Stock assessment of narrow-barred Spanish mackerel (*Scomberomorus commerson*) in Western Australia

Principal Investigator: M. Mackie

Co-Investigators: D.J. Gaughan and R.C. Buckworth

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Fish for the future

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Cover black & white picture: Adult Spanish mackerel, courtesy of the Food and Agriculture Organisation of the United Nations (ref. No. A47/2000); FAO Fisheries Synopsis No. 125, Vol. 2 (1983) Scombrids of the world.

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PRINCIPAL INVESTIGATOR: Dr. Michael Mackie

ADDRESS:
Fisheries Research Division
Department of Fisheries
P.O. Box 20, North Beach, WA, 6920
Telephone: 08 9246 8444 Fax: 08 9447 3062
Email: mmackie@fish.wa.gov.au

OBJECTIVES

- Determine the age, growth and reproductive biology of *S. commerson* in Western Australia (WA).
- Determine the most realistic measure of effort for the commercial fleet and identify the historical changes in fishing efficiency.
- Evaluate a biomass dynamics model for stock assessment of *S. commerson* in WA.
- Use yield per recruit and egg per recruit models to determine appropriate levels of fishing mortality for *S. commerson*; and estimate the current level of fishing mortality.
- Evaluate the feasibility of future use of the daily egg production method for estimating spawning biomass of *S. commerson* in WA.
- Provide advice to industry and fishery managers on the status of the *S. commerson* stocks and provide views on the effectiveness of a range of management options.

Additional

- Develop and assess cost-effective methods for the ongoing monitoring of *S. commerson* stocks in WA.

NON-TECHNICAL SUMMARY

OUTCOMES ACHIEVED

- Initiation of steps to formally manage the commercial mackerel fishery, and provision of data and advice required to complete the process. Although implementation of management of the fishery is still underway, the current project provided research data and industry liaison to further the process.
- Provision of data and knowledge required to fulfil Ecological Sustainable Development reporting for the fishery. This was essential given the export market for mackerel.

In WA waters narrow-barred Spanish mackerel (*Scomberomorus commerson*) are fast growing, reach sexual maturity at a young age (<1.5 yrs) and can live more than 20 years. Females grow faster, reach larger lengths and dominate the larger size classes, although males dominate the older age classes. The fishery is based on 1 – 4 year old fish, which comprise about 70% of the commercial catch. The maximum age of Spanish mackerel in WA (22 yrs) is considerably greater than has previously been reported elsewhere. The current minimum legal length (MLL) of 900 mm is appropriate since it approximates the size at which 50% of females reach sexual maturity. Males mature at a smaller size and at the MLL more than 90% are mature.

Spanish mackerel are seasonally abundant along a large area of the tropical/sub-tropical coastline of WA. The seasonal appearance of this species in shallow coastal waters is probably associated with feeding and gonad development prior to spawning, which occurs at particular locations. The peak reproductive period extends from October to January in the Pilbara region but may occur a month or so earlier in the Kimberley region. Little or no spawning was evident south of Exmouth.

Most Spanish mackerel appear to have fairly restricted long-shore movement patterns. The habitat of most of the population outside of the main fishing season is still unclear, although anecdotal evidence suggests that they move off the coast into deeper water at this time.

The commercial mackerel fishery extends from Geraldton to the Northern Territory (NT) border and is currently accessed by a significant proportion of the WA licensed fishing fleet. Approximately twelve fishers target Spanish mackerel full time during the six or so months when this species is abundant on the coast. Many other fishers catch Spanish mackerel opportunistically whilst targeting other species. The commercial fishery is expected to come under formal management in 2004 (Chapter 11, Appendix 6.0). Most of the recreational catch is taken between Perth and Dampier. The species is a prized sports fish and recreational catches are 80% or more of commercial catches in the Gascoyne and west coast regions.

The daily egg production method was shown to be logistically and economically unfeasible for estimating spawning biomass of Spanish mackerel. Use of a biomass dynamics model to estimate biomass of this species was also unsuccessful except for the west coast region. The model suggests that Spanish mackerel in this region are not under heavy fishing pressure relative to the spawning (standing) stock biomass.

Yield per recruit (YPR) analyses indicate that Spanish mackerel are resilient to fishing mortality at the current MLL. However the models also suggest that this size at first capture is below that which optimises YPR. A further increase in the MLL is impractical though because of the difficulty in removing hooks from larger-sized mackerel. Economic impacts to fishing operations also need to be considered, since fish between 900 and 1000 mm total length may comprise about a third of the catch. Uncertainty over mortality estimates prohibit specific recommendations of optimum age and size at first capture from YPR analyses.

Egg per recruit (EPR) analyses confirm that the reproductive output of females in the Kimberley region is robust to fishing and the optimum levels of YPR are sustainable. However, EPR by female Spanish mackerel in the Pilbara region appears less robust. As this region may possibly also be the main source of recruits for the west coast region caution is required to ensure that recruitment overfishing does not occur in this region.

Management of the commercial mackerel fishery will be based on trends in the catch and effort data. This requires implementation of a fishery-specific log book. The catch rate data will also complement and be used in more sophisticated models incorporating age-structure, so that more reliable examination of population dynamics and management options can be made. However, it is important to note that catch rates of schooling species such as Spanish mackerel may not provide a true reflection of the status of the fishery.

Further options for management include spatial and temporal closures. Temporal closures are already being considered under the new management plan to reduce management costs for the fishery. As a means of ensuring sustainability of the fishery, spatial and temporal closures provide alternatives to quota cuts in the event of adverse trends in catch rates or model scenarios. To be of greatest benefit the closures should be focussed on the main locations and times of spawning to protect spawning fish. The social and economic impact to fishers of closures should be considered since the fishery is already seasonal and much of the catch includes reproductively active fish. Nonetheless, with monitoring via the vessel monitoring system (VMS) it should be possible to selectively close reefs whilst permitting others to be fished.

In order to facilitate ongoing collection of data for Spanish mackerel, various length-weight-age conversion equations have been developed during the current project. Methods used in the study of Spanish mackerel reproduction and growth have also been published as Research Reports to assist future sampling.

KEYWORDS:

narrow-barred Spanish mackerel, *Scomberomorus commerson*, Reproduction, Spawning, Age, Growth, Mortality, Otoliths, Diet, Biomass dynamics, Yield-per-recruit, Egg-per-recruit, Reference points, Fisheries management.

1.0 Introduction

1.1 Background

The narrow-barred Spanish mackerel (*Scomberomorus commerson*) is the largest member of the genus and widespread in tropical and subtropical waters of the Indo-West Pacific (Collette and Nauen 1983). Reaching over 2.4 m in length and 45 kg in weight, this streamlined pelagic species is seasonally abundant in coastal waters where it often schools in large numbers. It is targeted by commercial, recreational and artisanal fisheries throughout its range, with annual global catches increasing from 135 350 to 204 954 tonnes between 1991 and 2000 (FAO 2000). The countries with the largest reported catches of *S. commerson* in 2000 were Indonesia, India, Egypt, Madagascar, and Pakistan.

Biological and stock assessment research on *S. commerson* have been conducted in the waters of South Africa (Govender 1994), Yemen (Edwards *et al.* 1985), Oman (Al Hosni and Siddeek 1999) and India (Devaraj 1981, Dudley *et al.* 1992). The species has also been studied in Australian waters off the Northern Territory (NT; Buckworth 1999) and Queensland (QLD; Munro 1942, McPherson 1987, 1992, 1993). The commercial catch of *S. commerson* in Australia is low by world standards (1 160 - 1 617 t between 1994 - 1998, FAO 2000). However the troll-caught product is high quality and sought after by domestic and export markets.

S. commerson is also considered a premier light-gamefish, and the recreational catch is likely to be comparable to that of commercial fishers in more populated areas of the Australian coastline (Mackie 2001, A. Tobin, FRDC Spanish mackerel project, CRC Reef, Townsville *pers. comm.*). Sustainability of these recreational and commercial catches are of concern, particularly along the east coast where the species has been fished for longer and more heavily than elsewhere in Australia. Commercial fishers on the west coast have also expressed concern over the increased interest in the mackerel fishery generated by development of the export market. As demersal fisheries along the Western Australia (WA) coast became managed by limited entry, other commercial wetline boats focus on fisheries such as the mackerel fishery which remain open access. Recreational anglers and recreational fishing bodies have also noted the need for management of such an important recreational species. Additionally, Department of Fisheries research scientists have become worried about the increasing catches, lack of biological information and schooling behaviour of *S. commerson*, which potentially make it vulnerable to rapid depletion.

To determine feasible management strategies, the need for scientific advice on the exploitation status, stock structure and aspects of *S. commerson* biology has become urgent. As such, two complementary Fisheries Research and Development Corporation (FRDC) funded research projects were commenced on this species. The first of these, a joint project between NT, QLD and WA into the nation-wide stock structure of *S. commerson* began in 1998 (FRDC project 98/159). The second project, which is described in this report, commenced in 1999 with the purpose of providing biological information and a stock assessment of *S. commerson* in WA waters (FRDC project 99/151).

1.2 Need

The Department of Fisheries in Western Australia is currently reviewing the open access wetline sector of the WA commercial fishery with a view to improving the management of stocks exploited by this sector. In reviewing the existing catch data it became clear that the major tropical species exploited by the wetline boats and other finfish sectors is *S. commerson*.

Due to limited information on the biology and population dynamics of *S. commerson* in WA waters, an urgent management requirement to begin research on this species was identified. Research information was collected in parallel with the development of management arrangements and can be used to implement and adjust management controls as data became available.

For these management arrangements to be effective, however, there was also an urgent need to understand the degree of residency of *S. commerson* in WA waters and relative to NT and QLD. The results for the project investigating the stock structure (FRDC project 98/159; NT, WA & QLD) using the isotopic ratios of oxygen and carbon in otolith carbonate, mitochondrial DNA and parasitic fauna suggest that there are likely to be a number of distinct stocks, or rather distinct fishery management units.

1.3 Objectives

- Determine the age, growth and reproductive biology of *S. commerson* in WA.
- Determine the most realistic measure of effort for the commercial fleet and identify the historical changes in fishing efficiency.
- Evaluate a biomass dynamics model for stock assessment of *S. commerson* in WA.
- Use yield per recruit and egg per recruit models to determine appropriate levels of fishing mortality for *S. commerson*; and estimate the current level of fishing mortality.
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- Provide advice to industry and fishery managers on the status of the *S. commerson* stocks and provide views on the effectiveness of a range of management options.

Additional

- Develop and assess cost-effective methods for the ongoing monitoring of *S. commerson* stocks in Western Australia.

2.0 Methods

2.1 Description of the fishery

Description of the commercial and recreational fishery for *S. commerson* in Western Australia was based on historic commercial catch and effort data, recreational survey data, interviews with commercial and recreational fishers, and observations made by research staff whilst collecting data and samples onboard fishing vessels, from fish processors and at fishing competitions.

2.1.1 Catch and effort statistics

Catch and effort data of *S. commerson* by the commercial line fishery were obtained from the Western Australian Department of Fisheries (WA DoF) catch and effort statistics (CAES) database. This data is derived from compulsory commercial fishing returns sent by commercial fishers to the WA DoF. Interviews with commercial and recreational fishers were used to identify issues with the CAES database and thus improve catch and effort data for subsequent analyses. Because *S. commerson* are landed in various forms (e.g. whole, trunk or filleted) it was also necessary to assess current conversion factors used to convert landed weight to whole weight and, if necessary, develop more appropriate conversion factors. Refer to Section 2.2.2 for sampling details, and to Chapter 3.2 for problems encountered when using the CAES data.

2.1.2 Information from fishers about the fishery

Formal interviews were held with twenty current or previous commercial mackerel fishers or processors and four dedicated recreational fishers (including a spear-fisher). In each interview a series of questions relating to the capture, biology and ecology of *S. commerson* were asked. Many more informal observations were also made from discussions with commercial and recreational fishers over the phone and whilst collecting samples.

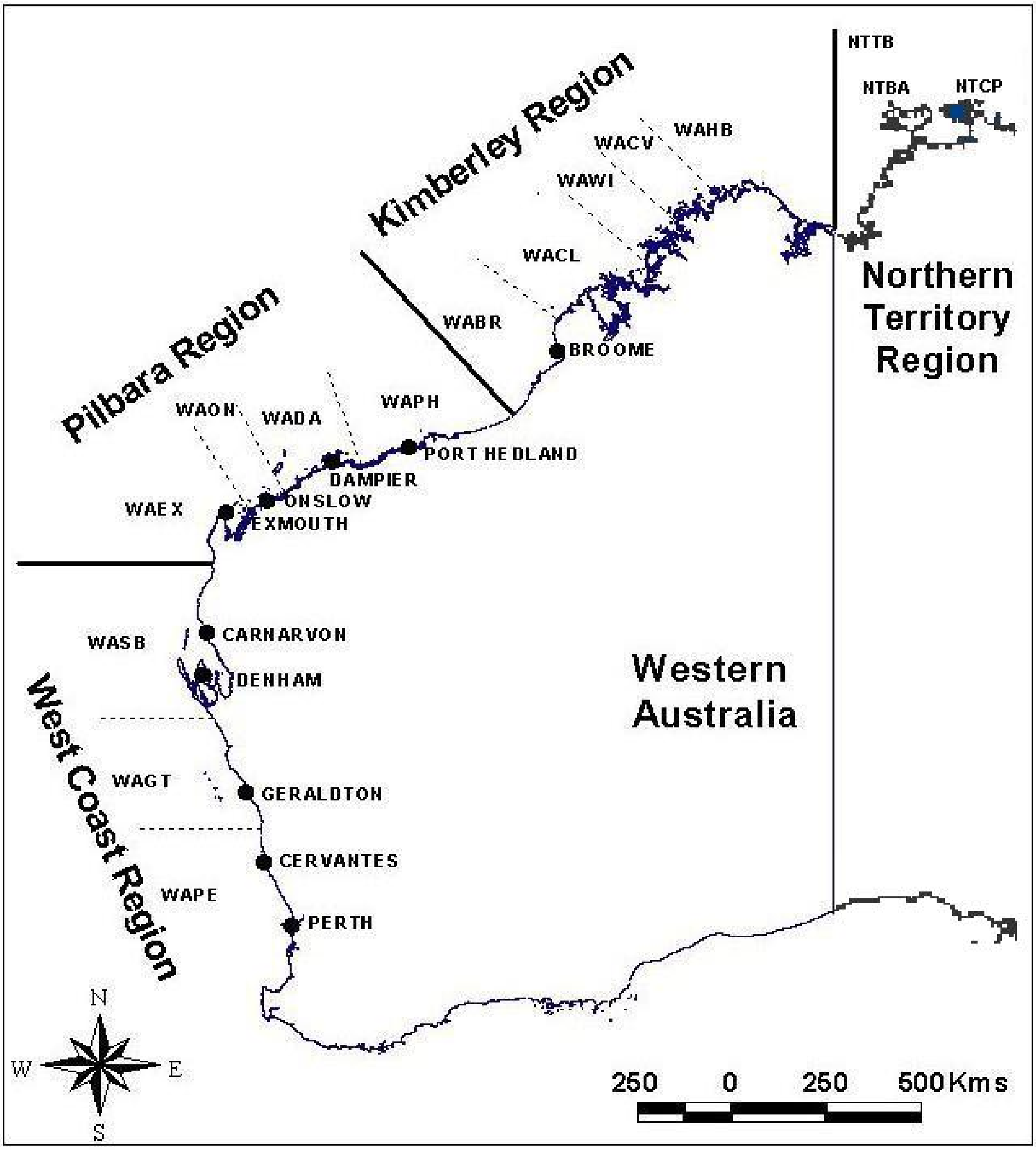


Figure 2.1 Biological sample collection regions and areas around Western Australia.

2.2 Biological information

2.2.1 Collection of samples

Fresh samples of *S. commerson* were collected onboard commercial, recreational and research vessels, from commercial fish processors, and at recreational fishing competitions between July 1999 and April 2002. Additional samples of *S. commerson* sent to Perth by commercial fishers usually comprised the head, viscera and gonads of each fish and were frozen or on ice for a number of days before processing. Frozen frames (fillets removed) were also collected from recreational anglers on occasion.

Sampling of small *S. commerson* (113 to 600 mm fork length (FL)) was conducted in the Dampier region of Western Australia (Figure 2.1) from January until April 2000. Most of these fish were juveniles (undifferentiated sex), although small males and females were also collected. These fish were mainly collected around channel markers off the port of Dampier using small baited hooks or lures. A number were also obtained from the bycatch of prawn trawlers working out of nearby Point Samson and some came from recreational anglers. The smallest specimen (FL= 58 mm) was collected off Port Hedland by a commercial mackerel fisher after it was regurgitated by a captured tuna.

The Western Australian coast was divided into 12 general areas based on the locations of fishing ports and mackerel fishing areas (Figure 2.1). Most of the biological samples came from the areas of:

1) Cape Voltaire (WACV), 2) Cape Leveque (WACL), 3) Broome (WABR), 4) Port Hedland (WAPH), 5) Dampier (WADA) and 6) Shark Bay (WASB),

with others collected less frequently from

7) Holothurian Bank (WAHB), 8) White Island (WAWI), 9) Onslow (WAON), 10) Exmouth (WAEX), 11) Geraldton (WAGT) and 12) Perth/Cervantes (WAPE).

Additional samples were collected from 3 areas in the western Northern Territory, these were 1) Timor Box (NTTB), 2) Coburg Peninsula (NTCP) and 3) Bathurst Island (NTBA).

For data analyses these samples were pooled into three regions (Figure 2.1):

Kimberley – east of 120° E (includes WAHB, WACV, WAWI, WACL, WABR),

Pilbara – north of 23° S to the Kimberley border (includes WAPH, WADA, WAON, WAEX), West coast – south of 23° S (includes WASB, WAGT, WAPE). Note that in some analyses this region was divided into the Gascoyne region (23° to 27° S) and the south region (south of 27° S).

The seasonal nature of *S. commerson* catches and inclement summer weather pattern restricted the annual time series of samples from the three regions. Only in the Pilbara region was it possible to obtain a complete monthly series of samples, although these were limited between late spring and early autumn.

2.2.2 Processing of samples

In the field the full range of biological measurements were usually possible from the fresh whole specimens. These were length to caudal fork (fork length; FL), total length (TL), head length (HL; from tip of the snout to the firm edge of the operculum) and upper jaw length (JL; from tip of the snout to the posterior edge of the upper jaw [premaxilla and maxilla]) (Figure 2.2). All measurements were in mm. Note that TL was usually taken to the upper fork of the tail, which is 2 % greater than the TL measured using the lower fork (r^2 of regression between upper and lower lobes = 0.9965, n= 484,). Refer to Mackie and Lewis (2001) for further details. Additionally, FL was estimated for the head only samples from the established relationships between HL and JL with FL (see Section 4.1.1).

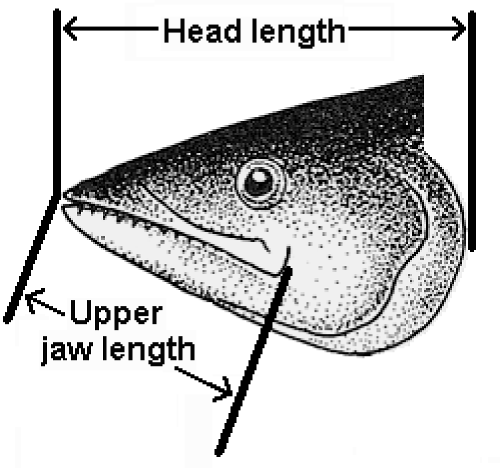


Figure 2.2 Detail of head (HL) and upper jaw length (JL) measurements made on *S. commerson*.

Where possible whole weight (WW), processed weight and head weight (HW) were obtained. Processed weight included clean weight (viscera and gonads removed), trunk weight (gutted/gilled weight; head, viscera and gonads removed) and frame weight (fillets removed). Heads were removed at the first vertebrae and weighed with gills in place. Body weights were to 0.1 kg, head weight to 0.1 gram. To determine fillet weight for calculation of conversion equations (Section 2.1) the frame weight was subtracted from whole weight to obtain 'meat weight', with a further 10% of this weight removed (to allow for trimming of belly flap and rib cage). This latter percentage was determined from discussion with fishers and observations of their filleting procedures.

Gonads were usually removed from the fish within a few hours of capture, weighed if possible (to 0.01 gm), macroscopically staged and preserved (see Section 2.2.3). The sagittal otoliths were removed from most specimens in the field but some heads were frozen and sent to the laboratory.

In the laboratory the frozen samples (heads with visceral mass or frames) were thawed in freshwater, weighed and measured (see above). Gonads were macroscopically staged, blotted dry and weighed, the sagittal otoliths removed and the stomach contents identified (if possible) and weighed (to 0.01 gm).

2.2.3 Reproduction

Methods used in this study to process and stage *S. commerson* gonads are detailed in Mackie and Lewis (2001). In the field, fresh gonads of *S. commerson* were removed and macroscopically staged soon after capture (see Mackie and Lewis 2001). Where possible the whole gonad was then weighed and a 10 cm thick section of one lobe preserved in 10% formalin solution. If the gonad could not be weighed fresh it was preserved whole to be weighed later in the laboratory or, if space was limited, only a 10 cm thick section preserved. To ensure adequate fixation of the whole gonad several cuts were made along each lobe so that formalin could enter.

The macroscopic staging system was simplified to ensure maximum accuracy, yet was compatible with the microscopic system (refer to Mackie and Lewis 2001 for details, including pictorial description of the ontogenetic and seasonal relationship between these stages):

Undifferentiated: J (juvenile). *Females*: Stage 1 (virgin/immature), Stage 2-3 (mature resting), Stage 4 (reproductively developed), Stage 5 (spawning). *Males*: Stage 1 (virgin), Stage 2 (mature resting), Stage 3 (reproductively developed/ripe), Stage 4 (spawning).

The microscopic staging system was used in analyses of the preserved, histologically processed samples (Mackie and Lewis 2001). This system had more stages than the macroscopic system and allowed more detailed description of reproductive development and hence spawning:

Undifferentiated: J (juvenile). *Females*: Stage 1 (virgin/immature), Stage 1a (immature developing), Stage 2 (mature resting), Stage 3 (mature developing), Stage 4 (reproductively developed), Stage 5a (pre-spawning), Stage 5b (spawning/running ripe), Stage 5c (post-spawning), Stage 6 (spent). *Males*: Stage 1 (virgin/immature), Stage 1a (immature developing), Stage 2 (mature resting), Stage 3 (reproductively developed/ripe), stage 4 (spawning).

