounder. Trans. Am. Fish. Soc. 113, 365–369.

Campana, S.E., 2001. Accuracy, precision and quality control in age determination, including a review of the use and abuse of age validation methods. J. Fish. Biol. 59, 197–242.

Chen, Y., Jackson, D.A., Harvey, H.H., 1992. A comparison of von Bertalanffy and polynomial functions in modeling fish growth data. Can. J. Fish. Aquat. Sci. 49 (6), 1228–1235.

Claereboudt, M.R., Al-Oufi, H.S., McIlwain, J., Goddard, J.S., 2004. Relationships between fishing gear, size frequency and reproductive patterns for the kingfish (*Scomberomorus commerson* Lacepede) fishery in the Gulf of Oman. In: Payne, A.I.L., Obrien, C.M., Rogers, S.I. (Eds.), Management of Shared Fish Stocks. Blackwell, Oxford, pp. 1–12.

Claereboudt, M.R., McIlwain, J.L., Al Onfi, H.S., Ambu-Ali, A.A., 2005. Patterns of reproduction and spawning of the kingfish (*Scomberomorus commerson* Lacépède) in the coastal waters of the Sultanate of Oman. Fish. Res. 73, 273–282.

Collins, M.R., Schmidt, D.J., Waltz, C.W., Pickney, J.L., 1989. Age and growth of king mackerel, *Scomberomorus cavalla*, from the Atlantic coast of the United States. Fish. Bull. 87, 49–62.

DeVries, D.A., Grimes, C.B., 1997. Spatial and temporal variation in age and growth of king mackerel, *Scomberomorus cavalla*, 1977–1992. Fish Bull. 95, 694–708.

Dudley, R.G., Arundhati, P.A., 1989. Growth and population characteristics of *Scomberomorus commerson* in Oman based on length data. In: Report of the Workshop on Tunas and Seerfishes in the Arabian Sea Region. IndoPacific Tuna Program Workshop, Muscat, Oman, February 1989. IPTP/89/GEN/16.

Dudley, R.G., Aghanashinikar, A.P., Brothers, E.B., 1992. Management of the Indo-Pacific Spanish mackerel (*Scomberomorus commerson*) in Oman. Fish. Res. 15, 17–43.

Fable, W.A., Johnson, A.G., Barger, L.E., 1987. Age and growth of king and Spanish mackerel, *Scomberomorus maculatus*, from Florida and the Gulf of Mexico. Fish. Bull. 85, 777–783.

Gayanilo, F.C., Sparre, P., Pauly, D., 1995. The FAO-ICLARM Stock Assessment Tools (FiSAT) User's Guide. FAO Computerized Information Series, Fisheries. ICLARM Contribution No. 1048, 126 pp.

Govender, A., 1992. Age and growth of two key exploited linefish species off Natal: The slinger (*Chrysoblephus puniceus*) and the King mackerel (*Scomberomorus commerson*). Fish, Fishers and Fisheries. In: Proceedings of 2nd San Marine Linefish Symposium, Durban, October 23–24.

Govender, A., 1994. Growth of the king mackerel (*Scomberomorus commerson*) off the coast of Natal, South Africa – from length and age data. Fish. Res. 20, 63–79.

Govender, A., 1995. Mortality and biological reference points for the king mackerel (*Scomberomorus commerson*) fishery off Natal, South Africa (based on a per-recruit assessment). Fish. Res. 23, 195–208.

Hilborn, R., Walters, C.J., 1992. Quantitative Fisheries Stock Assessment. Choice, Dynamics and Uncertainty. Chapman and Hall, New York.

Jenkins, G.P., Milward, N.E., Hartwick, R.F., 1985. Occurrence of larvae of Spanish Mackerels, genus *Scomberomorus* (Teleostei: Scombridae), in shelf waters of the Great Barrier Reef. Aust. J. Mar. Freshw. Res. 36, 635–640.

Manooch, C.S., Naughton, S.P., Grimes, C.B., Trent, L., 1987. Age and growth of king mackerel, *Scomberomorus cavalla*, from the US Gulf of Mexico. Mar. Fish. Rev. 49 (2), 102–108.

McPherson, G.R., 1992. Age and growth of the narrow-barred Spanish mackerel (*Scomberomorus commerson* Lacepede, 1800) in North-eastern Queensland waters. Aust. J. Mar. Freshw. Res. 43, 1269–1282.

Pauly, D., 1980. On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks. J. Cons. Int. Explor. Mer. 39 (2), 175–192.

Radebe, P.V., Mann, B.Q., Beckley, L.E., Govender, A., 2002. Age and growth of *Rhabdosargus sarba* (Pisces: Sparidae), from KwaZulu-Natal, South Africa. Fish. Res. 58, 193–201.

Ricker, W.E., 1975. Computation and interpretation of biological statistics of fish populations. Bull. Fish. Res. Board Can. 191, 382.

Russ, G.R., Lou, D.C., Higgs, J.B., Ferreira, B.P., 1998. Mortality rate of a cohort of the coral trout, Plectropomus leopardus, in zones of the Great Barrier Reef Marine Park closed to fishing. Mar. Freshwater Res. 49, 507–511.

Schmidt, D.J., Collins, M.R., Wyanski, D.M., 1993. Age, growth, maturity, and spawning of Spanish mackerel, *Scomberomorus maculatus* (Mitchill), from the Atlantic coast of southeastern United States. Fish. Bull. 91, 526–533.

Siddeek, M.S.M., Al-Hosni, A.H., 1998. Biological reference points for managing kingfish, *Scomberomorus commerson*, in Oman waters. NAGA, The ICLARM Quarterly, October–December, 32–36.

Smith, S.L., 2001. Understanding the Arabian Sea: reflections on the 1994–1996 Arabian Sea expedition. Deep Sea Res. II 48, 1385–1402.

Sturm, M.de.L., Salter, P., 1990. Age, growth, and reproduction of the king mackerel *Scomberomorus cavalla* (Cuvier) in Trinidad waters. Fish. Bull. 88, 361–370.

Sutter, F.C., Williams, R.O., Godcharles, M.F., 1991. Growth and mortality of king mackerel *Scomberomorus cavalla* tagged in the southeastern United States. Fish. Bull. 89, 733–737.

Zar, J.H., 1996. Biostatistical Analysis. Prentice Hall, New Jersey.