Potential batch fecundity

Scomberomorus commerson is a batch spawning species (Munro 1942, Devaraj 1983). Estimates of batch fecundity were therefore made from counts of hydrated oocytes in pre-spawning ovaries (Stage 5a) as per procedures detailed in Mackie and Lewis (2001). All except one of these ovaries were obtained from the north Kimberley region during 1999 - 2001.

Analyses of data

All analyses were made using S-Plus statistical software.

- *Morphometrics*

Comparisons of FL with TL and WW, by sex and region, involved linear and non-linear regression analyses with the simplest models to adequately explain the data developed by reduction of the fully parameterised model. Model parameters were tested at each step using analysis of variance, with significance level for the linear models set at $P = 0.05$, and for non-linear models at $t > 1.96$. Data sets used in these analyses were truncated to encompass only data for which there was complete overlap between the three regions.

Quadratic regressions to estimate FL from JL and HL were developed by simplification of the fully parameterised model based on reduction of the Akaike's Information Criterion (the AIC), followed by testing of the remaining terms using *F*-tests (the AIC is more conservative when deciding to drop terms from the model). This data was grouped by sex and region to enable the best prediction of FL from the head samples obtained from fishers. For these analyses the West Coast region was split into the Gascoyne region, which included Carnarvon and Denham catches, and the South region, which included catches from Geraldton to Perth. Analyses were performed using data for Kimberley females as the reference group against which the data for other groups were compared. A Box-Cox likelihood profile was used to decide if and how the data should be transformed prior to analyses.

- *Sex ratios*

Analyses of sex ratios by month were based solely on data where the whole catch or a known random sample of a catch was processed, whereas analyses of sex ratios by FL were based on all samples from which length measurements were obtained.

- *Reproductive biology*

Size at sexual maturity

Mean size at maturity for both male and female Spanish mackerel were estimated from histological and fresh macroscopically staged gonads using a logistic general linear model, with standard errors estimated by bootstrapping. Because of low sample sizes for immature fish, the data were pooled spatially and temporally.

- *Spawning*

Potential batch fecundity

To determine if ovaries with migratory nucleus stage oocytes provided biased estimated of fecundity, the slopes of the regressions of batch fecundity and FL, and batch fecundity and WW for these ovaries and those with hydrated stage of development were compared using t-tests. Each regression was forced through a point coinciding with the length (or weight) at 50% sexual maturity (809 mm FL and 4 kg) and the approximate batch fecundity for that length or weight. The latter was set at 300 000 eggs, based on the fecundity of the smallest fish with hydrated oocytes that was obtained in the study which, at a FL of 854 mm had a batch fecundity of 330 000 eggs. Analysis of the data in this manner assumes that the batch fecundity of females prior to the average size at sexual maturity is nil. Data was pooled between years for analysis.

Spawning fraction and frequency

Estimates of captured female spawning frequency in the Kimberley region during September and October 1999 were made using the hydrated oocyte method (Hunter and Macewicz 1985). Spawning fraction was estimated from the histological samples as the number of ovaries with hydrated or migratory nucleus stage oocytes divided by the total number of mature ovaries in the catch. Spawning frequency was subsequently determined as the inverse of the spawning fraction. These data were compared with estimates made using the number of ovaries macroscopically identified as having hydrated oocytes.

Annual reproductive cycle - gonad indices

In the field it was often not possible to obtain clean weights (gutted and gilled) and many of the samples sent to the laboratory consisted only of the head and visceral mass. Hence there was limited data for the usual estimate of gonadosomatic index (GSI) based on cleaned body weight. Thus, other gonadosomatic indices based on the ratio between gonad weight and whole body weight (WWI), head weight (HWI), and head length (HLI) were calculated. Prior to analyses the relationship between gonad and whole weight was investigated so that only data within the range where they were not correlated were used.

The possibility of lunar influences on sex ratios in the pooled 1999 and 2000 Kimberley catches were examined using the Exact Binomial Test.

2.2.4 Age, growth and mortality

Detailed methods for the collection, preparation, sectioning and interpretation of whole and sectioned *S. commerson* sagittal otoliths for counts of microincrements and annuli are given in Lewis and Mackie (2003). A minimum of 500 otoliths from each region (Kimberley, Pilbara, and West coast) were weighed (to 0.0001g) and measured (total length, posterior to anti-rostrum length and width at the core) with digital vernier callipers (to 0.01mm).

Interpretation of otolith structure

- *Adult otolith sections*

Terminology used in the description of *S. commerson* otoliths follows that of Kalish *et al.* (1995). After familiarisation with the otolith structure and with regular re-calibration using a reference set of otoliths with clear annuli, the otoliths were read on two independent occasions by the primary reader (PL), and a secondary reader (MM) examined a sub-sample of the otoliths once (N=200). At each reading the slides were selected randomly from the storage box and readings were done using a phase contrast compound microscope at X40 magnification. Each otolith was given a readability index value (Table 2.1), a marginal increment category (Table 2.2) and a count of the visible annuli.

Table 2.1 Readability category index used in the analysis of *S. commerson* otoliths.

Category	Readability
1	Unreadable
2	Poor
3	Fair
4	Good
5	Perfectly readable

Table 2.2 Otolith margin category index used in the analysis of *S. commerson* otoliths.

Category	Otolith margin appearance
0	Opaque margin
1	1-50% of previous translucent margin
2	51-100% of previous translucent margin

Where the two ages given by the primary reader agreed this was the final age for that otolith. For the remaining otoliths, where the two ages differed, the sections were re-examined by the primary reader. If this final reading agreed with an earlier reading this was given as the final age estimate. However, if the three readings differed the sample was rejected.

- *Juvenile otolith sections*

Microincrements (putative daily growth increments) in the otoliths of *S. commerson* were assumed to be formed on a daily basis from the results obtained for the related species *S. niphonius* (Shoji *et al.* 1999a) and *S. maculatus* (Peters and Schmidt 1997). Microincrements were defined as a pair of adjacent bands, one light (translucent) and one dark (opaque), with consecutive microincrements forming a regular concentric pattern around a central primordium. Microincrements relate to the proteinaceous discontinuous zone and calcium carbonate incremental zone described by Watabe *et al.* (1982). For the majority of sections (96.5%) it was possible to count these microincrements from the core to the otolith margin. The first discernible microincrement after the primordium was assumed to have formed on the day of hatching.

Microincrements were counted on two separate occasions; where these differed by ≥ 10% a third count was done. For all otoliths the final age assigned was the average of the two counts that differed by less than 10%. If the three counts differed by more than 10% the otolith was excluded from the study. To be incorporated into the adult otolith data the average microincrement counts were converted to fractions of a year.

- *Whole adult otoliths*

The usefulness of whole sagittal otoliths for ageing compared to sectioned otoliths was investigated. Whole otoliths were selected so that approximately 100 from each sectioned otolith readability group and approximately even numbers from each of the three regions (Kimberley, Pilbara and Gascoyne) were obtained. The whole otoliths were immersed in 70% glycerol solution and the distal surface examined under a dissecting microscope with reflected light and a black background. The primary reader (PL) examined each whole otolith on two separate occasions, each time counting the annuli, assessing the marginal increment category (Table 2.1) and giving the otolith a readability index (Table 2.2). As with the adult otolith sections, if the ages from the two initial readings differed the otoliths were read again and 1) discarded if there was no agreement or 2) assigned an age equal to the final reading when it agreed with a prior reading. Refer to Lewis and Mackie (2003) for full details.

Validation of otolith increment periodicity

Validation of the temporal periodicity of annuli within the otoliths of *S. commerson* was attempted by chemically marking of the otoliths with calcein solution, for detailed methods see Appendix 3. The calcein solution was injected into the peritoneal cavity of fish captured in the Dampier and Shark Bay regions prior to tagging and release. The tags (2 x dart tags) were secured into the dorsal muscle just below the first dorsal fin so that the barb of the tag was secured behind the interneural bones located below the fin. The tagging project was conducted over 27 days in the Dampier region and 9 days in the Shark Bay region between October 1999 and August 2000.

Validation of otolith annuli was also made by marginal increment analysis. The variations in monthly percentages of each marginal increment category, particularly for the opaque margin, were examined for an annual periodicity in each region and for each sex. Data for the Pilbara region were pooled into 3 age groupings (1-2 yo, 3-5 yo and 6 yo+) to provide sufficient sample sizes. Due to the seasonality of the fishery, monthly otolith samples throughout the year were only obtained for the Pilbara region; a continuous 18 month time series was achieved for this region.

Analyses of data

- *Conversion of annuli counts to ages*

To allow for individual variation in the timing of annulus formation and improve the resolution of the length-at-age data (0.5 yr instead of 1 yr age classes), the absolute age of each fish was determined from the otolith annuli count, marginal increment category and date of capture. Adjustment for individual variation in formation of the annulus was based on methods used by Devires and Grimes (1997) on *S. cavalla*. These authors assigned the age of fish with a marginal increment of greater than 80% during the peak period of annulus formation as the annuli count plus one, allowing for the annulus that was about to form or was forming but not yet visible. All other fish were given the annuli count as their age. In the present study the peak period of annulus formation was determined to be November until February (See Section 5.1.1). Thus, to coincide with the spawning period of *S. commerson* (Section 4.1.3) as well as to allow for the lag between formation and appearance of the annulus, the period of annulus formation in Western Australia was determined to be September to February.

The following criteria were used to allocate an adjusted age to each individual, based on the annuli count, the time of capture, and the period of annulus formation in *S. commerson* otoliths.

1) If month of capture = September to February and MI = 2
   then adjusted age = annuli count + 1
2) If month of capture = September to February and MI = 0 or 1
   then adjusted age = annuli count
3) If month of capture = March to August (regardless of marginal increment)
   then adjusted age = annuli count

After adjustment for individual variability, further adjustment was made to allow for the time since the spawning season to improve the resolution of the data. This was done using the same time periods as above – appropriate because both the peak in spawning and the timing of otolith annuli formation were similar. Note that care must be taken if these times are different not to give unrealistic increases to the age of the fish (eg. by adding one to the annuli count to allow for time of annuli formation plus another half year to allow for time of year when caught). For *S. commerson* the final adjusted age (0.5 year resolution) was determined as:

1) If month of capture = September to February
then final adjusted age = adjusted age

2) If month of capture = March to August
then final adjusted age = adjusted age + 0.5

- *Precision of annuli counts*

The precision of the annuli counts and ages from the initial 2 readings by the primary reader were established by calculating the average percent error (APE) (Beamish and Fournier 1981). This is a measure of the precision of the annuli counts and age determinations by the primary reader that is not independent of the age of the species. The APE between the counts and ages given by the secondary reader and those of the primary reader, for the sub-sample of otoliths, were also calculated.

In addition the readings were further investigated by the test of symmetry (Hoenig *et al.* 1995). This test was used to show up any differences in methodology or interpretation of the otoliths that would not be detected by APE.

- *Comparison of whole and sectioned otolith results*

Age and marginal increment categories assigned to each whole otolith were compared to similar data obtained from the section of their otolith pair. This was done using a paired t-test to test the null hypothesis of no difference between ages, calculating the APE as a measure of precision, and test of symmetry to examine potential biases in interpretation of the whole and sectioned otoliths.

- *Relationship between otolith and body parameters and age*

Linear regression analyses were used to describe the relationship between the otolith parameters of weight, total length and antirostrum length, and the body parameters of WW and FL. Data was natural log transformed where required to linearise regressions prior to analysis and meet assumptions of normality and homogeneity of variances.

These otolith and body parameters were then used in combination to determine the linear regression model that most accurately described the relationship with age and/or would be most appropriate for future prediction of age during monitoring of *S. commerson* stocks. Prior to analyses ages and weights were transformed to linearise the relation between the transformed variables and the various lengths:

$$\text{ages} = \left(\frac{age}{(1+1.3age)} \right)^2$$

whole weight = $(\text{whole weight})^{1/3}$

otolith weight = $(\text{otolith weight})^{1/3}$

Note that data for juvenile fish were not used in these analyses to ensure the regressions provided the best fit to data for older fish, which where the focus of the age predictions. The most accurate/appropriate variables for describing the transformed age were then identified using the Best Subsets Regression procedures in Minitab version 12. This was done by determining which variable(s) provided the best and most parsimonious description of the variation in transformed age, based on the coefficient of determination and residual error values. These variables were then combined to produce a single variable, weighted by the ratio of their constants to provide a robust linear regression for estimation of age for each sex and region (to simplify the regression a single ratio was used for each sex and region).

- *Growth*

Annuli counts

Growth of *S. commerson* was modelled from length-at-age data using the von Bertalanffy growth equation, as this has previously been used in growth studies of this species. Data for juvenile fish (which develop into either male or female) was included in the data sets for both sexes prior to analyses.

The von Bertalanffy growth equation is defined as:

$$L_t = L_\infty(1-\exp^{-K[t-t_0]}) + \varepsilon$$

where L_t is the mean length at age t, L_∞ is the asymptotic mean length, K is the brody growth coefficient (a rate constant that determines the rate at which L_t approaches L_∞), t is the age of the fish (in 0.5 year intervals), t_0 is the theoretical age at which mean length is zero, and ε indicates that residuals are assumed to be distributed normally about the fitted growth curve.

Comparison of the von Bertalanffy growth parameters for males and females within each region were made using the likelihood ratio methods of Cerrato (1990). The validity of this analysis to tests of von Bertalanffy growth parameters depends on the degree of bias and non-normality in the parameter estimates, and unequal or unknown error variances are dealt with in an approximate way. The method assumes that the variance is constant for each curve but different between curves. The full model is that the curves differ in all parameters. The alternative models are that (1) both curves are the same (simplest model), (2) that the L_∞ values are equal, (3) that the K values are equal, (4) that the t_0 values are equal, (5) that the L_∞ and K values are equal, (6) that L_∞ and t_0 values are equal, and (7) that the K and t_0 are equal. The formulae of the method was modified slightly to allow the tests to be applied in an approach similar to a stepwise multiple regression, where model complexity was gradually increased and significance of the decreased sum of squares tested at each stage (P. Stephenson, I. Wright, WA Marine Research Laboratories, *pers. com.*) using the likelihood ratio test of Gallant (1975):

$$\Lambda^{-2/n} > \left(1 + \frac{q}{f_1 + f_2} F^{\alpha}_{q.f_1+f_2}\right),$$

where Λ is the likelihood ratio, $f_i = n_i - 3$, q is the number of linear restraints, and F is the upper α percentile point of the F-distribution with q and $f_1 - f_2$ degrees of freedom (Cerrato 1990).

- *Mortality*

Estimates of the instantaneous rate of total mortality (Z) were made for each region and sex using standard age-based catch curve analysis (Beverton and Holt 1957, Ricker 1975). This method assumes that the samples provide a true representation of the relative abundance of each age class, and that annual recruitment and total mortality are constantly applied to each recruited age-class (Haddon 2001). In addressing these assumptions, only unbiased samples comprising the whole catch or a randomly obtained portion of the catch were used in analyses. The log of the relative frequency of each age class within these samples against age was subsequently plotted, with the gradient of the regression describing the data for those fully recruited age classes (descending data points) providing the estimate of Z.

Natural mortality (M) was estimated using the empirically derived equations of Hoenig (1983):

$M = \exp(1.46 - 1.01 \times \ln(t_{max}))$,

Where t_{max} = maximum age. Because the Hoenig equation uses maximum age, this estimate of mortality may equate to Z if fishing pressure is light, however, this is not the case with *S. commerson* in WA waters. Natural mortality was also estimated using the empirical equation of Pauly (1980). This equation predicts natural mortality from the von Bertalanffy growth parameters, K (per year) and L_∞ (cm), and mean annual surface temperature, T (°C):

$M = \exp(-0.0066 - 0.279 \times \log(L_\infty) + 0.6543 \times \log(K) + 0.4634 \times \log(T))$

Various derivatives of this equation were also used to obtain alternative estimations of *M* (refer to Appendix 5, Table A5.7 for details).

- *Age length keys*

Age length keys were generated for males, females and the sexes combined for each region. The frequency of individuals in each 50 and 100 mm FL interval grouping was determined for each year class. From this the percentage of each FL group was calculated for each age to produce the key. Additionally, head length (HL)- fork length (FL) keys were generated for use in future monitoring of *S. commerson*.

2.2.5 Diet

The stomach contents of 1531 *S. commerson* were examined in the laboratory and prey items weighed (to 0.01g) and identified to the lowest taxonomic group. The lengths (TL, FL or tube length, for squid) of any complete prey items were also measured (in mm). The identified prey items were grouped into either small pelagic fish, medium to large pelagic fish, reef associated pelagic fish, reef associated demersal fish, cephalopods, crustacea and other items. The overall percentage occurrences of these groups in the diet of *S. commerson* were calculated to determine the most common diet. Additionally, the weight of gut contents and length of prey items were compared with fish size to examine ontogenetic changes in diet.

2.3 Environmental information

Sea surface temperature (SST) data was derived from NOAA-AVHRR satellite imagery complemented by buoy and other *in situ* measurements, to produce daily SST fields on a 1° latitude and longitude grid (Reynolds and Smith 1994). This data was used in examination of *S. commerson* reproductive cycles, spawning activity and otolith marginal increment development. Kimberley SST recordings were obtained for the northern area (13.5° S, 125.5° E), Pilbara region was the average of recordings for the Pt Hedland (19.5° S, 118.5° E) and Dampier areas (20.5° S, 115.5° E), and data for the west coast region was for the Carnarvon area (24.5° S, 112.5° E).

Daily tidal variation was obtained from the Admiralty Tide Tables (National Tidal Facility, 2000) for the Cape Voltaire area of the Kimberley region for comparison with reproductive cycles and spawning activity of *S. commerson*.

Data for length of day (photoperiod) was obtained from the internet site, http://www.saunalahti.fi/~jjlammi/sun.php3 , for the latitudes 15°, 20° and 27° S (Kimberley, Pilbara and west coast regions, respectively). This was also used in examination of reproductive biology and otolith marginal increment development.

2.4 Stock assessment

2.4.1 Biomass dynamic model

Background

Biomass dynamics (surplus production) models provide a simple means of assessing the overall productivity of the exploited stock (Hilborn and Walters 1992, Haddon 2001). In their most basic form these models provide a single measure of productivity without reference to age- or size-structure, growth, recruitment or other parameters of the stock. These models allow for stock assessments when data are limited and provide an independent check of the outputs of other models.

Use of biomass dynamics models require a time series of spatially stratified catch and effort data. This was available from the CAES database (see section 2.1), although the following should be considered with such data:

- Catch per unit effort (CPUE) is not directly proportional to abundance in highly aggregating species.
- Catch rates may vary seasonally due to seasonal migrations.
- The effective fishing effort increases more quickly than nominal effort if there are continuing increases in fishing efficiency.
- The catch and effort data needs to have contrast in order to properly model the dynamics of the population.

These points were relevant to *S. commerson* because of the schooling nature of the species and characteristics of the fishery. In particular an important pre-requisite of the modelling process was to validate and standardise the available effort data, using information obtained from interviews with fishers (Section 2.1.2) and observations made whilst collecting samples.

The biomass dynamic model

The basis of biomass dynamics models is the logistic model, first employed by Schaefer (1954, 1957) to estimate stock size and hence total production from catch and effort data:

$$B_{t+1} = B_t + rB_t\left(1 - \frac{B_t}{K}\right) - C_t \ ,$$

where B_t = the stock biomass at time t, r = the population growth rate, K = the virgin biomass, and C = total catch at time t. With this equation, maximum production occurs at $K/2$, suggesting that a stock should be fished down in order to increase potential fishing yield. This assumes that the relationship between stock biomass and production is symmetrical, but as this may not necessarily be the case Pella and Tomlinson (1969) modified the Schaefer model to include an asymmetry term such that maximum production does not necessarily occur at $K/2$. However, there are several unrealistic assumptions with these (and other similar) models, particularly that the population is in equilibrium with inputs and outputs (Haddon 2001).

Two approaches were taken in attempting to fit biomass dynamics models to the standardised catch and effort data for *S. commerson*. The first, following Haddon (2001), used a modified Fox (1970) form of the logistic equation to calculate a series of expected biomass values:

$$f(B_t) = Ln(K)rB_t\left[1-\left(\frac{Ln(B_t)}{Ln(K)}\right)\right],$$

where $f(B_t)$ is the production of biomass as a function of biomass at the start of year t, K is the virgin biomass (B_0) or the average biomass level prior to exploitation, and r is a growth rate parameter (derived from the intrinsic rate of natural increase). A series of estimated catch rates ($C\hat{/}E$) were then estimated using the equation $C\hat{/}E = q\hat{B}_t$, where q is a catchability coefficient (which itself was derived from $C\hat{/}E$ and $\hat{B}_t$). These estimates are then compared with the observed catch rates by maximising the log likelihood function with respect to r, K, q, and B_o using the equation (Haddon 2001):

$$LL = -\frac{n}{2}(Ln(2\pi) + 2Ln(\hat{\sigma}) + 1),$$

where LL is log-likelihood, n is the number of observed catch rates, and σ is the standard deviation $= \sum \frac{\left(Ln\frac{C}{E} - Ln\frac{\hat{C}}{E}\right)^2}{n}$

The second modelling approach also utilised the Schaefer (1954) model (see above), with Bayesian methods used to estimate process error, and observation error determined from:

estimated $\text{CPUE}_t = qB_t$ + observation error,

where parameters are as described above, and q, r, and K were estimated directly from the model (I. Wright, WA Marine Research Laboratories, *pers. comm.*).

2.4.2 Yield and egg per recruit models

The aim of YPR analyses is to determine the fishing mortality rate which optimises yield. This is generally not achieved by fishing as hard as possible so that a large number of small/young fish are captured, but rather by controlling effort to catch fewer, larger (older) fish (Russell 1942). As such, YPR models estimate, for the whole cohort over time, overall gains in biomass by growth (minus losses due to total mortality) at varying levels of F and ages at first capture. Assumptions underlying the classical Beverton and Holt (1957) YPR model include (Sparre and Venema 1992):

- Constant (unspecified) recruitment.
- All fish of a cohort are hatched on the same date.
- Knife-edge recruitment and selection.
- Constant F and M after the fish are recruited to the fishery.
- Complete mixing of the stock.
- The length-weight relationship has the exponent 3 (i.e. $W=aL^3$).

The main benefit of the Beverton and Holt model is analytical simplicity, although violation of the above assumptions limit its usefulness. For this reason Quinn and Deriso (1999) developed a generic approach that could be adapted and extended to most fisheries:

$$\frac{Y(t_\infty)}{N_r} = \sum_{x=t_r}^{t_\infty} \mu_x L_x W_x ,$$

where μ is the exploitation fraction (C_x / N_x), L is the cumulative survival (survival, S_x, is usually calculated as $\exp[-(M_x + s_x F])$, and W is the mean weight of fish. This approach was adapted for modelling data for *S. commerson* within each region (P. Stephenson, WA Marine Research Laboratories, *pers. comm.*) using the Mathcad 2000 mathematical programming software. Data used in the models were obtained from age, growth and reproductive analyses (Chapters 4 and 5; Table 2.3)

Sustainability of the fishing rate predicted to attain maximum yield is not directly considered in standard YPR analyses. As such care is required when assessing the potentially risky estimates of target fishing mortality and age at first capture that are derived from YPR analyses. Thus, rather than using a fishing mortality that maximises yield per recruit (F_{max}), a more conservative and widely used level of F is that which intercepts the YPR curve at the point where it is 10% that at the origin ($F_{0.1}$; Hilborn and Walters 1992).

In contrast to YPR analyses, Egg Per Recruit (EPR) methods attempt to avoid recruitment overfishing through a balance of yield and reproductive output. Such analysis requires information on the average fecundity of a mature female at age t (f_t), according to the generic equation (Quinn and Deriso 1999):

$$\frac{N_0}{N_r} = \sum_t f_t L_t$$

where $\frac{N_0}{N_r}$ is the expected lifetime egg production of a r-year-old fish, and L_t is the cumulative survival from age r to age t (where survival, S_x, is usually calculated as exp[-(M_x + $s_x F$]). This equation was also adapted for modelling data for *S. commerson* within each region using the Mathcad 2000 mathematical programming software. The data required for YPR and EPR analyses (parameters of the von Bertalanffy growth equation, fecundity at age, size and age at sexual maturity, and rates of fishing and natural mortality rate) were obtained from the biological studies detailed in Chapters 4 and 5. Note that fecundity estimates were extrapolated beyond the data range in order to provide estimates for all ages. The age at first capture (t_c) was assumed to be similar to the age corresponding to the 900 mm TL minimum legal size limit. This TL was firstly converted to FL and then to age using appropriate conversions for each region, and therefore differed slightly between regions (Table 2.3). Estimates of natural mortality required for the EPR models were obtained from maximum age of females using the Hoenig (1983) equation, and were 0.35, 0.23 and 0.25 for the Kimberley, Pilbara and west coast regions, respectively.

Table 2.3 Data used in Yield and Egg Per Recruit models for *S. commerson*. *P*; proportion within the catch. Length at first capture is FL in mm.

	Wgt = a x ln**(age)** + b		**Age (yr)**			**Length**	**P**
	a	b	max	1st capt.	95% mat.	1st capt.	
Kimberley	$3.4\text{x}10^{-9}$	3.12	12	1.43		810	
$\text{Kimberley}_{\text{Fem}}$	$3.4\text{x}10^{-9}$	3.12	12	1.43	2.71	810	0.55
$\text{Kimberley}_{\text{Male}}$	$3.4\text{x}10^{-9}$	3.12	11	1.47		810	
Pilbara	$3.4\text{x}10^{-9}$	3.12	22	1.43		816	
$\text{Pilbara}_{\text{Fem}}$	$3.4\text{x}10^{-9}$	3.12	18	1.38	2.49	816	0.55
$\text{Pilbara}_{\text{Male}}$	$3.4\text{x}10^{-9}$	3.12	22	1.48		816	
West coast	$3.4\text{x}10^{-9}$	3.12	18	1.43		813	
$\text{West coast}_{\text{Fem}}$	$3.4\text{x}10^{-9}$	3.12	17	1.44	2.75	813	0.55
$\text{West coast}_{\text{Male}}$	$3.4\text{x}10^{-9}$	3.12	18	1.43		813	

2.4.3 Feasibility of the daily egg production method (DEPM)

To determine the feasibility of utilising the DEPM to obtain a biomass estimate of *S. commerson* a literature review into the information required for such a survey and a field program investigating the sampling methods were conducted.

The objectives of the field component were to locate spawning *S. commerson* adults and then trial alternative plankton sampling techniques to assess the potential for sampling planktonic *S. commerson* eggs and gather auxillary information such as the precise time and location of spawning. The trip was conducted in the Kimberley region of Western Australia between the 1st and 9th of October 2001. The timing and location was based on the results of previous trips to this region, during September and October when spawning *S. commerson* adults were regularly sampled at a number of reefs (see section 4.1.4). Ideally the timing would coincide with the period of peak spawning activity based upon the monthly gonad somatic index (GSI) data from the region, however, due to logistical problems there was a considerable time lag between the collection and processing of this data.

Sampling was conducted from the 20 metre P.V. Walcott and four metre tender. Adult samples were collected at a number of reefs north of Broome but the main focus for the study was the Cape Voltaire region (Figure 2.1). Adult samples were obtained from the commercial mackerel fishers in this region.

At the reefs where spawning adult *S. commerson* were obtained, plankton samples were collected every hour during the spawning period in the afternoon and early evening (See Section 4.1.4). Based on the literature review and prior knowledge of reef fish spawning most samples were obtained from the reef edge parallel to the current flow (the reef shoulder) (Figure 2.3). Samples were generally obtained each hour using a doubled Bongo net (Smith and Richardson 1977), 60 cm diameter mouth with 500 micron mesh from the PV Walcott and a doubled CalVET net, 30 cm diameter mouth with 300 micron mesh from the tender. Before each sample was collected the type of tow, flow meter reading, time, depth and wind conditions were recorded along with the rope length used, duration of tow and final flow meter at the completion of each tow.

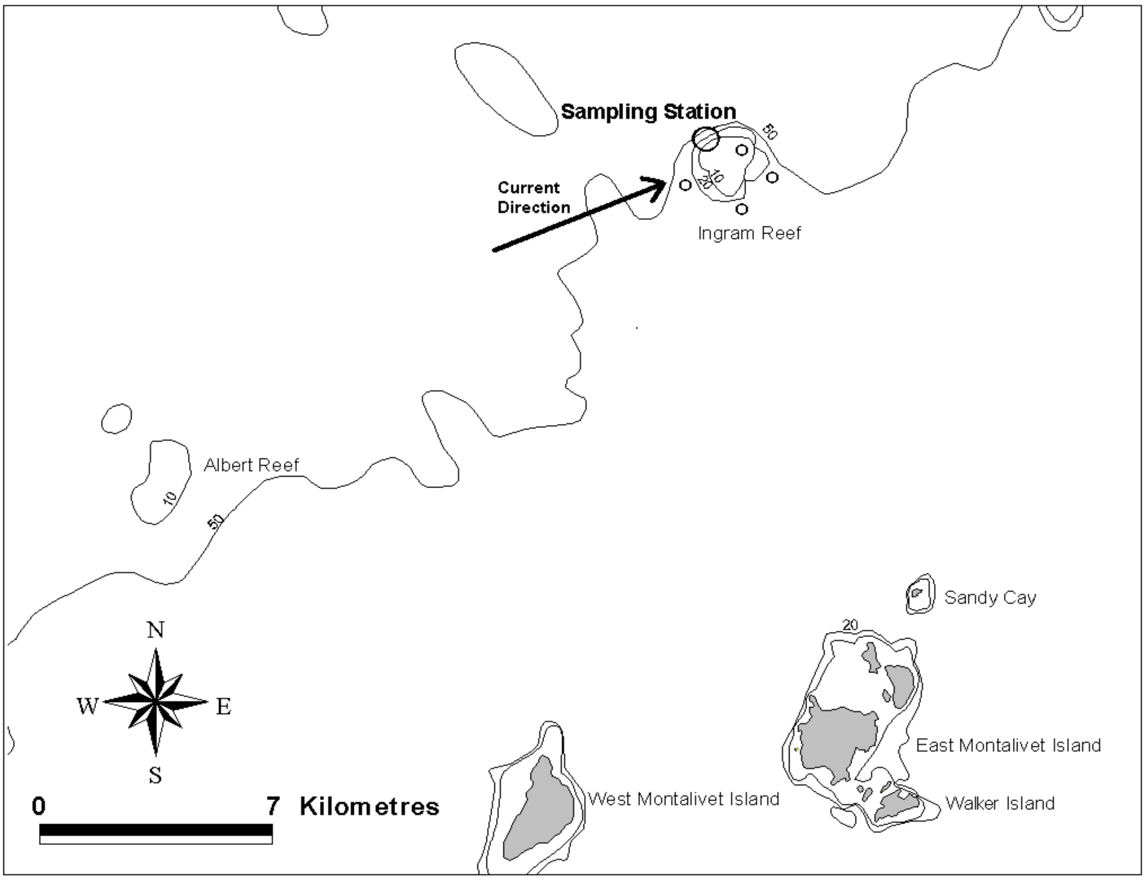


Figure 2.3 Location of DEPM sampling station (larger circle) and secondary sampling sites (small circles) in relation to spawning reef and direction of current at the start of sampling.

On each sampling occasion three tow methods (surface, oblique and vertical) were conducted with the CalVET net and the first two methods with the larger Bongo net.

Surface tows were deployed with the vessel moving ahead at approximately two knots such that the net sampled just below the surface without breaking the surface. The duration was either three or five minutes for the CalVET net and approximately three minutes for the Bongo net. With the oblique tows the rope was slowly released while the vessel moved ahead at approximately two knots so that the net sampled the water column on the way down and close to the bottom. The length of rope deployed was usually twice the depth. Once the required length of rope was released the vessel was stopped and the net retrieved at approximately one metre per second. Vertical net pulls were only done from the tender using the CalVET net. The boat was stationary and the net deployed vertically to within five metres of the bottom and subsequently pulled up, by hand, at a rate of approximately one metre per second. The duration of the retrieve was recorded and not the total deployment time as the net only sampled while being retrieved.

Plankton samples were preserved in 5% neutral buffered formalin. An attempt to grow out fish eggs in ten litre buckets with aerators was unsuccessful.

The female ovary samples were histologically processed and analysed using the methods given in Section 2.2.3 and Mackie and Lewis (2001). Preserved hydrated oocytes and their oil globules were also measured with an eyepiece micrometer under a dissecting microscope as reference sizes for *S. commerson* eggs in the preserved plankton samples.

Plankton samples were examined for fish eggs and larvae using a dissecting microscope. Eggs larger than 0.9 mm in diameter and larvae were sorted, counted and measured using an eyepiece micrometer. The presence of fish eggs smaller than 0.9 mm was also noted, although these are smaller than the literature sizes for *S. commerson* eggs (Munro 1942) and not used in analyses. Particular attention was paid to fish eggs between 0.9 to 1.2 mm diameter, as these were most likely to be *S. commerson* eggs. For each of these the presence and diameter of an oil globule was noted. The larvae were stored in 70% Ethanol while the eggs were stored in fresh 10% buffered formalin.

The volume of water sampled by each plankton net tow was calculated using the following equation.

$$Volume\,of\,Water\;(l) = 2\times\left(\frac{3.14\times(D)^2}{4}\right)\times\left(\frac{F\times Rotor\,Const}{999999}\right)\times1000$$

where

D = Net Mouth Diameter (0.3 m for the CalVET Net and 0.6 m for the Bongo Net)

F = Difference in flow meter counts (End of tow flowmeter reading – Start of tow reading)

Rotor Const.= 26873 (General Oceanics Flowmeter Operators Manual)

From the volume of water sampled the number of eggs and larvae per sample was converted to a density (number per 100,000 litres of water sampled). This figure was chosen as the Bongo net samples filtered between 30,000 to 90,000 litres of water and the CalVET net sampled only 3,000 to 30,000 litres, depending upon tow type

The data were subsequently examined to determine the temporal occurrence of fish eggs that could be those of *S. commerson*, other fish eggs with a diameter greater than 0.8 mm, and fish larvae. Differences in the densities of these groups between nets and tow types were also investigated.

3.0 The Western Australian mackerel fishery

M. Mackie

3.1 History of the commercial fishery

The narrow-barred Spanish mackerel, *Scomberomorus commerson*, is the largest and most abundant of the four *Scomberomorus* species found in the coastal waters of Western Australia. It is also the main target of the present day troll fishery, comprising about 80% of the total mackerel catch. As *S. commerson* is rarely caught by any of the other fishing methods used along the west coast, and because fishers are generally targeting this species when trolling, the history provided here of the WA mackerel fishery is virtually synonymous with the history of the troll-based capture of *S. commerson*. Of secondary importance in this fishery is the grey (or broad-barred) mackerel, *S. semifasciatus*, which may make up more than 80% of the remaining catch by the fishery. This species is mainly caught in the west coast region where it has become increasingly targeted in recent years. Although usually captured by jigging rather than by trolling, *S. semifasciatus* is generally only targeted by mackerel fishers and is considered a part of the troll-based mackerel catch. The remainder of the catch in this fishery includes various species caught in minor quantities (Table 3.1). The fishery also uses considerable numbers of smaller fish for bait (usually garfish and mullet). Because the gear and methods used in this fishery generally have little effect on the environment, the fishery is regarded as relatively benign.

S. commerson has no doubt been caught along the west Australian coast since long before European settlement, particularly in the north by visiting Indonesians and others. An early post-settlement reference to *S. commerson* is given by W. Saville-Kent, then Commissioner of Fisheries to the Western Australian Government, in an extract from the Western Australian Year Book, 1893-4. He noted the abundance of “giant mackerel of the genus *Cybium*” (a synonym for Spanish mackerel and wahoo) and various other high value fish species throughout the area of the tropical north west that had been investigated at that time. In 1929, F. Aldrich the Chief Inspector of Fisheries, mentioned the conspicuous presence of mackerel in waters north of Carnarvon, and noted that the barred-Spanish mackerel was a ‘fine edible variety’. However, fish resources northward of Shark Bay were virtually untouched at that time due mainly to a lack of facilities (Aldrich 1929).

One of the earliest catch reports was given in the ‘Report of the eighth annual conference of inspectors held at the Fisheries Department, Perth, on December 13, 14, and 15, 1950’. In this an Inspector Bowler noted that "the take of Spanish mackerel was only about 8, 000 pounds" in the Geraldton area. During the ninth annual conference held the following year, a Mr Bowler (presumably the Inspector) noted that 4, 630 pounds of Spanish mackerel were caught in the Geraldton area – much less than the 114 tons of snapper and 32 tons of dhufish. Clearly, even back then the seasonal appearance and fluctuating abundance made *S. commerson* an elusive target, and most fishers would have caught them opportunistically whilst targeting other species. This is still the case in the present day fishery, with few fishers exclusively targeting *S. commerson*, *S. semifasciatus* or other troll-caught species. Even for most of the dedicated mackerel fishers the fishery is only seasonal. As such the commercial 'WA mackerel fishery' has developed as a subsidiary of other fisheries along the coast.

Apart from the Geraldton data no mention of mackerel catches elsewhere in the state were given during the 1950 - 51 annual conferences of inspectors. Mackerel were obviously of minor importance at that time, as suggested by the fact that Roughley (1951), in the first edition of his comprehensive description of Australian fisheries, required more than three pages to describe the east coast mackerel fishery and just one sentence for that on the west coast: "In Western Australia the Spanish mackerel is found in considerable quantities north of Geraldton, but in that State it is not greatly favoured as a food-fish except when smoked; in that form it is considered to be unrivalled amongst Western Australian fish". Lack of facilities would have restricted catches at the time. The collection of catch data must also have been logistically difficult. From 1964 this data was tabulated by the Commonwealth Bureau of Census and Statistics before the responsibility was transferred to the Department of Fisheries in 1975 and maintained as the current catch and effort statistics (CAES) system. This database includes mackerel catches from its inception for all regions of the WA coast (see Section 3.2).

The history of the commercial mackerel fishery is marked by the activities of particular individuals. Interviews with some of these fishers or persons who knew them have been used to provide the following account of the development of the current day fishery. As previously noted, the commercial fishery originated in the Geraldton area and moved northwards as the coast was opened up. One of the pioneers of mackerel fishing in the Shark Bay area was Tony Standring, who operated out of Denham on the 30 foot, carvel hulled motor-sailer 'White Wings' from about 1965 to 1986. After that he moved to a 45 foot pearl lugger style vessel called 'Dampier' until retiring in 1990. In 1975 when Marshall Hipper commenced fishing the Shark Bay area there was only one other commercial fisher targeting mackerel (and snapper) besides he and Tony. Fishing trips were from 3 – 6 days and mackerel were trunked, cooled in a chiller and stored on ice. Product was sent to Perth via the fish processing factory in

Denham. During a typical fishing day they might troll for mackerel in the morning and afternoon and bottom fish for pink snapper (*Pagrus auratus*) during the day, depending on what was biting.

Trolling gear used in the west coast region has changed through time. Originally the main line was made of thick, braided, nylon sash-cord and 250 pound breaking strain wire trace, with either baited triple-ganged 10/0 - 12/0 hooks, spoons or jigs. Similar gear is still in use in the Kimberley region today. However, the troll rigs have become progressively lighter in the west coast region, with a switch in about 1980 to heavy (400 - 500 pound) monofilament main line and gunwhale mounted hand reels or game rods. There was a further change in the west coast region during the early 1990s, as fish became harder to catch, to lighter rod and reel outfits fitted with 40 – 80 pound line (although a combination of light and heavy lines are often used, including one line that is weighted with lead and sits deeper in the water).

The general nature of mackerel fishing has changed little through time in the Shark Bay and Geraldton area, with most of the catch still trunked and sold on the domestic market. The use of lighter lines and faster boats are the main differences. Electronic equipment has brought relatively minor increases in fishing efficiency in this region. Establishment of an export market by Ian Foster and the KAI Fish Factory in Carnarvon has seen a change to smaller (often trailerable), faster boats and short 1 – 2 day trips in the Carnarvon and Quobba areas. The catch is kept whole on ice and sent overseas via Perth (mainly to Taiwan). During the 1980s there were about 2-4 mackerel fishers in the Carnarvon area. The number of ‘full-time’ mackerel fishers (i.e. fishers that exclusively target mackerel when they are abundant on the coast) has fluctuated at a low level since this time, although a large catch of mackerel in this area is soon followed by an increase in the number of ‘part-timers’ on the mackerel grounds.

An early fishing pioneer involved with the opening up of fishing grounds north of Carnarvon was Finn Fossa, who began fishing for rock lobster around Geraldton in 1958 before switching to finfish in 1977 on the 45 foot fibreglass ‘Western Explorer’. Finn operated out of Denham in Shark Bay from January through to about June/July each year before moving to Onslow in the south Pilbara region, where he fished from about July through to November/December. Mackerel were trunked and frozen or brined whereas all demersal fish were gilled and gutted, during fishing trips that might last 3 days to 3 weeks (average around 10 days). Mackerel were sold as trunks and usually attained a higher price than most demersal species. In 1986 Finn bought the 50 foot plank-hulled ‘Santa Margherita’ and in 1987 started a combined demersal trap/mackerel operation out of Onslow. During the early 1980s fisheries in this area were small due to poor onshore facilities and limited focus on mackerel. Besides Finn, the only other fishers catching mackerel in quantity at this time were Geoff and Peter Lyon on the 'Icarus'. However, in the mid-1980s mackerel catches jumped in the Pilbara region as more fishers began targeting them. This reportedly coincided with (and was probably due to) increased abundances of *S. commerson* at that time.

The northward push by fishers had been preceded years before by Bill Miller, who made his way to the Pt Samson area in 1944 aboard the State Ship 'Koolinda'. Bill and his partner originally set up a freezer plant but dabbled in a range of jobs including kangaroo shooting and gold mining. Samson Fisheries was established in 1946 with Bill originally fishing from a 13 foot boat and supplying visiting ships and the locals. In the late 1950s a cyclone virtually wiped out the fishery, but Bill built a new processing plant in 1959 and had two boats fishing. *S. commerson* were sold on the Perth market, where they were a rare commodity at the time. Bill eventually bought the 60 foot motor sailer 'Collier', which had large freezer capacity and was used as a mothership for 5 – 6 small catch boats. Product was loaded onto a passing State Ship for sale in Perth. In the mid-1960s the 'Collier' was sunk in a cyclone, and Bill moved into prawn fishing in 1967. By then the processing facility was also handling the catch of other fishers that had become established in the area. Bill later bought a replacement for the 'Collier' and kept fishing until the early 1980s.

There are currently about 4 – 5 boats who target mackerel in the Pilbara region, including two that usually fish the Kimberley region. The most prominent present day fisher in this region is Hayden Webb, who commenced in the Point Samson area in 1989 before moving to Pt Hedland in 1992. He fishes with one crew onboard his fast 50 foot aluminium 'Serious Fun', targeting *S. commerson* during trips lasting 3 – 5 days. As Hayden generally fishes isolated reefs, electronic aids (particularly GPS) are crucial to his operation. Once caught the fish are trunked, cooled in brine and layered in ice at sea, before being transported on ice to Perth for sale on the domestic market. John Higgins, who has been commercially fishing in the Pt Samson area since the late 1980s also targets *S. commerson* throughout the year. His operation is similar to that of Hayden, although using a 28 foot aluminium boat he is more restricted in fishing area. Hayden and John are the only operators who target *S. commerson* throughout the year in WA waters.

During the 1980s there was also increased focus on mackerel fishing in the Kimberley region. In 1981 the Department of Fisheries chartered the 21.3 m steel hulled 'Rachel' and completed an exploratory research trip in the north west (mainly between Pt Hedland and Broome;

Donohue *et al.* 1982). This trip provided preliminary catch and biological information on *S. commerson*, and the owners of ‘Rachel’, Ian Lew and Pam Canney, subsequently commenced their present day mackerel fishing operation in this northern region.

However, whilst the Kimberley region may have been the last frontier for WA based fishers, it had already been visited at various times since the 1930s by Japanese, Russian, Chinese and Taiwanese fishers (Nowara and Newman 2001). Catch data for these foreign vessels is poor and they mostly operated in NT waters. The best data is for the Taiwanese fishers following declaration of the Australian Fishing Zone in 1979. Taiwanese pair trawlers were present in the north since 1972 but these targeted demersal species and caught few mackerel (Edwards 1983). However, they did at time target aggregations of squid – said by Kimberley fishers to be important prey to *S. commerson* – and therefore may have had an indirect effect on mackerel abundances. Taiwanese gillnet fishers arrived in about 1974 and mainly caught shark and tuna species, although they also took significant numbers of *S. commerson* and minor quantities of *S. queenslandicus* and *S. munroi*. In WA waters most gillnet catches were taken in the Cape Londonderry area to the west of Joseph Bonaparte Gulf. As in the present day fishery catches were strongly seasonal, with the best months from April to June. In the ‘western area’, which extended from north of Broome eastwards to the western tip of Bathurst Island in the NT, annual catches of between 5 and 80 tonnes (average approx. 50 t) of *S. commerson* were reported by the Taiwanese between 1980 and 1986 (Walter 1981, Millington and Walter 1981, Stevens and Davenport 1987).

In 1986 the Taiwanese gillnet operations ended due to prohibitive restrictions imposed on the length of their nets. Few Australian boats were targeting mackerel in the Kimberley region at the time. Nonetheless, the northern areas had been fished since at least the 1970s by NT based fishers, who spent about three months of the year catching mackerel in the area. They included Bert Hojetzki who started mackerel fishing in 1977 on a 58 foot ex-pearl lugger and is still fishing on the 62 foot home built ‘Sturmvogel’. These boats were few and rarely encountered each other whilst at sea. They generally remained in the north of the Kimberley region, although when the Darwin based ‘Rachel’ started fishing for mackerel it remained in the north of WA for long periods and ranged south into the Pilbara region.

Since 1996 the ‘Rachel’ has been based in Broome. Aside from this and the ‘Sturmvogel’, the present day mackerel fishery is dominated by three other boats - the ‘Olivia’, ‘Lazy River’ and ‘Candice’. The 20 m steel hulled ‘Olivia’, operated by Jeff and Tony Westerberg, began mackerel fishing from Broome in 1991 and fishes throughout the Kimberley region. The wooden hulled 50 foot ‘Lazy River’ and 60 foot steel-hulled ‘Candice’, both operated by Mark Ferris, are based in Darwin and only fish the northern area. Fishing operations of the main fishers in the Kimberley region differ from those in other regions, partly because of the large distance to many of the fishing grounds. This is the only region where dories are now permitted, and only by the five main boats because of their historic use of them (two dories are permitted for each except the ‘Rachel’ which has three). As such, the crews usually number about 4 – 5. The trips are generally between 1 – 4 weeks, and the fish are filleted, layered into cardboard boxes and frozen at sea for sale on the domestic market. GPS and other electronic aids are essential in this region for finding the main reefs on which mackerel are found. Heavy sash cord main lines are still used by the main boats in this region, with perhaps the only change in gear being a shift from mostly jigs, spoons and lures towards triple ganged hooks baited with garfish. The main boats troll up to seven lines whereas each dory will fish 2 – 3 lines. Each of these main boats therefore has considerably greater fishing power but also greater running costs than mackerel boats in other regions.

The WA mackerel fishery is thus unique in the fishing methods used and the vast area over which it extends. Although small by world standards, with 390 t of *S. commerson* and 56 t of ‘other’ mackerel captured in 2001, it has a combined value of about $2.5 million to the fishers and is important to the state. This is particularly so given the high value placed on mackerel (especially *S. commerson*) by recreational anglers (see Section 3.3). Current regulations on *S. commerson* include a minimum legal size of 90 cm total length and a recreational bag limit of four fish per angler per day. The commercial fishery is currently open-access, and therefore any fisher with a WA wetline license can catch mackerel. However, following extensive liaison between the Department of Fisheries and industry members the fishery is likely to come under formal management in 2004. This management will probably be based on a total allowable commercial catch within each region, and only those boats with sufficient historic catches prior to a benchmark date (3rd November 1997) will be permitted access. The amount of quota apportioned to these boats will be determined from their historic catch as a proportion of total catch in each region, although only those with a minimum holding will actually be able to fish.

Table 3.1 List of species caught in the commercial Western Australian troll-based mackerel fishery. Data obtained from the CAES system, commercial fishers and onboard observation of catch by research staff. Percentages of catch are approximate because many species are lumped together or cannot be identified as troll caught in the CAES system.

Species	Common name	% of catch
Scomberomorus commerson	narrow-barred Spanish mackerel	> 80
S. semifasciatus	grey or broad-barred	> 5
S. munroi	Australian spotted mackerel	< 1
S. queenslandicus	Queensland school mackerel	< 1
Grammatorcynus bicarinatus	shark mackerel	< 1
Acanthocybium solandri	wahoo	<1
Rachycentron canadus	cobia	<1
Scomberoides spp.	queenfish	<1
F. Carangidae	trevally (various species)	<1
Sphyraena spp.	pike / barracuda	<1
various	tuna (e.g. blue, yellowfin, mackerel)	<1
various	sharks (various species)	<1
various	billfish	<1
various	demersal reef species (e.g. coral trout, spangled emperor)	<1
various	other pelagic species (e.g. rainbow runner, dolphin fish)	<1

3.2 Catch and effort by the commercial fishery

Validation of CAES database conversion equations

Along the WA coast mackerel are landed either whole, trunked (headed and gutted) or filleted. Conversion equations are therefore required to convert these landed weights to a standard whole (live) weight. Prior to the present study, the weight conversion equations used in the CAES system to convert landed to live weights were based on fish with a 'snapper'-type body shape:

Whole weight (kg) = 3 x fillet weight
Whole weight (kg) = 1.25 x trunk weight
Whole weight (kg) = 1.08 x gilled/gutted weight

However, the amount of flesh obtained from fish with this shape is lower than that obtained from mackerel, particularly when the fish are filleted. Thus, in recent years the old conversion equations have over-estimated live weight by 50 – 80% in the Kimberley region (Figure 3.1). Consequently the value of the fishery has also been considerably over-estimated. Similarly, catches have previously been over-estimated by about 10 –20% in the Pilbara region where most of the catch is trunked. In contrast there is little difference between whole weight estimated from the old and new conversion equations in the west coast region where much of the catch is exported whole. The new conversion equations developed for *S. commerson*:

with non-zero intercept (weights in kg):

Whole weight = -0.06 + (fillet weight x 1.62)
($n = 241$; $r^2 = 0.9834$)

Whole weight = -0.21 + (head/gutted weight x 1.20)
($n = 91$; $r^2 = 0.9959$)

Whole weight = -0.08 + (gutted/gilled weight x 1.05)
($n = 202$; $r^2 = 0.999$)

forced through zero (as required for the CAES system; weights in kg):

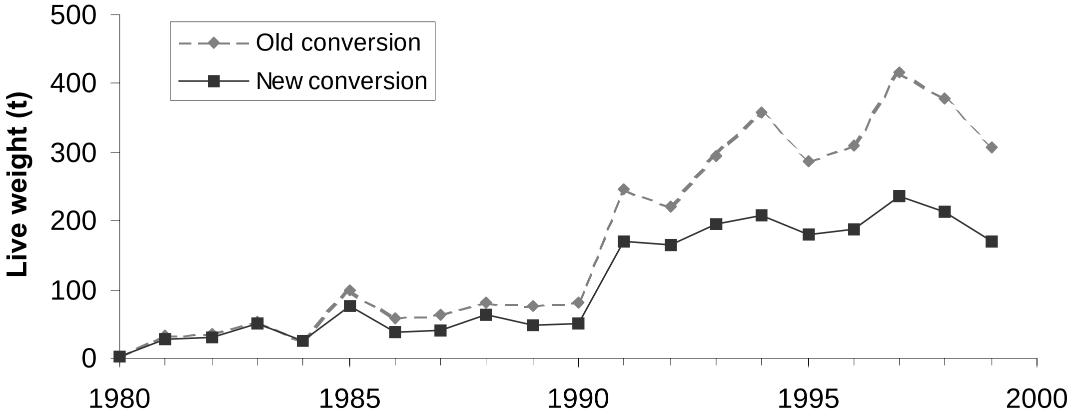
Whole weight = fillet weight x 1.608
Whole weight = head/gutted weight x 1.176
Whole weight = gutted/gilled weight x 1.048

These latter conversion equations are now used for all mackerel species in the CAES database.

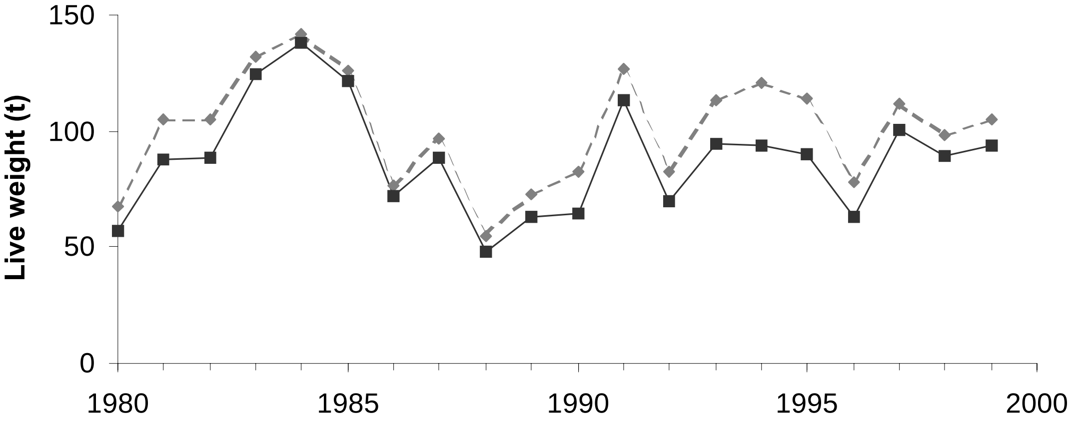
Appraisal of the WA Department of Fisheries CAES database.

The catch and effort database for the commercial mackerel fishery has limitations that affect reliability of the data. These arise from the nature of the fishery and the lack of detail allowed for by the current monthly catch returns system:

a) Kimberley



b) Pilbara



c) west coast

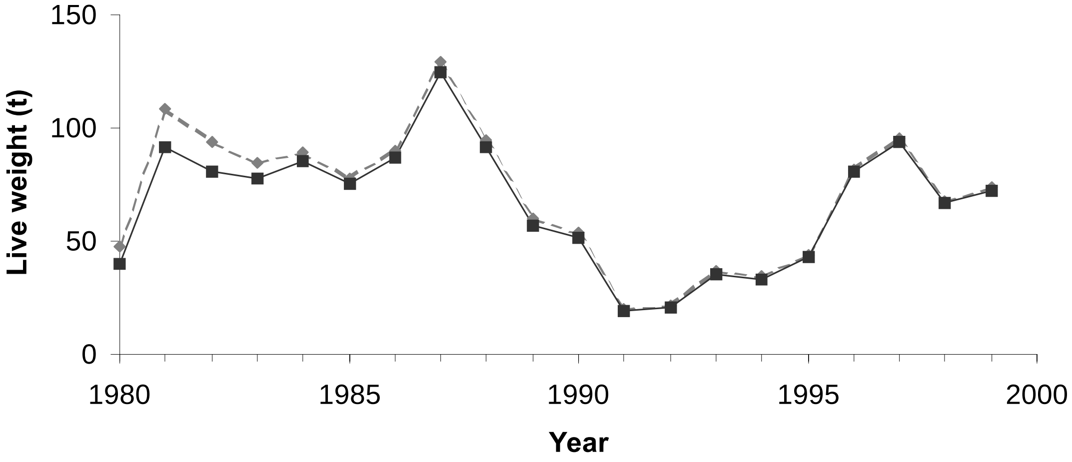


Figure 3.1 Estimates of the annual *S. commerson* landed live weight (t) obtained from the old and new weight conversions for a) the Kimberley region, b) the Pilbara region, and c) the west coast region.

- Many fishers who catch mackerel do so only on a part-time basis. The effort that these fishers spend on catching mackerel is therefore often combined with the effort used in catching other target species (by varying and undeterminable amounts). Usually these types of effort are different. For instance, a demersal snapper-fisher catching a few mackerel whilst trolling between snapper fishing grounds.
- Many returns are only marked as ‘mackerel’, which may contain an unknown percentage of *S. commerson* as well as other mackerel species.
- Returns may indicate that multiple fishing methods were used. If only mackerel were caught during that time then only trolling was recorded in the database. However, some records in the past may have included all fishing methods, with the mackerel catch split between them.
- Use of hours fished or number of hooks used per day are often not a reliable estimate of fishing effort since the monthly returns often do not explicitly detail these values.
- Returns may record more than one type of fishing method and species capture, but will only provide one figure for days fished. It is therefore unclear whether the days fished should be divided between fishing methods or whether the whole figure should be applied to all fishing methods.

Validation and standardisation of the commercial effort data

Just as the issues raised above with the CAES database mainly affect effort data, there are also characteristics of the fishery itself that affect the spatial and temporal compatibility of effort data. For instance:

- Improvements to fishing gear have occurred through the years. These include changes to the type of lines, particularly in southern regions of the fishery.
- Introduction of navigation aids such as Global Positioning Systems (GPS) and plotters, and improvements to echo sounders.
- Changes in boats, particularly in the west coast region where small, fast, trailerable boats are used by the main fishers in various areas.
- fishing methods and gear vary spatially along the WA coast. The coast is therefore divided into three regions that reflect these spatial variations (Kimberley, Pilbara and

west coast). These regions are also used in other analyses because of the wide range over which Spanish mackerel are captured along the coast:

Kimberley region: The use of dories (5-6.5 m dinghies) is restricted to this region, which extends east of longitude 121ºE (previously 120ºE) to the NT border. Dories troll two to three lines and work to a mother boat that is about 20 m in length. Fishing gear used in this sector is relatively heavy (8-10 mm rope with a 200+ kg mono line and wire trace), crews number between three and five, and fishing trips generally last between one and three weeks. Mackerel captured in this sector are usually filleted, boxed and frozen aboard the mothership.

Pilbara region: This sector extends from longitude 114ºE to 121ºE and north of 23ºS. Vessels used in this area are between 9 and 15 m in length (no dories), with one to two crew using 180 kg mono line and wire trace. In recent years the main catches from this sector have come from the Port Hedland area. Fishing trips usually last less than a week, and the product is trunked, brined, and sold locally or sent to Perth markets.

West coast region: This sector extended south of 23º S, and included the Gascoyne region (27° to 23° S) and the west coast region (south of 27ºS). Vessels used in these regions are between 7 and 15 m in length (no dories) and are crewed by one to two persons for trips lasting one to five days. Gear used is rod and reel with 20-30 kg line and wire trace. Fish caught by Carnarvon and Quobba based fishers are usually kept whole in brine for export, whilst fish landed at other ports are usually trunked and sold locally or sent to Perth markets. Few commercial catches are made south of Geraldton.

Data for these regions are separated for reporting of catches but may be combined in other analyses because of sample sizes. To allow for other temporal and spatial changes in fishing effort, the effort data for vessels known to target *S. commerson* was weighted according to the criteria given below (n = 22). Although not the most accurate unit of effort, 'successful fishing days' was considered the most reliable unit and hence used in analyses. This data extends back to 1979, although few boats were present in the earlier years, particularly in the Kimberley region where only one of the selected vessels was fishing through most of the 1980s (Table 3.2). The criteria used to weight the data of vessels known to target *S. commerson* included:

- Introduction of dories (Kimberley region only): Only the main mackerel fishers in the Kimberley region are permitted to use dories (dinghies) as well as the mothership to catch mackerel. Although there are likely to be differences in the fishing power of these dories from different motherships (e.g. not all have sounders), a general increase in effort of 25% per dory is considered a reasonable estimate. This represents a total increase of 50% in effort for the main fishers who use two dories. Although one vessel uses 3 dories, its estimated effort increase was also capped at 50%. Discussion with fishers were used to assist with this process of weighting effort appropriately.

- Fisher experience: To allow for the increase in the fishing skills of a fisher, the first, second and third year of operation were considered to be 70, 80, and 90%, respectively, of the 'peak' skill level that was attained during the fourth year of operation within a particular area (assuming the same skipper remains on the vessel, which was generally the case for the vessels used in analyses, or if a new skipper was involved it was in partnership with the previous skipper). Note that weighting for these first two criteria were applied to the individual vessel's data prior to pooling whereas weighting for the following criteria occurred after pooling.
- Use of faster, trailerable boats in the west coast region: This occurred in about 1995, and increased efficiency by approximately 5% as it reduced the time taken to move between locations.
- Introduction of Global Positioning System (GPS) and plotters: This is likely to have made the fishers in the Pilbara and Kimberley regions approximately 50% more efficient, as it enables them to locate offshore lumps and fish them more efficiently. This equipment was introduced in about 1986, with increases to nominal effort introduced from this date in a stepwise manner to reflect improvements to the system and operator skills. (1986 – 1989: 20% increase; 1990 – 1993: 40% increase; 1994 onwards: 50% increase). This equipment has been less important to fishing operations in the west coast region where fishing has mainly occurred along well defined fringing reefs. However, since about 1997 GPS has become more utilised as the fishers target offshore lumps. Consequently, an increase to nominal effort of 5% is applied from 1990 to 1996, and of 25% from 1997 onwards.

In addition to effort weighting to reflect changes in real fishing effort, a change in catchability (q) was used in biomass dynamics modelling to allow for changes from heavy to light fishing gear in the west coast and Pilbara regions (Section 7.1.1.). Although the time taken to retrieve hooked fish is increased with the light gear, it improved the ability of fishers to catch fish when they are off-the-bite and reduces the risk of gear breakage with bigger fish. In the west coast region the fishers changed from the heavy, hand-retrieved sash cord (that is still in use in the Kimberley region), to a combination of sash cords and game rods in about 1980.

Eventually, in about 1992, the fishers stopped using the sash cords. Therefore, there has been an apparent increase in catchability of about 40% between 1980 and 1992, with a decline in this catchability to about 25% after 1992 because the sash cords were not replaced with an equivalent number of rods. Changes to q in the Pilbara region are considered to be similar.

Note also that catchability of Spanish mackerel may also vary in response to a number of environmental and biological factors, including time of moon (and associated tidal strength, particularly in the Pilbara and Kimberley regions), current, time of day and year, water turbidity and temperature, wind strength, presence of sharks and reproductive condition. However, until more is understood about the link between catchability and these parameters they have not been considered in the modelling.

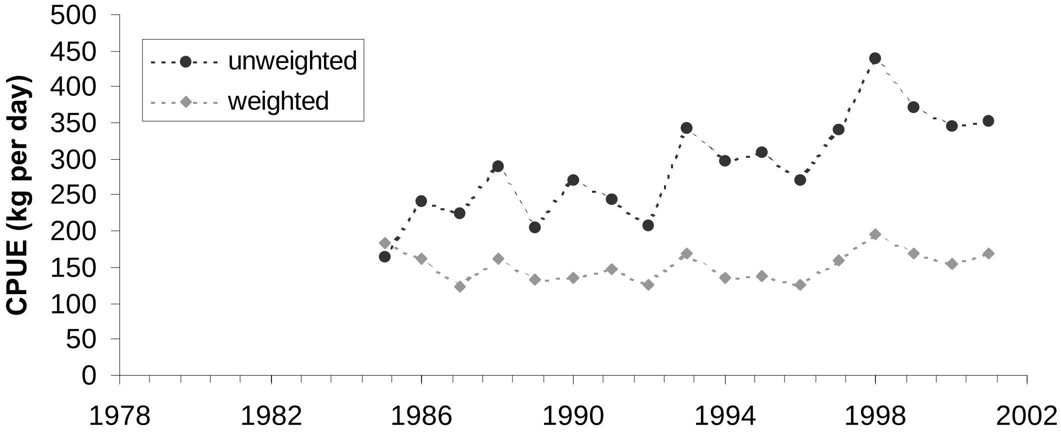
Table 3.2 The number of vessels that were used in analyses of *S. commerson* catch rates between 1979 and 2000. Kim; Kimberley region, Pilb; Pilbara region. WC; west coast region.

Year	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00
Kim	0	0	0	0	0	0	1	1	1	1	3	3	5	7	5	6	5	5	5	4	6	4
Pilb	0	2	1	2	2	4	3	3	3	3	5	6	6	6	5	7	8	6	8	8	7	7
WC	4	2	3	3	3	5	5	4	4	4	6	5	5	4	6	5	6	6	7	8	6	8

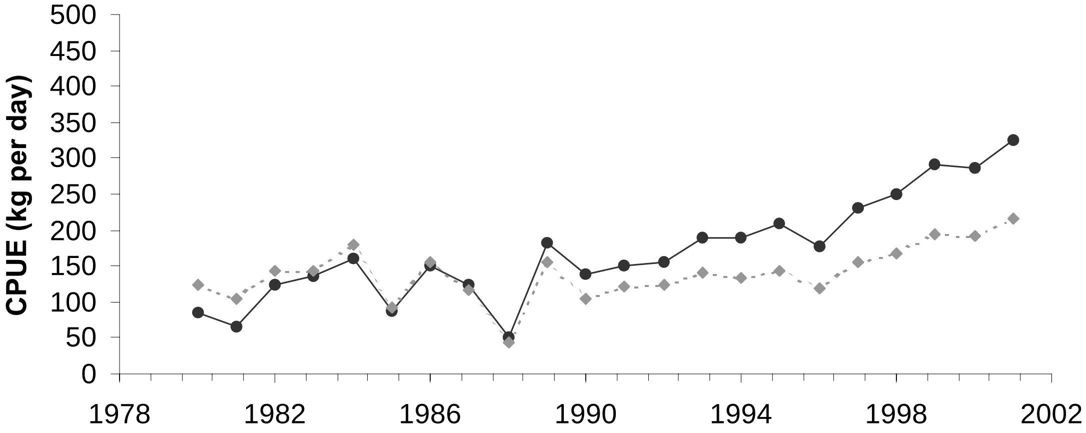
Trends in the catch and effort data

Standardisation of the effort data to allow for changes in efficiency and fishing power produced significant changes to estimated catch rates through time in the Kimberley region (Figure 3.2a). Such changes highlight the misleading information that may be obtained from data that has not been validated by research projects such as the present one. The weighted Kimberley data indicate that catch rates have remained within 124 and 196 kg/day (mean 151kg/day) with only a slight increasing trend. Data for the Pilbara region show a similar pattern in catch rates for weighted and unweighted data up to 1988, ending a period of considerable variation in catch rates during the 1980s (Figure 3.2b). Weighted catch rates have increased slowly since 1990, peaking at 195 kg/day in 2001. Weighted and unweighted data for the west coast region have remained similar through time (Figure 3.2c). The pattern in this data suggests cycles of peaks and troughs in catch rates rather than increasing trends as in the other regions.

a) Kimberley region



b) Pilbara region



c) West Coast region

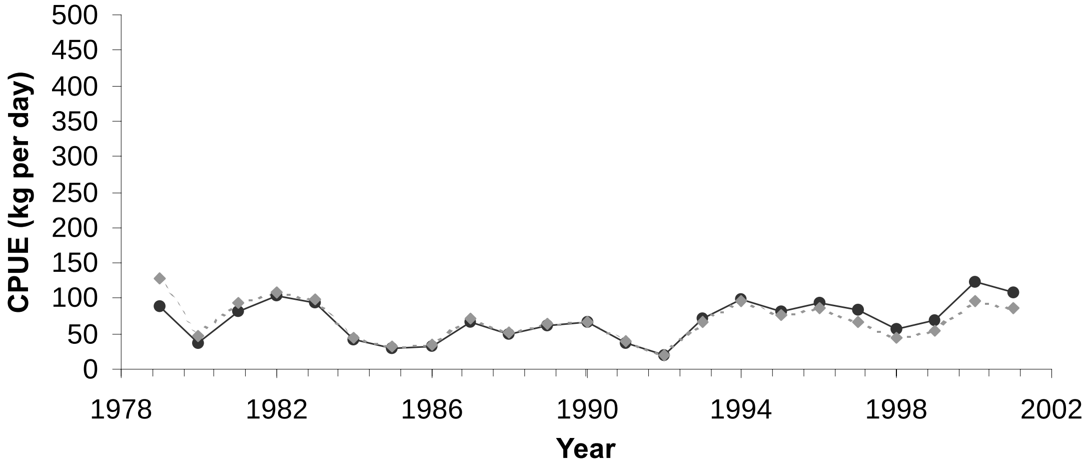


Figure 3.2 Catch per unit effort for *S. commerson* from a) the Kimberley region, b) the Pilbara region, and c) the west coast region, based on catch returns of the main boats.

3.3 The recreational fishery

Because of its fighting and eating qualities *S. commerson* is a popular target of recreational fishers. Light rod/reel outfits and small boats are typically used, generally in combination with trolled lures or drifted baits. Shore-based fishing for mackerel is also popular at Steep Point (Shark Bay) and the rock platforms of Quobba station north of Carnarvon. A drifted bait may be kept near the surface using balloons tied to the main line. Balloons (often gas filled) are also used by shore-based anglers to carry the line out to sea. *S. commerson* are also targeted by spear fishers, with a new state spear fishing record of 39.5 kg recently speared near Exmouth.

Most recreational catches are taken between Perth and Dampier, with distance and isolation limiting recreational fishing in the north where most of the commercial catch is taken. Recreational catches may vary considerably from year to year, particularly in the southern areas at the limit of *S. commerson's* distribution. For instance, during the summer of 1979-80 there were large schools of *S. commerson* in close to the Perth metropolitan beaches (Craig Redman, *pers. comm.*). This is a rare phenomenon at this latitude (32° S), although around this time Barry Paxman, who has been spear fishing mackerel for almost 40 years, also remembers seeing schools of thousands of *S. commerson* west of Rottnest Island. There have been lesser peaks in the abundance of *S. commerson* in the south since that time, such as during the summer of 1988-89, and early in both 2000 and 2001 when fish were caught as far south as Albany. These recent peaks in abundance followed the appearance in the previous year of large numbers of undersized fish in the Gascoyne and Pilbara regions, suggesting a link between good recruitment and subsequent higher abundances/extended distribution of *S. commerson*.

There is little data on actual catches of *S. commerson* and other mackerel species by recreational fishers. Surveys were conducted from Augusta to Kalbarri during 1996-97 (Sumner and Williamson 1999), from False Entrance (Shark Bay) to Exmouth Gulf during 1998-99 (Sumner *et al.* 2002), and in the Pilbara region during 1999-2000 (Williamson *et al. in prep.*). As in the commercial fishery, *S. commerson* was the most commonly caught mackerel species (Table 3.3). Notably, recreational anglers caught few *S. semifasciatus*. These surveys also show that the number of *S. commerson* lost to sharks whilst being landed were about 7 and 15% of the total recreational catch in the Gascoyne and Pilbara regions, respectively. With these shark losses included (commercial fishers lose relatively few fish to sharks), the catch by recreational fishers was 81% and 12% of the commercial catch of *S.*

commerson and ‘other’ mackerel species, respectively, south of Shark Bay during 1996-97 (Mackie 2001). Similarly, recreational fishers caught 81% and 33% of the commercial catch of *S. commerson* and ‘other’ mackerel species, respectively, between Shark Bay and Exmouth Gulf during the 1998-99 survey. Further north, the 1999-2000 Pilbara survey indicated that recreational fishers caught 20% and 59% of the commercial catch of *S. commerson* and ‘other’ mackerel species, respectively between Onslow and Pt Hedland.

Thus, recreational anglers took 45% and 16% of the total *S. commerson* catch during the surveys in the west coast area south of Exmouth Gulf and in the Pilbara region, respectively (40% and 20%, respectively, of the total catch of all mackerel species combined; Mackie 2002). Reported catches of Spanish mackerel by recreational charter vessels have been relatively minor since 1990, ranging between 0.8 and 3.1 tonnes per year (mean = 1.8 tonnes), with 0.9 tonnes recorded during 2001. Most (80-100%) of the charter catch was taken in the Gascoyne and Pilbara regions. These regions in particular are likely to experience increased population growth and hence greater recreational fishing pressure on mackerel stocks. Management of fishing activities by all sectors is therefore essential, and has been recognised in the launch of the Integrated Fisheries Management Strategy by the Department of Fisheries in 2000. The goal of this strategy is equitable and ecologically sustainable division of WA’s coastal fish resources among all user groups.

Table 3.3 The number of mackerel estimated to have been caught by recreational fishers during Department of Fisheries surveys in three regions of WA (Sumner and Williamson 1999, Sumner *et al.* 2002, Williamson *et al. in prep.*). Estimated weight of the catch are also shown in brackets. Note that the catch information for the Pilbara region is preliminary, includes data for catches taken in the Broome area, and does not include data for shore-based fishers and boats launched from the beaches (this additional catch is likely to be minor though). Data for catches from charter vessels were not included in the surveys. S. Bay; Shark Bay.

Region	***S. commerson***	***S. munroi***	***S. queenslandicus***	***S. semifasciatus***	***Grammatorcynus bicarinatus***
Augusta to Kalbarri	2,025 (13 tonnes)	326	0	0	0
S.Bay to Exmouth	7,557 (47 tonnes)	664	1,947 (4 tonnes)	0	1,852 (4 tonnes)
Pilbara	3,342 (21 tonnes)	6,653	2,004 (4 tonnes)	306	183
TOTAL	81 tonnes		8 tonnes		4 tonnes

4.0 Reproduction

M. Mackie and P. Lewis

4.1 Results

The gonads of 5128 male, female and juvenile *S. commerson* were macroscopically staged during this study (Table 4.1). Of these, 1624 were processed using histological techniques for more detailed examination, with the focus on ovaries (84% of histological samples) for description of reproductive biology.

4.1.1 Morphometrics

Lengths of *S. commerson* directly measured in this study ranged from 58 to 1720 mm fork length (62 to 1840 mm total length), and whole weights from 1.51g to 40.6 kg (Table 4.2). Maximum fork length estimated from head lengths of the head-and-gut only samples was 1584 mm (based on conversions given below).

Whole weight – fork length relationship

The non-linear relationship between WW and FL indicated differences in the sex-region interaction (Table 4.3), due mainly to differences between regions rather than sex (Tables 4.4 and 4.5). Regressions for WW and FL within each region (data for sex pooled) are, therefore:

Kimberley: WW (kg) = 7.15e-9 x FL (mm)$^{3.01}$ (n = 2003)
Pilbara: WW (kg) = 1.71e-9 x FL (mm) $^{3.22}$ (n = 420)
West Coast: WW (kg) = 2.40e-9 x FL (mm)$^{3.17}$ (n = 129)

There was considerable variation between fish weight and length due in part to measurement error since weight can be difficult to measure accurately at sea (Figure 4.1). It is also likely to reflect seasonal variations in fish condition, since fish caught at the start of the season are sometimes noticeably light for their length. This variability is likely to override any benefits of having separate regressions for each region. Therefore, a general equation that includes data for all mackerel, including males, females and juveniles for conversion of FL to WW is appropriate:

Pooled: WW (kg) = 3.40e-9 x FL (mm)$^{3.12}$ (n = 2842)

(SE of constants: a = 2.78e-10, b = 0.01).

Total length – fork length relationship

There were also significant differences between sex and region in the TL – FL relationship, due mainly to regional differences (Tables 4.6 and 4.7, Figure 4.2). Regressions for TL and FL within each region (data for each sex pooled) are, therefore:

Kimberley: TL (mm) = 41.62 + (1.06 x FL (mm)) (n = 1091)
Pilbara: TL (mm) = 34.82 + (1.06 x FL (mm)) (n = 482)
West Coast: TL (mm) = 38.68 + (1.06 x FL (mm)) (n = 106)
(multiple $r^2 = 0.9955$).

Despite the statistically different TL-FL relationships between regions, the differences in intercept for the above regressions are minor compared to measurement error (< 7 mm versus > 2 cm for TL measurements). Differences in sample sizes may also have influenced the analyses. Therefore, for practical purposes all data for sex and region are pooled together to provide one regression for conversion of FL to TL:

Pooled: TL (mm) = 42.74 + (1.06 x FL (mm)) (n = 1679, $r^2 = 0.996$)

Fork length estimators

Refer to Figure 4.3 for regressions between HL – FL and JL – FL (data pooled by sex and region). The Box-Cox likelihood profile indicated that only a mild transformation of the data was necessary (lambda = 0.8). However, as the transformation did little to stabilise the slightly heterogeneous variance of the data, and to keep the regressions simple, the data were not transformed for analyses. The simplest model that incorporated both HL and JL to predict FL, by sex and region, accounted for 97% of the variation in the data. This model was complex as it comprised thirteen terms (including polynomial terms), with significant higher order interactions in terms combining the effects of region (data not shown). Further, this model required measurement of both jaw and head lengths. Examination of the relationship between FL and each predictor variable (HL and JL) separately, was made to determine if these simpler models provided an adequate estimation of FL with minimal loss in predictive power.

- *Head length – fork length relationship*

ANOVA indicated significant differences between region and sex but not in the interaction of these effects in the fully parameterised model (Appendix 4, Table A4.1). Using the AIC and *F*-test to drop terms that did not add significantly to the model, this was reduced to a four term model explaining 97% of the variability in FL:

Kimberley (n = 1234): $FL = -205.3115 + (7.5891*HL) - 0.008*(HL^2)$

Pilbara (n = 921): $FL = (-205.3115 - 8.9923) + (7.5891*HL) - (0.008 + 0.0003)*(HL^2)$

Gascoyne (n = 183): $FL = (-205.3115 - 29.7759) + (7.5891 *HL) - (0.008 + 0.0009)*(HL^2)$

South (n = 115): $FL = (-205.3115 - 13.1197) + (7.5891*HL) - (0.008 + 0.0011)*(HL^2)$

Where FL = fork length (mm) and HL = head length (mm). Refer to Appendix 4, Table A4.2 for the FL ± SE predicted from each value of HL.

- *Upper jaw length – fork length relationship*

Results of the ANOVA testing the JL – FL relationship were similar to that for the HL – FL relationship (Appendix 4, Table A4.3). The full model was subsequently reduced to a four term model that explained 95% of the variability in FL:

Kimberley (n = 2922): $FL = -204.8015 + 13.115*(JL) - 0.0249*(JL^2)$

Pilbara (n = 958): $FL = (-204.8015 - 13.7751) + (13.115 *JL) - (0.0249 + 0.0012)*(JL^2)$

Gascoyne (n = 185): $FL = (-204.8015 - 43.3212) + (13.115 *JL) - (0.0249 + 0.0034)*(JL^2)$

South (n = 115): $FL = (-204.8015 - 16.6423) + (13.115 *JL) - (0.0249 + 0.0036)*(JL^2)$

Where FL = fork length (mm), and JL = jaw length (mm). Refer to Appendix 4, Table A4.4 for the FL ± SE predicted from each value of JL.

The accuracy of these regression models in estimating FL was tested by comparing the model estimate with the actual measurement for each fish (Figure 4.4). These graphs show that the HL based equation is slightly better than that based on JL, probably because HL is less influenced by individual variation in the shape and protrusion of the jaw. It is also generally easier to measure, although to do this properly the head should firstly be removed from the trunk (this is relatively easy to do; refer to Lewis and Mackie 2002). Further, most samples obtained from fishers comprise only the head and gut anyway. Figure 4.4 also shows that the model for fish in the Kimberley region is very good throughout the range of data, whereas that for the Pilbara region is good up to about 1400 mm FL and that for the west coast region is good up to about 1100 mm FL. It also shows that the model for the Kimberley region does in fact give a better estimate of FL for fish in the other regions also, and therefore this model should be used throughout WA.

4.1.2 Sex ratios

Overall sex ratios in each region were biased towards females, generally by 5 – 10% in the monthly samples with only a few samples containing more males than females (Table 4.8, Figure 4.5). This bias was increased when only fish larger than the legal minimum size limit (900 mm TL) were considered, with the percentage of female within the Kimberley, Pilbara and west coast regions being 55.1 (n = 2757), 57.0 (n = 742) and 63.8% (n = 265), respectively (overall percentage females was 56.1).

Female bias in samples were greatest during a trip to the Kimberley region in June 2000 when 570 females and 216 males were captured (sex ratio of 1M:2.6 F). At this time the fish were non-reproductive (gonad stages F2 and 3), although another trip to the same location in the following month (gonad stages F2 and 3), provided 134 females and 101 males (1M:1.3F). In contrast, sex ratios of *S. commerson* captured during the peak spawning period in the north Kimberley region during 1999 were generally only slightly biased towards males (1.1M:1F, n = 588), but with considerable daily variation either way. This pattern was mirrored in another trip to the same area at the same time of year in 2000 (male bias of 1.2%, n = 701; Figure 4.6), again with considerable inter- and intra-daily (a.m. and p.m.) variation. Sex ratios in the Kimberley region during 1999 and 2000 also varied according to the lunar cycle, with relatively more males captured over the first quarter and full moon periods, and approximately equal numbers over the new moon and last quarter periods (Table 4.9).

Breakdown of sex ratios by size class show a change over from male to female bias as size class increases (at least in those size classes in which samples number > 30; Figure 4.7). This change over was steeper in the Kimberley region, particularly after 850 mm FL where the proportion of females increased by about 10% per 50 mm, with 1:1 ratio at about 1000 mm, and all females at lengths greater than 1300 mm FL. In the Pilbara the changeover was shallower, with about 6% more females per 50 mm between 850 and 1400 mm FL, a 1:1 ratio at about 1000 – 1050 mm, and all females after 1450 mm FL. There was no apparent pattern for the West Coast region where samples per size class were small.

4.1.3 Reproductive biology

Description of gonad

The gonads of male and female *S. commerson* are bi-lobed, elongate organs, joined posteriorly to form a short gonoduct leading to the urogenital pore (e.g. Plate 10, Mackie and Lewis 2001). The germ tissue is bound by a muscular wall and tunica, and suspended from the dorsal posterior wall of the body cavity by mesenteries. In ovaries, oocytes develop within lamellae that are attached to the gonad wall (e.g. Plate 2, Mackie and Lewis 2001). The central region of these lamellae is comprised of muscular and vascular tissue. Yellow brown bodies if present are usually associated with the central region, with oocytes developing and maturing in the peripheral stroma. Development of oocytes occurs at a similar rate throughout the ovary (Mackie and Lewis 2001). Ovulated eggs are shed into a lumen extending the length of the ovary, and during spawning are released into the ocean via the gonoduct, to be fertilised externally.

Within the testis, sperm develop in crypts and are released into efferent (peripheral) sperm sinuses that open into a muscular central sperm sinus (Figure 4.8). From there, the sperm are released into the gonoduct during spawning. At the onset of reproductive activity the sperm tissue undergoes rapid maturation through to the spermatozoa stage of development, even whilst the amount of sperm tissue is still low and the gonad is dominated by vascular and connective tissue.

Gonad weight

Weight of ovaries in the samples ranged from 2.00 to 1908.30 g, whereas testes ranged from 0.84 to 840.10 g. Ovary weight of mature, non-reproductive (F2) females were between 0.4 and 1.1% of clean (viscera and gonad removed) body weight (mean 0.7% ± 0.03 SE, n = 45). In contrast, testis weight of mature, non-reproductive (M2) males ranged from 0.1 to 0.7% of clean body weight (mean 0.3% ± 0.01 SE, n = 49). For reproductively developed females (F4 –5), ovary weight ranged from 0.5 to 7.7% of clean body weight (mean 3.1% ± 0.20 SE, n = 70), whereas testis weight of reproductively developed males (M3-4) were between 0.1 and 4.8% of clean body weight (mean 1.0% ± 0.14 SE, n = 58). Note the small sample sizes relative to overall sample sizes are due to the difficulty in obtaining clean weight of mackerel. The data show substantial variation in the relative weight of reproductively developed gonads.

Ontogenetic development and size at sexual maturity

Data given here is based on histologically analysed samples, with data from macroscopic staging included where appropriate. Refer to Figures 4.9 and 4.10 for the length range of fish within each stage of ovarian and testicular development. Disregarding two abnormally large juveniles (1170 and 1251 mm FL) in which the gonads have remained tiny and undifferentiated, there was minimal overlap between the lengths of juveniles and immature females. The largest juvenile *S. commerson* was 563 mm FL (1.6 kg whole weight), whereas the smallest individual in which gametes could be identified in the rudimentary gonad was a male of 301 mm FL (0.3 kg whole weight), and the smallest female was 396 mm FL (0.6 kg whole weight). At this early stage of gonad differentiation the gonad was rudimentary in structure and comprised of a tiny, hollow tube with a thin tunica. Lamellae, sinuses and other features of the developed gonad were tiny or not present, with only a few small, isolated crypts of spermatocytes and occasionally spermatozoa (if male), or oogonia, chromatin nucleolus and peri-nucleolus stage oocytes (if female) embedded in the tissue lining the lumen.

Lengths of immature females overlapped substantially with the lengths of mature females in the histological samples. The first sign of ovarian reproductive development, as indicated by the presence of cortical alveoli stage oocytes, was observed in an immature female (F1a) of 666 mm FL (2.4 kg). These immature – developing females ranged up to 1157 mm FL, or 11.4 kg (mean 938 ± 8.3 SE, n = 122), whereas the largest immature (F1) female was 1195 mm FL (13.8 kg). The smallest mature female was 641 mm FL (2.3 kg; stage F4), and the smallest (macroscopically staged) spawning (F5) female was 825 mm FL (4.8 kg).

Size at sexual maturity should ideally be determined for fish captured during the reproductive period when it is easier to distinguish immature from mature gonads. However, this was too constrictive in terms of sample sizes, particularly of immature fish. Estimates of the size at 50% maturity of females were therefore calculated using all available data as well as data only taken during the reproductive season (October to April), with data for each area pooled to provide sufficient samples (virtually all immature samples were obtained from the Pilbara region). Both data sets provided similar estimates; 809 mm FL, ± 9.8 SE (898 mm TL) for all data and 788 mm FL (± 14.5 SE) for data taken during the reproductive period. Additionally, the size at which 10% of females were mature was 638 mm FL (± 19.6 SE), with 90% mature by 981 mm FL (±7.2 SE; refer to Figure 4.11a and Table 4.10 for sizes at which other proportions of the samples were sexually mature. These estimates obtained using all available data).

There was also considerable overlap between the lengths of immature and mature males (note, however, that relatively few testes were retained for histological processing). The largest immature male was 1140 mm FL (11.3 kg) whereas the smallest mature male (stage M3) was 491 mm FL (1.0 kg) and the smallest spawning (macroscopically staged) M4 male was 578 mm FL (1.6 kg). The size at which 10% of males were mature was 465 mm FL (± 24.9 SE), the size at which 50% of males were mature was 628 mm FL (± 13.8 SE) or 706 mm TL, and the size at which 90% were mature was 791 mm FL (± 10.5 SE; refer to Figure 4.11b and to Table 4.10 for sizes at which other proportions of the samples were sexually mature).

4.1.4 Spawning

Spawning range

Evidence of spawning was found in 237 of the ovaries examined histologically. Ninety (38%) of these were about to spawn when captured (F5a), 147 (62%) had recently spawned (F5c) and one was actively spawning (F5b). The ovaries of two other females staged macroscopically were also actively spawning. Note that macroscopic staging will not identify stage F5a ovaries in which the oocytes are in the migratory nucleus stage (MNS), and is unreliable for identifying stage F5c ovaries (Mackie and Lewis 2001). Most of these spawning fish (219) were captured in the north Kimberley region, whilst eighteen were captured in the Pilbara region (Figure 4.12). The most southern location from which a spawning female was obtained was Exmouth (one recently spawned fish), with no females showing histological (or macroscopic) evidence of spawning captured in the Gascoyne or more southern regions.

Potential batch fecundity

Histological evidence confirmed that the ovaries of *S. commerson* are of the asynchronous type, with oocytes of all stages present together within reproductively active ovaries (Wallace and Selman 1981). This development type, along with the presence of ovaries with both POFs and hydrated or MNS oocytes show that female *S. commerson* are serial or partial spawners (Hunter *et al.* 1985). Fecundity estimates therefore pertain to the number of eggs released per spawn (batch) and not annual fecundity.

The regression of FL and batch fecundity for ovaries in which oocytes were still in the MNS of development differed significantly from that for ovaries in which the oocytes were hydrated ($t = 4.599$, $P = 0.0001$). This was also the case for the whole weight – batch fecundity relationship ($t = 3.234$, $P = 0.0033$), perhaps because counts of oocytes that are still in the MNS often give an overestimate of batch fecundity (Figure 4.13a,b). There also tends to be greater variation between replicate counts for these ovaries, although results of the regression analyses should be treated cautiously because the regression data do not overlap well.

Final relationships between batch fecundity and WW or FL were therefore obtained only from data for ovaries in which the oocytes were in the hydrated stage of development:

Batch fecundity = $0.0011 \times FL^{2.896}$
$r^2 = 0.441$, $n = 21$

Batch fecundity = 31087 x $WW^{1.384}$
$r^2 = 0.714$, n = 19

Females with these ovaries ranged from 857 to 1143 mm FL and 5.3 to 12.7 kg whole weight, thus providing estimates for medium sized fish only.

Spawning fraction and frequency (females)

Spawning fraction was estimated for catches taken during September 1999 from the Kimberley region when virtually all ovaries (94%) were histologically processed. The analysis was based on the fraction of pre-spawning (F5a) ovaries captured during the morning. Afternoon samples were not used because the number of spawning fish is likely to be underestimated due to the low catchability of running ripe (F5b) females. Fifty-nine (34.5%) mature females in the morning samples were about to spawn (F5a). Spawning frequency (the inverse of the spawning fraction) is therefore 2.9 days. Furthermore, seventeen (29%) of these spawning females had evidence of spawning on two consecutive days (see below), indicating that a female will spawn twice during every 3.5 spawning events.

Spawning fraction was also estimated for the 1999 morning Kimberley samples as the proportion of macroscopically staged mature ovaries that contained hydrated oocytes. Thirty one of the 180 mature females were identified as such, providing an estimated spawning fraction of 17.2%, and a spawning frequency of 5.8 days.

Comparison of overall spawning fraction for Pilbara and Kimberley samples was made using the ratio of developed to spawning fish in the samples taken during the reproductive period. Data was restricted to samples with at least ten females. This analysis showed higher spawning fractions (between 33 and 56%) for the Kimberley region compared with the Pilbara region (4 – 28%).

Daily and monthly spawning patterns (females)

Analyses of *S. commerson* spawning are based on histologically prepared ovary samples obtained from the north Kimberley region in September 1999. These samples included 344 females, with the ovaries of 325 of these processed histologically (306 mature, 19 immature). Fifty four (36%) of the 151 spawning females (F5a-c) within these samples had spawned on two consecutive days. For example, 39 ovaries contained oocytes in the migratory nucleus (MNS) or hydrated stage of development (i.e. spawning was imminent when captured) as well as old post-ovulatory follicles (POFs; i.e. probably spawned within the past 12-24 hours), whereas 15 ovaries had both old and new POFs (i.e. spawning within the past 1-12 hours and

12-24 hours). No females appeared to have spawned on three or more consecutive days (eg ovaries contained new and old POFs as well as MNS or hydrated oocytes).

The 306 mature females included 171 captured during the morning fishing session (usually 0600 – 0900 hrs) and 135 in the afternoon (usually 1600-1800 hrs; Table 4.11). All except one of the females that were about to spawn (F5a; n = 60) were captured in the morning session. The ovaries of 28 of these females had migratory nucleus stage oocytes which were still in the process of final maturation prior to ovulation and spawning. In contrast, all females with ovaries containing new POFs (F5c, n = 23) were captured during the afternoon session. This cycle of oocyte maturation in the morning followed by afternoon spawning is illustrated in Figure 4.14. The presence of old POFs in the ovaries of females captured in both fishing sessions (n = 121), shows that these structures are present within the ovaries at least 24 hours after spawning. As no new POFs were present in ovaries sampled during the morning, the transition from new to old POF occurs during the night within about 12 hours of spawning. The absence of hydrated oocytes in the afternoon and new POFs in the morning also show that the entire cycle of oocyte maturation, ovulation and spawning is completed within a 24 hour period.

Examination of ovaries sampled in the north Kimberley region during 2000 confirm the spawning cycle observed in the 1999 samples (Table 4.11). All of the females in pre-spawning condition (F5a) were obtained in the morning session (n = 22), whereas all ovaries with new POFs (n = 15) were sampled during the afternoon. Ovaries with old POFs were sampled in both the morning and afternoon (n = 34). No spawning (F5b) females were obtained during 2000. Data for 2001 is limited (n = 63) and the samples were not obtained directly by research staff. This data is generally consistent with that of previous years as all post-spawning females were captured in the afternoon, although it was unusual that two of the four pre-spawning fish were also captured in the afternoon. Note that as in the previous two years the 2001 sampling trip occurred in September, however many ovaries had undergone atresia and relatively few of the fish were actively spawning.

Spawning females (F5a-c) were present in the samples on most days of the 1999 Kimberley field trip (Figure 4.15). The ratio of spawning (F5a-c) to non-spawning, developed ovaries (F4) was lowest over the new moon period and highest just prior to the first quarter (Figure 4.16). The data suggests that most females spawn during the period between the new and full moons when tidal currents are less strong, although there are clearly other influences on the catchability of spawning females.

Annual reproductive cycle - macroscopic and histological ovarian stages

Macroscopic examination of ovaries show that all female *S. commerson* within the Pilbara region were non-reproductive between March and June, during the downward cycle of water temperatures (Figure 4.17). As water temperatures reached a minimum in July and August (around 24º C), a small proportion of mature ovaries had become reproductively developed (F4). The proportion of developed ovaries during September (the start of the upward cycle of water temperatures) varied noticeably between years in the Pilbara region from 18.5% to 79% in 2001 and 2000, respectively. A small number of females were also actively spawning when sampled during September 2000. The peak reproductive period extended from October to January, with spawning fish captured during this period in 1999 and 2000 when the SST was still rising from about 25.5 to 28.5º C. A small percentage of ovaries showed no signs of reproductive activity during these peak spawning months. By February, when SST peaked at approx 30º C, reproductive development was declining and little spawning was likely to have occurred.

Although the time series of samples is incomplete for the Kimberley region, the annual reproductive cycle of ovaries appears to be similar to that for fish in the Pilbara region (Figure 4.17). However, in the West Coast region few reproductively developed ovaries and no spawning ovaries were obtained, noting that *S. commerson* are rarely captured in this region during the peak spawning period observed in the northern regions.

Histological assessment of samples from the Pilbara region confirm conclusions drawn from the macroscopic data (Figure 4.18). The percentage of resting ovaries peaked in March, with developing ovaries appearing in April and increasing in number through to August. A few reproductively developed ovaries also appeared in July and August, with most females reproductively active by September (particularly during 2000 as shown with the macroscopic data). October was again the first month when spawning fish were sampled, with spawning activity occurring between this month and January. Spawning activity was still evident in January, but was finished by February with the ovaries of most females spent or resting.

The monthly series of histological data for the Kimberley region is not complete (Figure 4.18). However, as 30 -50% of females captured in September during 1999 and 2000 were actively spawning it appears that *S. commerson* in this region may commence spawning a month or so earlier than those in the Pilbara region. About 60% of females were also spawning when sampled during October in 1999 and 2000, although only 35% were spawning during this month in 2001. The ovaries of fish in the October 2001 samples were notable because in many (54%) there was significant atresia occurring among the yolk globule stage oocytes. As a consequence, the ovaries of 40% of the females were or had regressed (i.e. were Stages 2, 3 or 6) compared to 24% in October 2000. Although samples were not obtained for November, discussion with fishers indicated that during this month in 2000 and 2001 catches improved and were dominated by fish with large developed and spawning gonads. In most years, little fishing occurs in November because of inclement weather and declining catches, and it is possible that 2000 and 2001 were also unusual years in the pattern of spawning activity. If spawning commences in August and concludes in November (same duration as in the Pilbara region) this encompasses SST ranging from the annual minimum of approx. 26.5 – 27° C to approx. 29 – 30° C (annual maximum approx. 30-31° C; Figure 4.18). Note also that in the Kimberley and Pilbara regions it was common to get a small proportion of atretic ovaries in the samples throughout the year, with peaks immediately after spawning has finished.

In the West Coast region, where no spawning and little reproductive activity was found in the ovaries, the maximum SST was around 28° C. This is above the lower temperature range of spawning in the two northern regions. The reproductively developed ovaries obtained from the West Coast region were collected over a range of SSTs, including when it was at a minimum (Figures 4.17 and 4.18).

Annual cycles of photoperiod were in synchrony with SST cycles in the Kimberley region but became progressively out of phase towards the south (Figure 4.17). In the Kimberley region peak spawning occurred between daylengths of 11.6 and 12.8 hrs (August to November), compared to 12.5 and 12.9 hrs (October to January) in the Pilbara. Spawning in the Kimberley region therefore occurred between the annual trough and peak (11.2 hrs in June, 13 hrs in December). However, in the Pilbara region spawning occurred over the peak of 13.3 hrs in December and was completed when photoperiod was decreasing.

Annual reproductive cycle - gonad indices

There was a positive relationship between gonad and whole weight (Figure 4.19). Restricting the data for females to WW from 9-18 kg (r^2 = 0.02, n = 180, P = 0.07) removed this relationship, thereby minimising the influence of gonad weight on GSI estimates, although this also resulted in considerable reduction in the data set. Subsequent GSIs were therefore estimated for the complete as well as the restricted data set. The data set for males was also restricted to WW from 3-14 kg. This still left a positive relationship in the regression (r^2 = 0.3439, n = 206), but sample sizes were too small to permit further decreases in numbers.

Gonad indices calculated from either WW, head weight or head length exhibited similar patterns (Figures 4.20 – 4.21). They also confirm the spawning cycle determined from visual examination of ovaries. The most complete data set is for females from the Pilbara region (Figure 4.20). In this region the GSI is minimal from March through to August. During September the indices increased considerably as ovaries were becoming reproductively developed. The peak in gonad indices occurred in November during 1999 and in October during 2000, coinciding with the peaks in the proportion of spawning (F5) ovaries in the samples during those years (Figure 4.17). The drop in gonad indices during December 1999 shows that the supplies of vitellogenic oocytes within the ovaries were reduced by this time, even though many females were still spawning (Figure 4.20). This drop continued until March when all the ovaries in the samples were in the resting stage. Data for males from the Pilbara region concur with that for the females. However there was a significant drop in all indices in November during 1999 and 2000 (Figure 4.20), suggesting rapid depletion and renewal of sperm. Although the data for 2001 is limited, it indicates decreased GSI for both males and females during the reproductive season compared to the previous two years, as was shown with the histological data for the Kimberley region.

Gonad indices data for the Kimberley and West Coast regions are limited, although for both regions the data agree with gonad staging data (Figure 4.21). The data for males and females from the West Coast region also confirm the low reproductive status of *S. commerson* in this area, with the peaks in GSI in the main spawning months of September to December well below those in the other regions.

Table 4.1 Number of fresh and frozen samples of *S. commerson* gonads obtained from each region between 1998 and 2001. Macro; macroscopically staged gonad. Hist; histologically staged gonads. Note that all histologically staged gonads were also staged macroscopically. K; Kimberley region, NT; Northern Territory, P; Pilbara region. WC; West Coast region.

	Males				**Females**				**Juveniles**			
	Fresh		**Frozen**		**Fresh**		**Frozen**		**Fresh**		**Frozen**	
	Macro	Hist	Macro	Hist	Macro	Hist	Macro	Hist	Macro	Hist	Macro	Hist
K	1180	117	135	1	1528	786	109	14	1	1	-	-
NT	41	6			114	73						
P	409	98	131	7	523	410	316	36	17	6	75	6
WC	53	13	127	5	81	38	288	7	-	-	-	-

Table 4.2 Fork length and whole weight statistics of *S. commerson* sampled during the study.

Region	Sex	Min FL (mm)	Max FL (mm)	Avge FL (mm)	SE FL	Min WW (g)	Max WW (kg)	Avge WW (kg)	SE WW
Kimberley	M	491	1201	938.4	2.5	1000	14.7	6.5	0.06
	F	476	1480	1017.7	2.5	1453	25.0	8.4	0.08
Pilbara	J	58	1251	374.6	12.5	15	1.5	0.5	0.02
	M	301	1381	989.6	7.6	283	22.0	8.5	0.24
	F	396	1650	1055.9	8.0	559	40.6	11.1	0.30
West Coast	M	551	1288	949.3	21.4	1345	20.4	9.0	0.52
	F	610	1720	972.2	16.7	1698	39.5	11.7	0.6

Table 4.3 Results of non-linear regression analysis comparing the relationship between whole weight and fork length by sex and region. Form of the data is a power curve described by the equation: Weight = a Length^{b} , where a and b are constants. Data for Kimberley males were used as the control against which data for Kimberley females (Kf), Pilbara males (Pm), Pilbara females (Pf), West Coast males (WCm) and West Coast females (WCf) were compared. Therefore, the values of a and b for Kimberley males are shown in the Table as 7.78e-9 and –4.04, whereas for Kimberley females a = 7.78e-9 - 1.78e-9 and b = -4.04 + 0.04, and so on. The asterisks indicate equations that were significantly different from the control (Kimberley males).

Variables	Value	SE	t value
a	7.78e-9	1.79	23.15
Kf	-1.78e-9	2.27e-9	-0.78
Pm	-6.20e-9	1.97e-9	-3.15*
Pf	-6.19e-9	1.95e-9	-3.17*
WCm	-6.29e-9	2.12e-9	-2.97*
WCf	-4.33e-9	2.85e-9	-1.52
b	-4.04	1.27	-3.18
Kf	0.04	0.05	0.79
Pm	0.23	0.07	3.51*
Pf	0.23	0.06	3.75*
WCm	0.24	0.10	2.40*
WCf	0.12	0.10	1.26

Table 4.4 Results of non-linear regression analysis comparing the relationship between whole weight and fork length within each region (sex pooled). Form of the data is a power curve described by the equation: Weight = a Length^b, where a and b are constants. Data for the Kimberley region were used as the control against which data for the Pilbara and West Coast regions were compared. Therefore, the values of a and b for the Kimberley region are shown in the Table as 7.15e-9 and 3.01, whereas for the Pilbara region a = 7.15e-9 – 5.44e-9 and b = 3.01 + 0.21, and so on. The asterisks indicate equations that were significantly different from the control (Kimberley).

Variables	**Value**	**SE**	**t value**
a	7.15e-9	1.05e-9	6.82
Pilbara	-5.44e-9	1.14e-9	-4.78*
West Coast	-4.74e-9	1.51e-9	-3.13*
b	3.01	0.02	142.37
Pilbara	0.21	0.04	4.88*
West Coast	0.16	0.07	2.36*

Table 4.5 Results of non-linear regression analysis comparing the relationship between whole weight and fork length by sex (region pooled). Form of the data is a power curve described by the equation: Weight = a Length^b, where a and b are constants. Data for females used as the control against data for males is compared. Therefore, the values of a and b for Females are shown in the Table as 3.32e-9 and 3.12, whereas for Males a = 3.32e-9 - 1.69e-10 and b = 3.12 + 9.24e-3.

Variables	**Value**	**SE**	**t value**
a	3.32e-9	5.70e-10	5.82
Male	-1.69e-10	8.00e-10	-0.21
b	3.12	0.02	126.57
Male	9.24e-3	0.04	0.25

Table 4.6 Results of linear regression analysis comparing the relationship between total length and fork length by sex and region. Data for Kimberley males were used as the control against which data for Kimberley females (Kf), Pilbara males (Pm), Pilbara females (Pf), West Coast males (WCm) and West Coast females (WCf) were compared.

Variables	**Value**	**SE**	**t value**	**P**
Intercept	41.37	1.79	23.15	0.00
FL	1.06	0.00	571.01	0.00
Kf	-0.60	0.60	-1.00	0.32
Pm	-6.84	0.80	-8.60	0.00*
Pf	-7.35	0.74	-9.92	0.00*
WCm	-2.60	1.51	-1.36	0.17
WCf	-4.04	1.27	-3.18	0.00*

Table 4.7 Results of linear regression analysis comparing the relationship between total length and fork length by region (sex pooled). Data for Kimberley used as the control against which data for other regions (Pilbara and West Coast) is compared.

Variables	**Value**	**SE**	**t value**	**P**
Intercept	41.62	1.76	23.69	0.00
FL	1.06	0.00	597.55	0.00
Pilbara	-6.80	0.53	-12.86	0.00*
West Coast	-2.94	0.97	-3.03	0.00*

Table 4.8 Sex ratios of *S. commerson* within the three regions. Also shown are the results of a Chi-square goodness of fit (GOF) test to analyse deviation of the sex ratios from unity, and a homogeneity test to compare the sex ratios between areas. M; male. F; female. Data is only for samples that included the whole catch.

	Kimberley	**Pilbara**	**West Coast**
Number (M:F)	1173:1473	299:366	51:85
Ratio (M:F)	1:1.3	1:1.2	1:1.6
GOF	Chi-square = 23.21 $P < 0.001$		
Homogeneity	Chi-square = 2.65 $0.25 < P < 0.50$		

Table 4.9 Results of generalised linear model with binomial family and logit link examining the relationship between moon phase and the proportion of female *S. commerson* in the catch each day during September and October in the Kimberley region. Data for 1999 (Sept 7 – Sept 25) and 2000 (Sept 24 – Oct 17) pooled. Null hypothesis was that the proportion of females during each moon phase = 0.5.

Moon Phase	**Total # Fish Captured**	**# of Females Captured**	***P***
First Quarter	594	256	0.00
Full Moon	446	200	0.03
Third Quarter	111	53	0.70
New Moon	384	211	0.06

Table 4.10 Length at maturity of male and female *S. commerson*. Histological as well as fresh macroscopically staged gonads were used in analyses. Data pooled for all areas and months, except for the percent mature '50*', which is for female *S. commerson* captured during or soon after the spawning season (October to April; n = 569).

	Female (n=2248)		**Male (n=1816)**	
Percent mature	**FL (mm)**	**SE**	**FL (mm)**	**SE**
10	637.5	19.6	465.3	24.9
20	701.0	14.9	525.4	21.8
30	743.1	13.0	565.4	18.3
40	777.7	10.7	598.2	16.0
50	809.4	9.8	628.3	13.8
50*	788.3	14.5	-	-
60	841.1	7.9	658.3	12.8
70	875.6	7.0	691.1	11.7
80	917.8	5.7	731.1	10.3
90	981.2	7.2	791.2	10.5

Table 4.11 Breakdown of data for *S. commerson* females captured in the Kimberley region during the spawning season. Note that data for 'F5c' only includes females that had spawned on the day of capture (i.e. excluding ovaries containing old POFs only). Data for 'Old POFs' includes all ovaries containing old POFs as well as other evidence of recent or imminent spawning.

		Histological analysis		**Morning session**					**Afternoon session**				
Year	Total caught	Total	# mature	Total	F5a	F5b	F5c	Old POFs	Total	F5a	F5b	F5c	Old POFs
1999	344	325	306	171	59	0	0	70	135	1	1	23	51
2000	406	115	103	59	22	0	0	21	44	0	0	15	13
2001	63	63	62	23	2	0	0	4	39	2	0	11	5

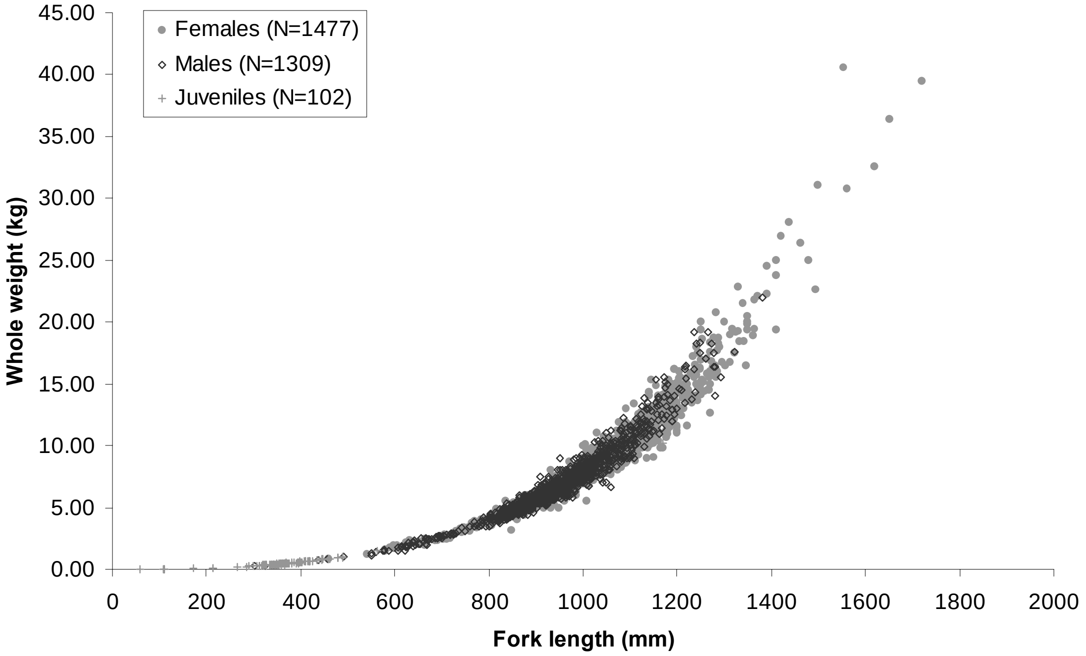


Figure 4.1 Relationship between fork length and whole weight for female, male and juvenile *S. commerson*, data pooled by region.

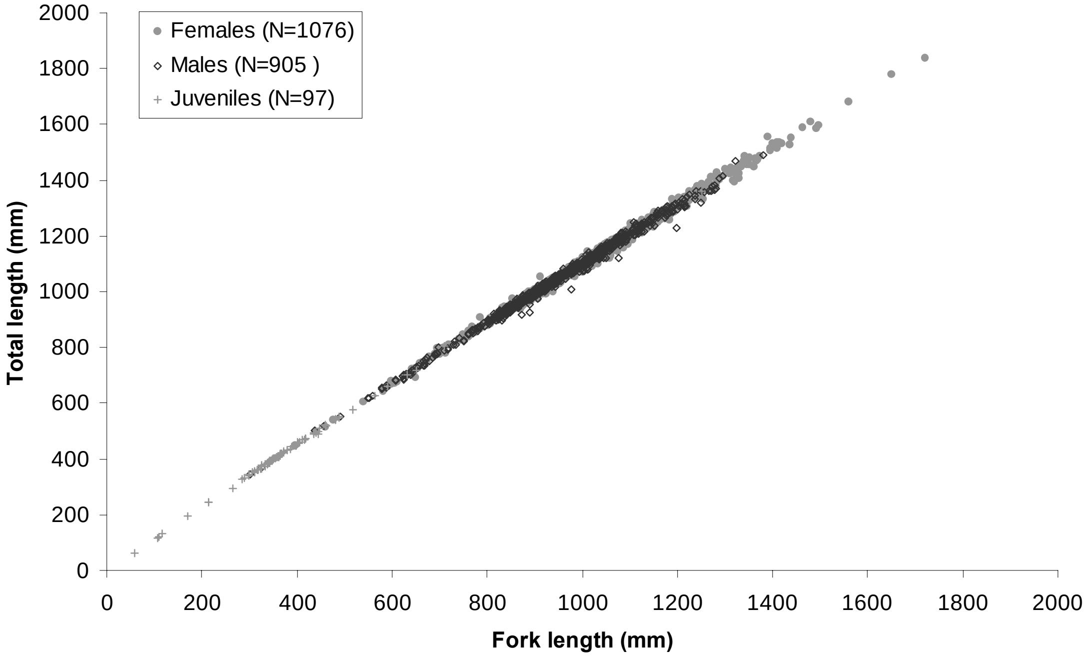


Figure 4.2 Relationship between fork and total lengths for female, male and juvenile *S. commerson*, data pooled by region.

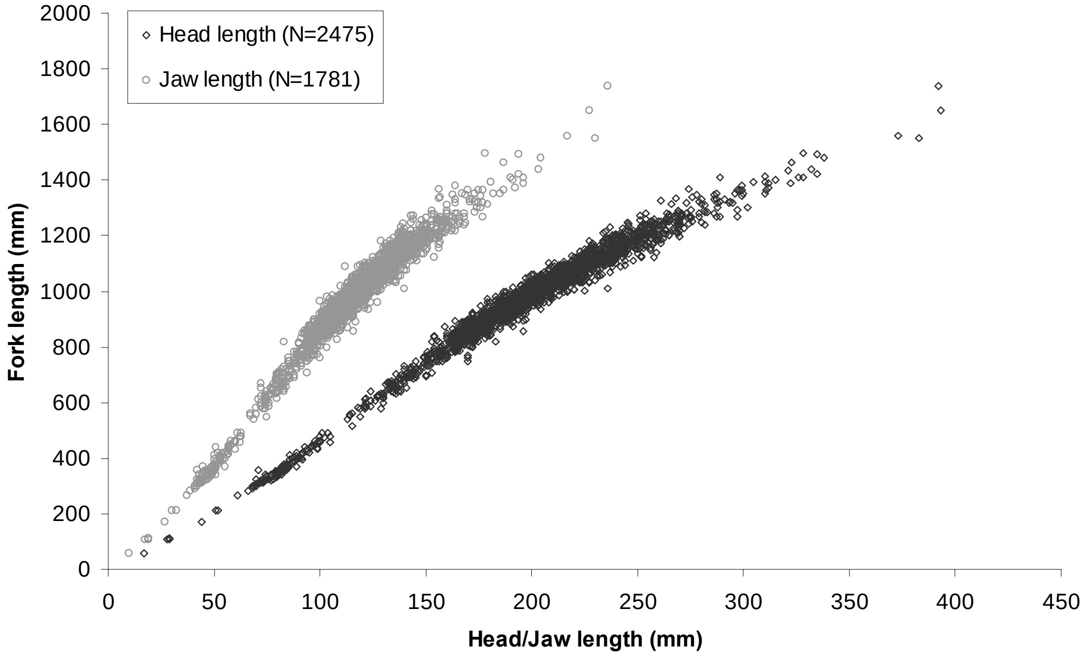
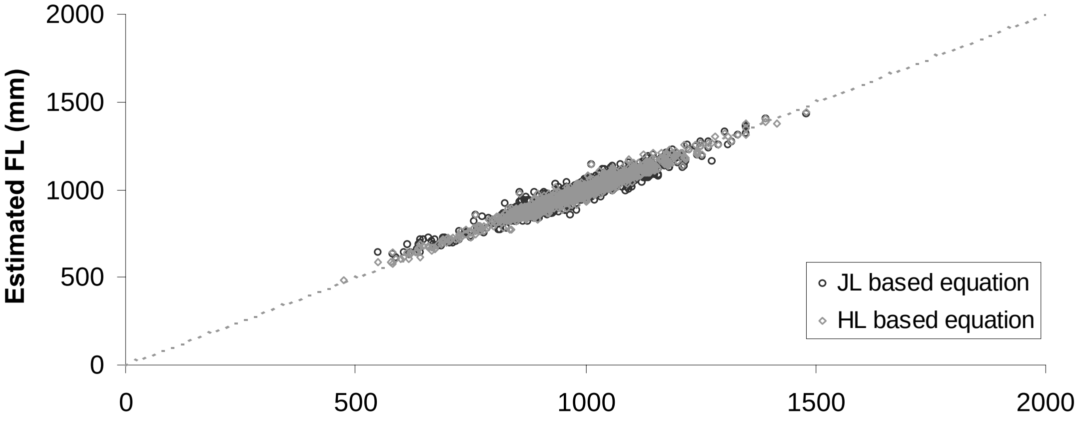
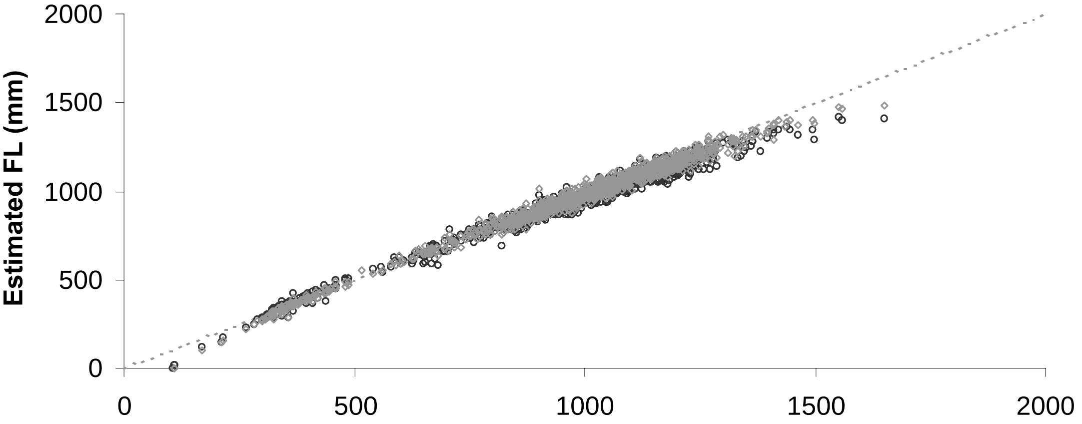


Figure 4.3 Relationship between fork, upper jaw and head lengths of *S. commerson*, data pooled for sex and region.

a) Kimberley region



b) Pilbara region



c) West coast region

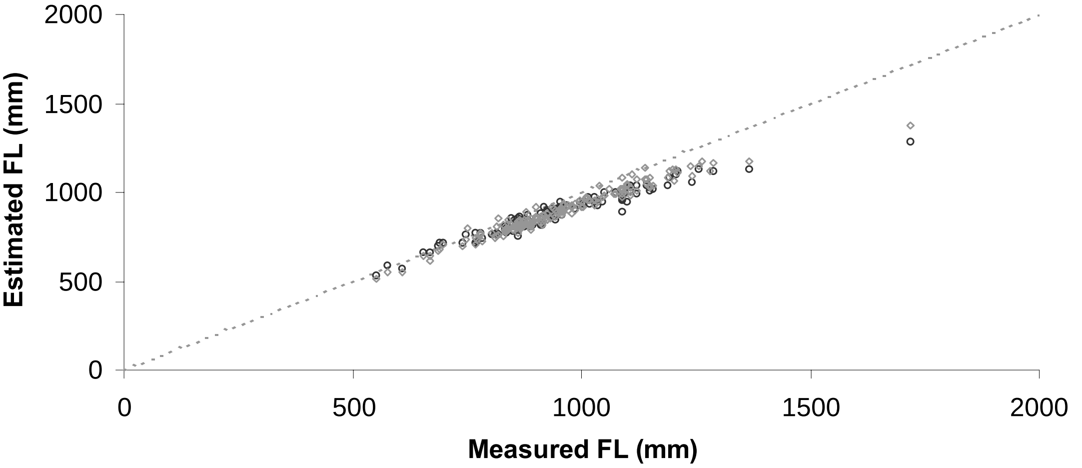
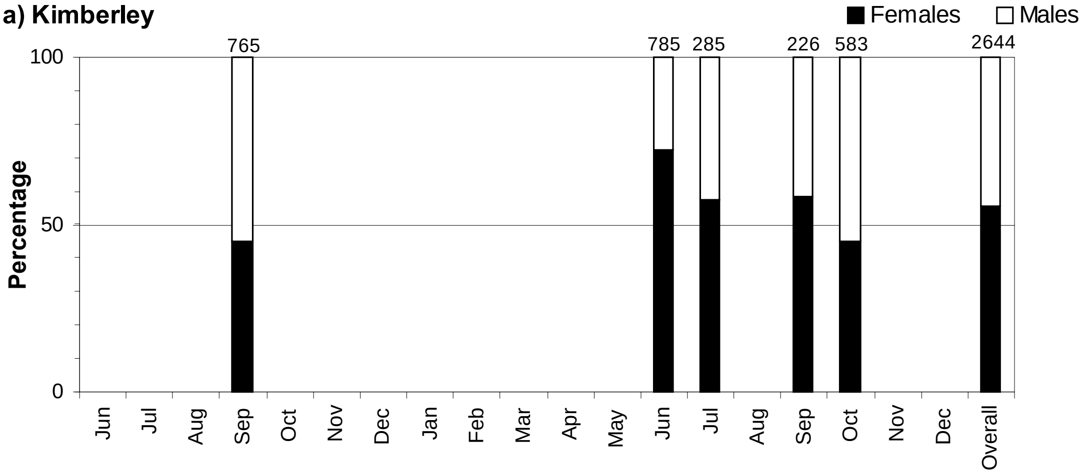
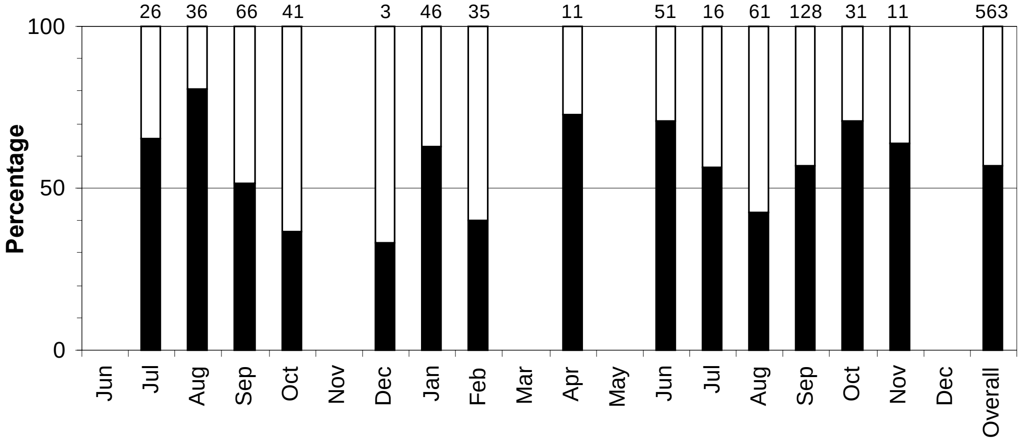


Figure 4.4 Comparison between estimated FLs from regional JL and HL based equations and measured FL of *S. commerson* for a) Kimberley, b) Pilbara and c) West coast regions. Dashed line is the line of parity.

a) Kimberley



b) Pilbara



c) West Coast

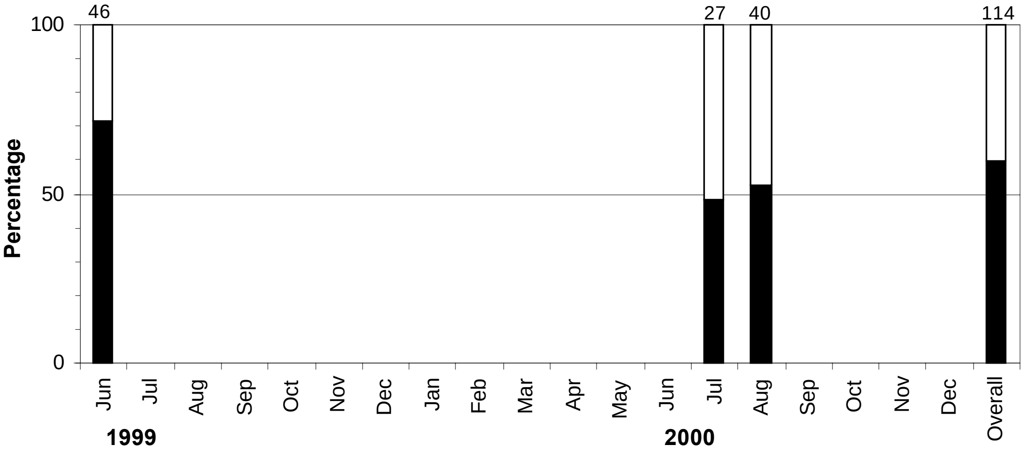


Figure 4.5 Percentage of male and female *S. commerson* within the monthly samples obtained from each region. Data is only for samples that included the whole catch. Sample size is given above each column.

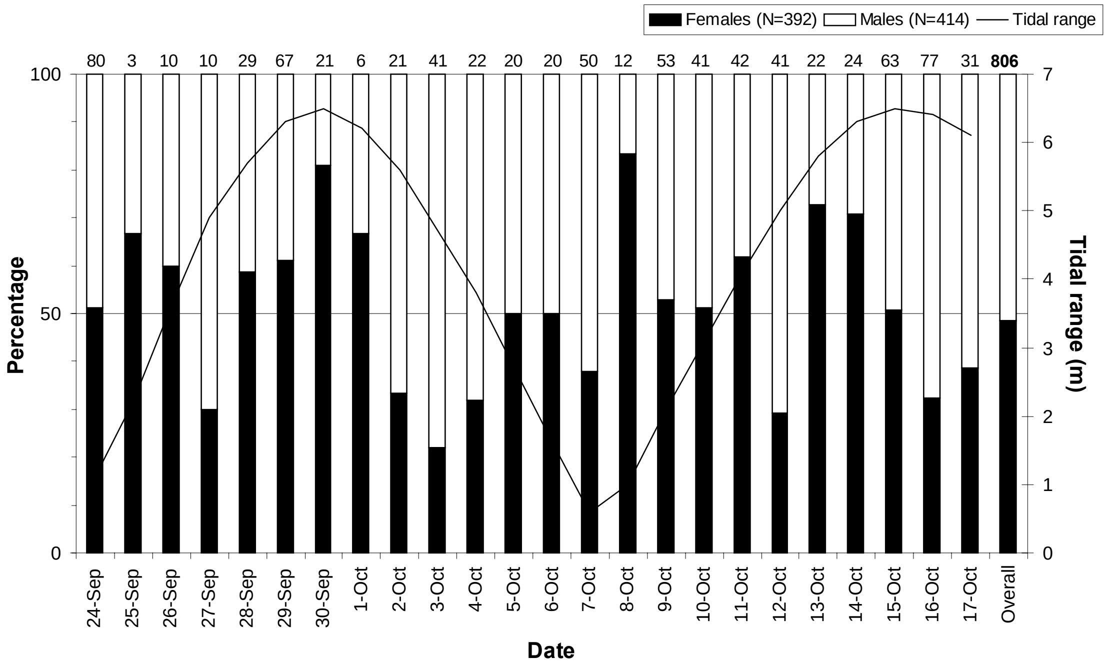


Figure 4.6 Percentage of male and female *S. commerson* within samples obtained from the north Kimberley region during the 2000 spawning period with the daily tidal fluctuation. The overall sex ratio for all samples combined is shown in the final column. Sample size is given above each column.

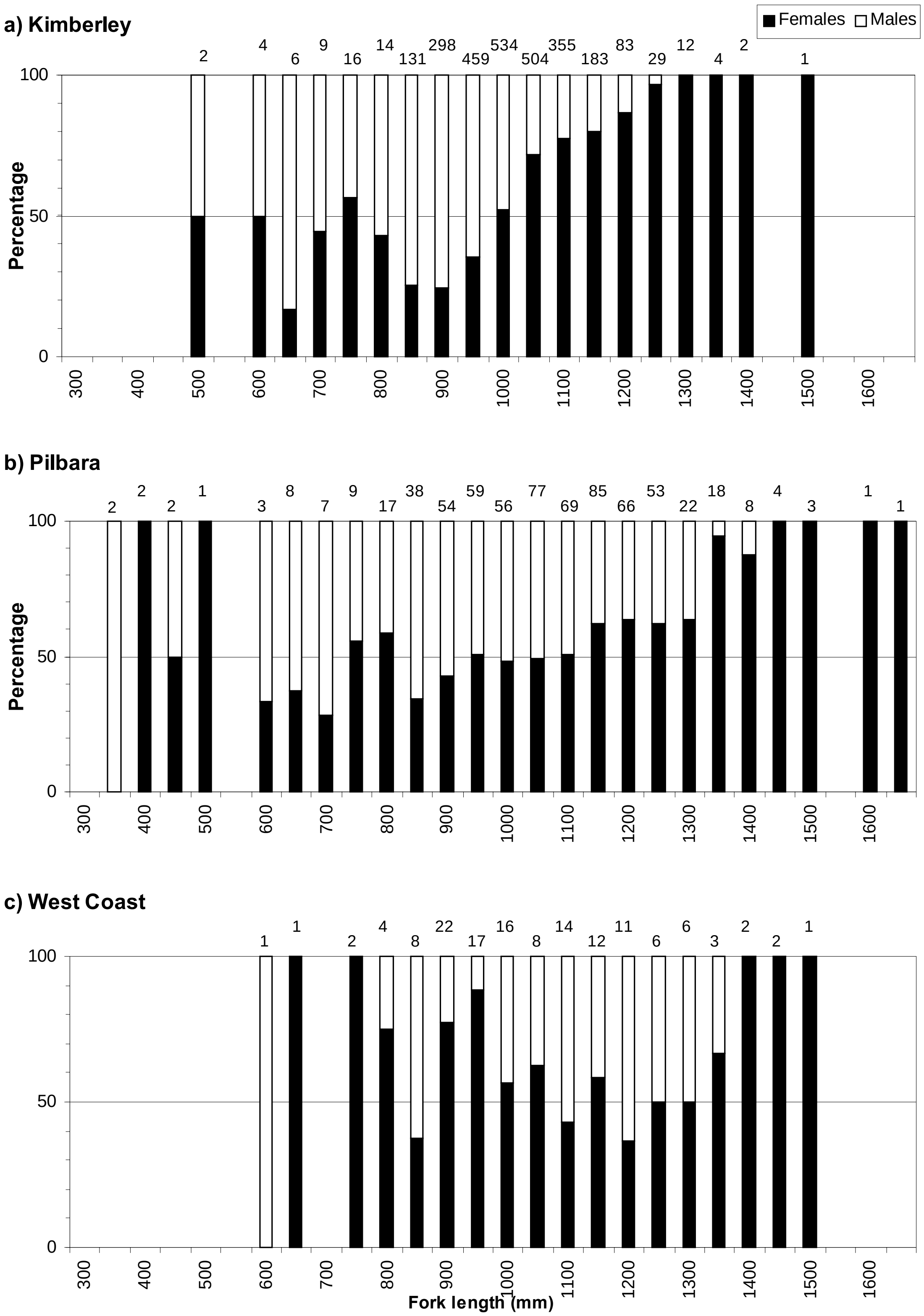


Figure 4.7 Percentage of male and female *S. commerson* within each 50 mm fork length class (Starting value of categories given). Sample sizes are given above each column.

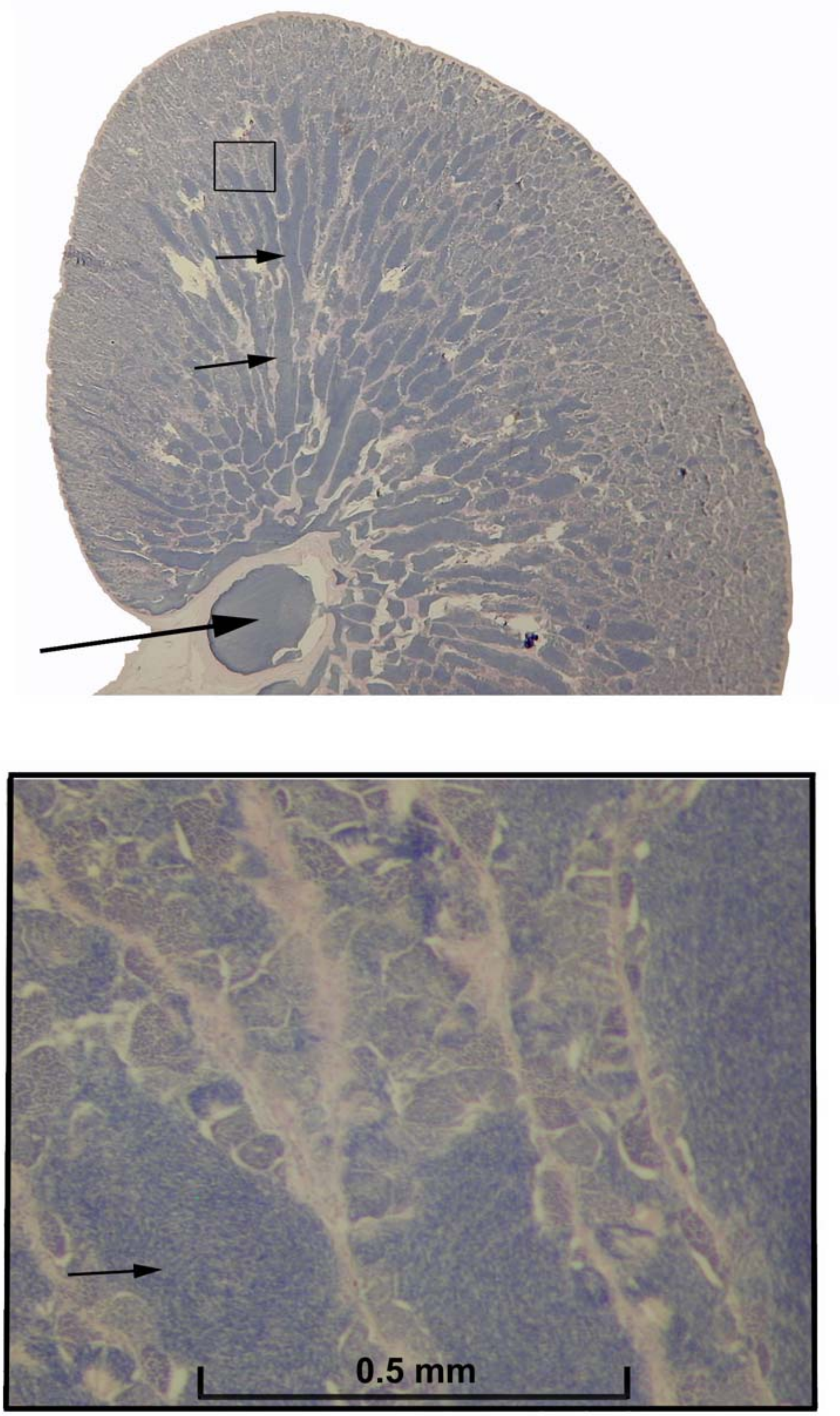


Figure 4.8 Histological section of male *S. commerson* testis showing central sperm sinus (large arrow) and efferent sperm sinuses (small arrows) plus detailed section showing crypts.

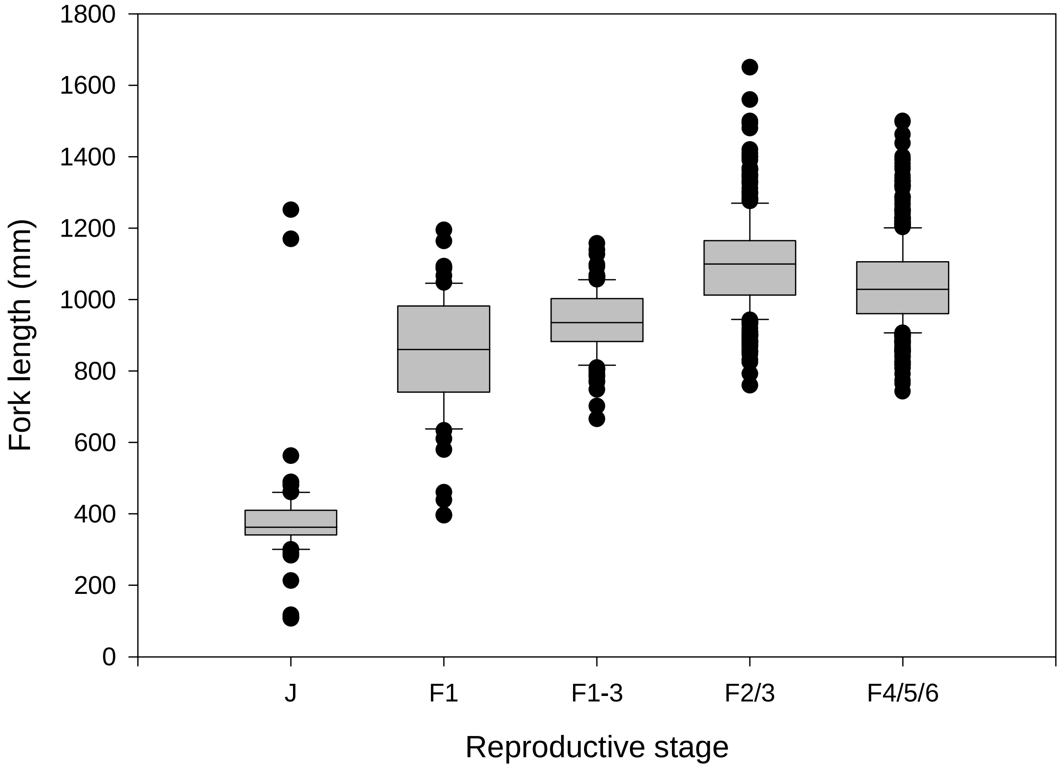


Figure 4.9 Length range of female *S. commerson* within each stage of ovary maturity (plus juvenile with undifferentiated gonads). Data is for histologically staged specimens. J; juvenile. F1 and F1a; immature ovaries. F2/3 and F4/5/6; mature ovaries. Refer to text and Mackie and Lewis (2001) for description of these stages. Box and whisker plot; box shows 25th and 75th percentiles with median, whiskers show 10th and 90th percentiles, circles show outliers. Sample sizes: J; 86. Immature females; 188. Mature females; 912.

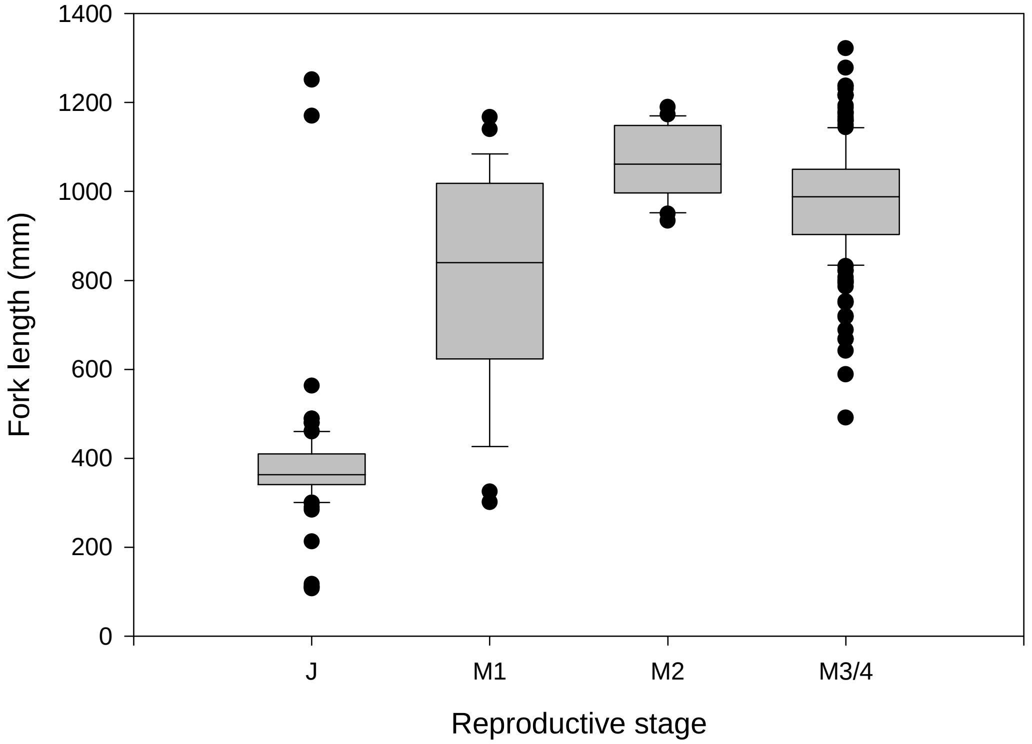
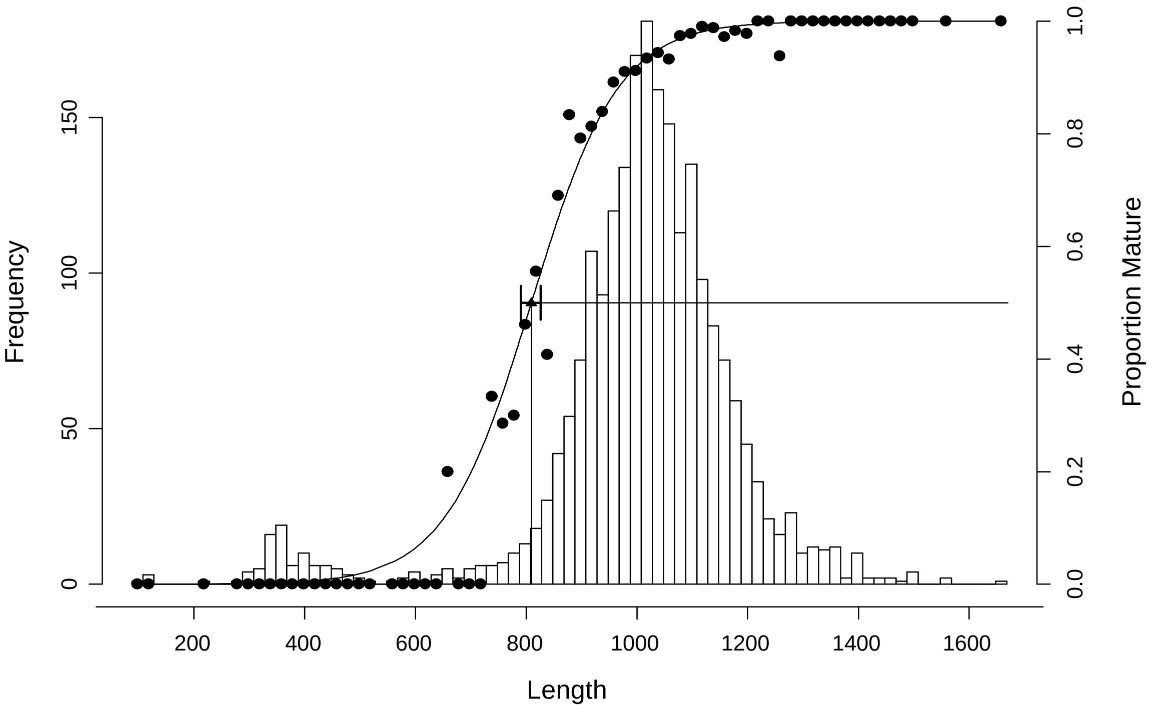


Figure 4.10 Length range of male *S. commerson* within each stage of testes maturity (plus juvenile with undifferentiated gonads). Data is for histologically staged specimens. J; juvenile. M1; immature testes. M2 and M3/4; mature testes. Refer to text and Mackie and Lewis (2001) for description of these stages. Box and whisker plot; box shows 25th and 75th percentiles with median, whiskers show 10th and 90th percentiles, circles show outliers. Sample sizes: J; 86. Immature males; 24. Mature males; 205.

a)



b)

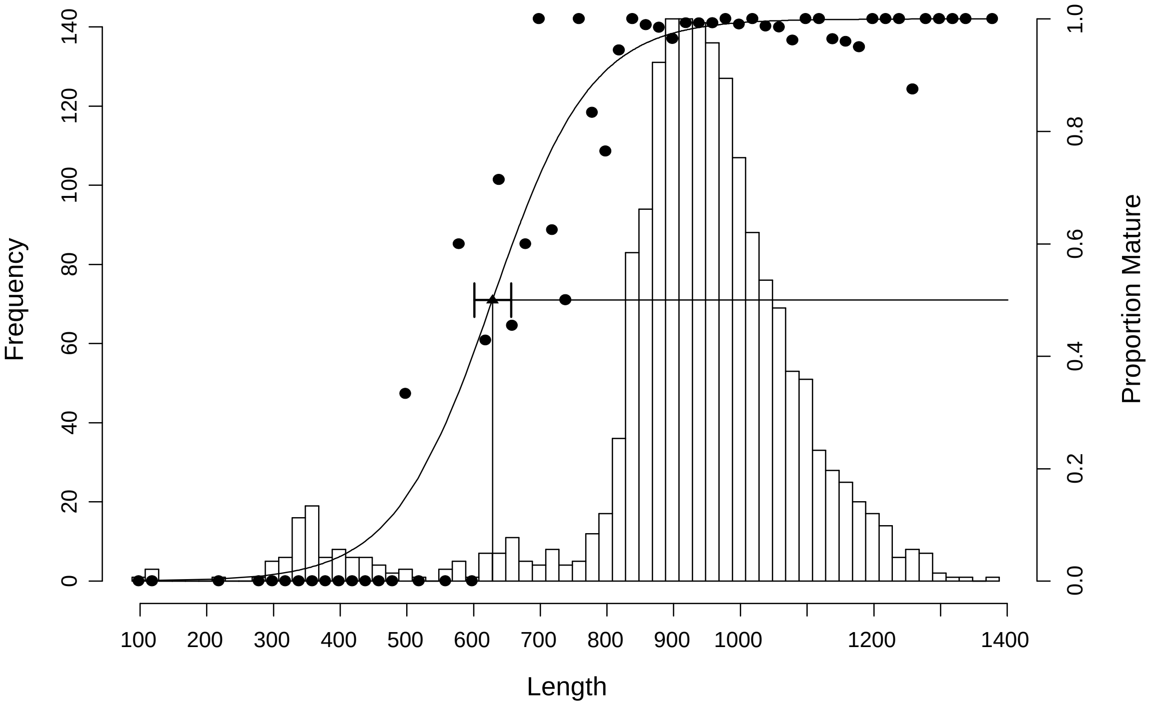


Figure 4.11 Proportion of *S. commerson* mature within the samples for a) females, and b) males. The number of fish within each length class is indicated by the vertical bars and the left y-axis, whereas the proportion of mature fish within each length class is indicated by the black circles and the right y-axis. The length at which 50% of fish within the samples were mature is indicated on the fitted maturity curve (± 95% CI). Lengths are fork length in mm. Note that data for juvenile fish of undifferentiated sex is included in both graphs.

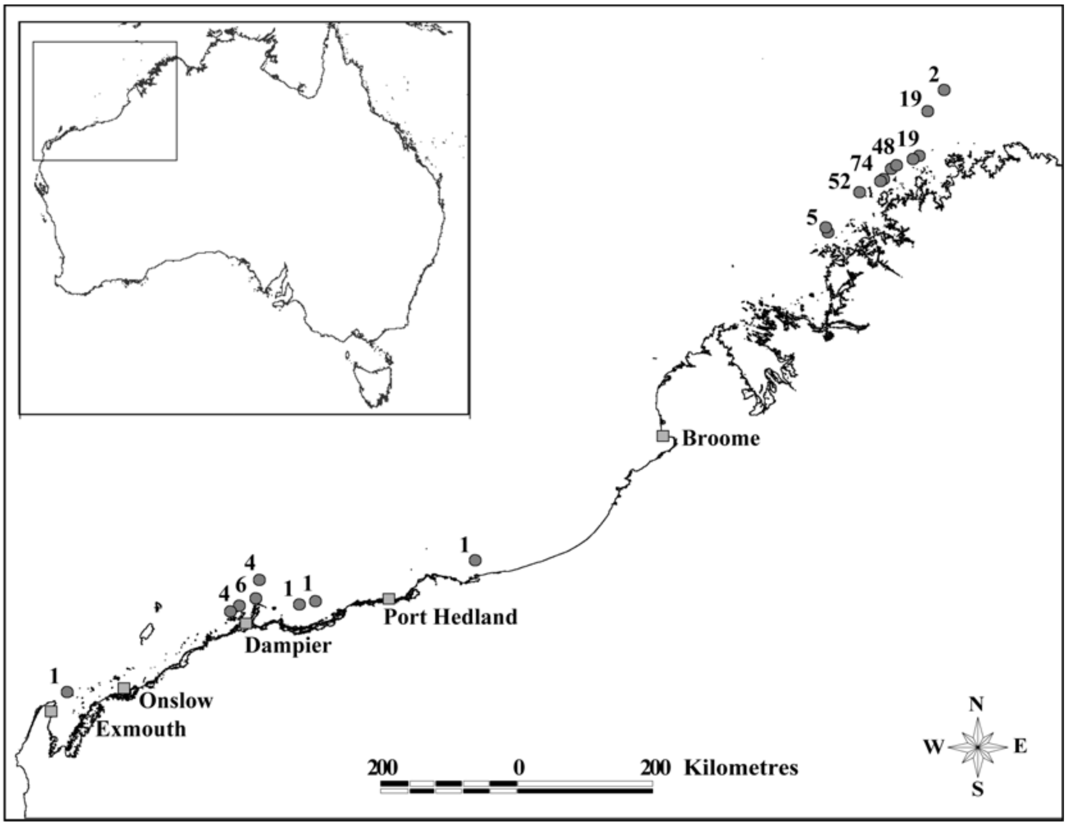
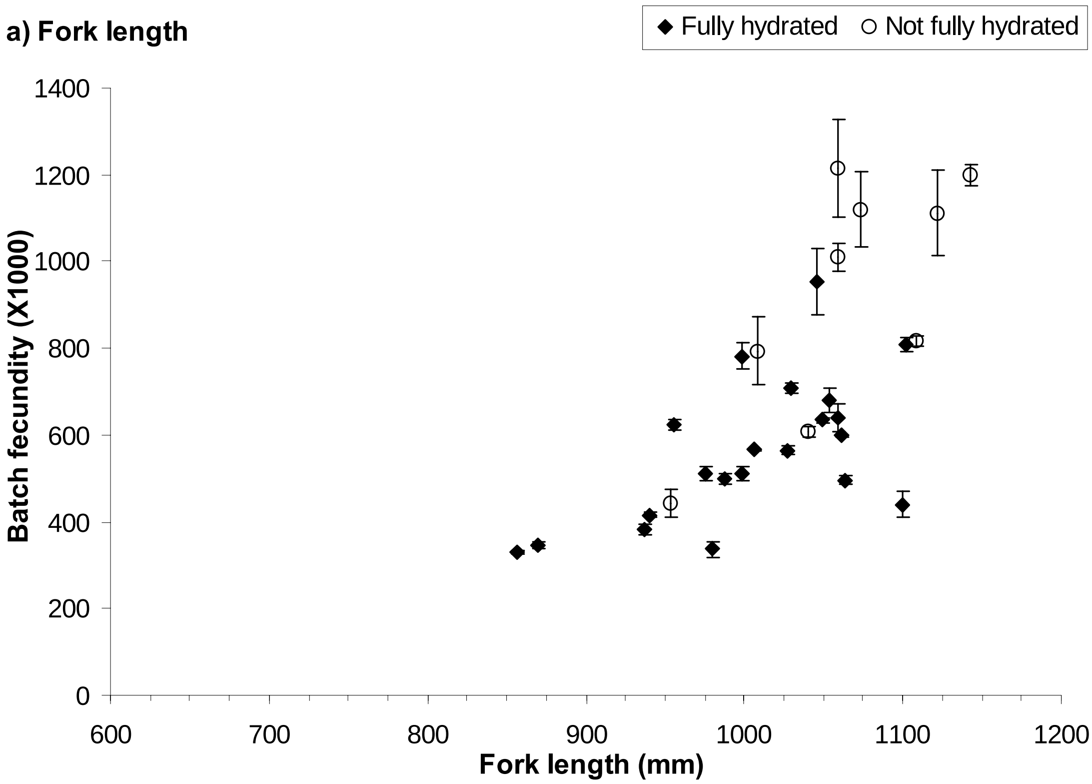
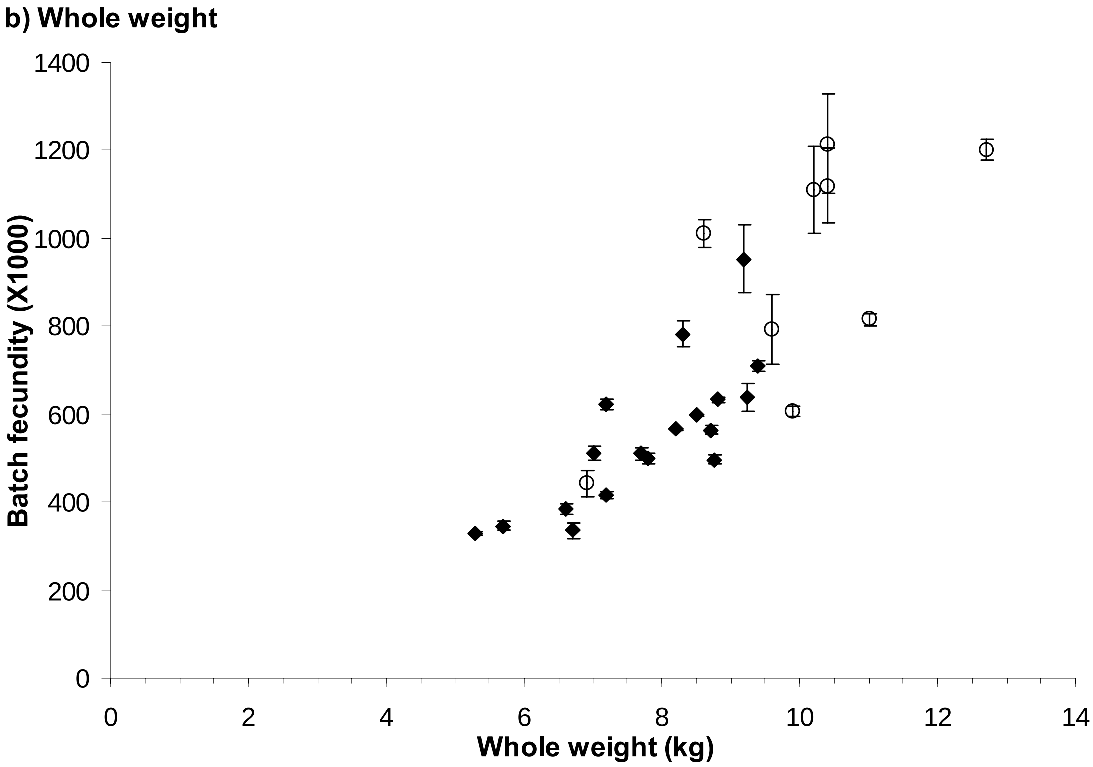


Figure 4.12 Map of Western Australia showing the locations and number of spawning *S. commerson* ovaries (histologically staged F5a, b or c) within the samples.



a) Fork length



b) Whole weight

Figure 4.13 Batch fecundity of *S.commerson* with standard errors, versus a) fork length and b) whole weight.

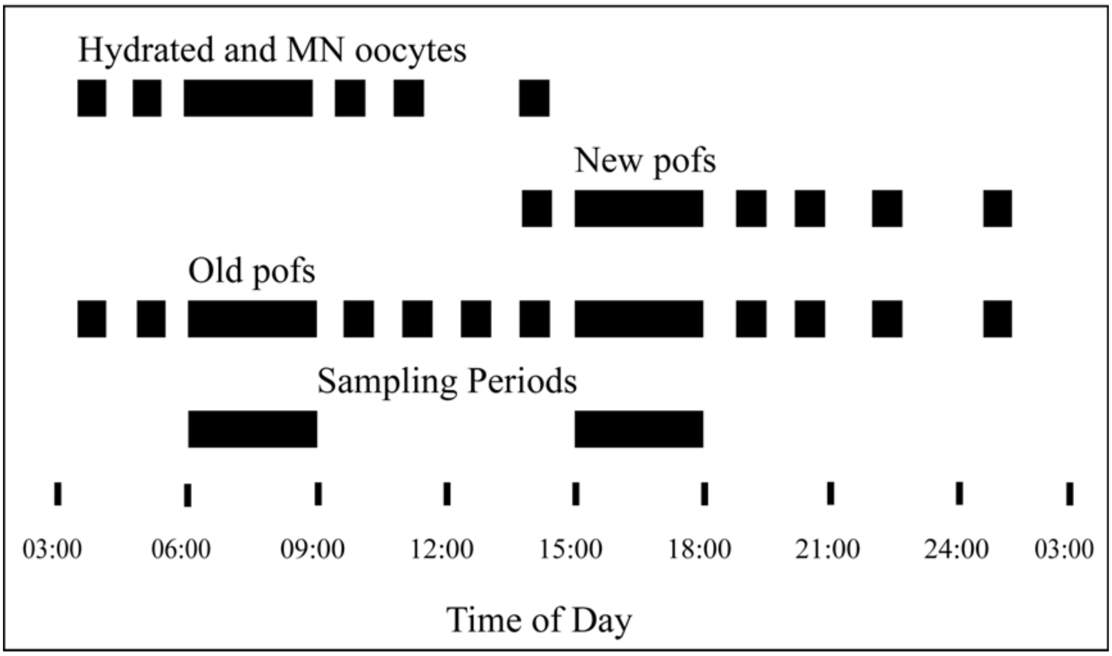


Figure 4.14 Time of day when structures associated with spawning were present in *S. commerson* ovaries (solid section of line). The likely duration of these structures is indicated by the dashed lines. Data is for samples obtained from the Kimberley region.

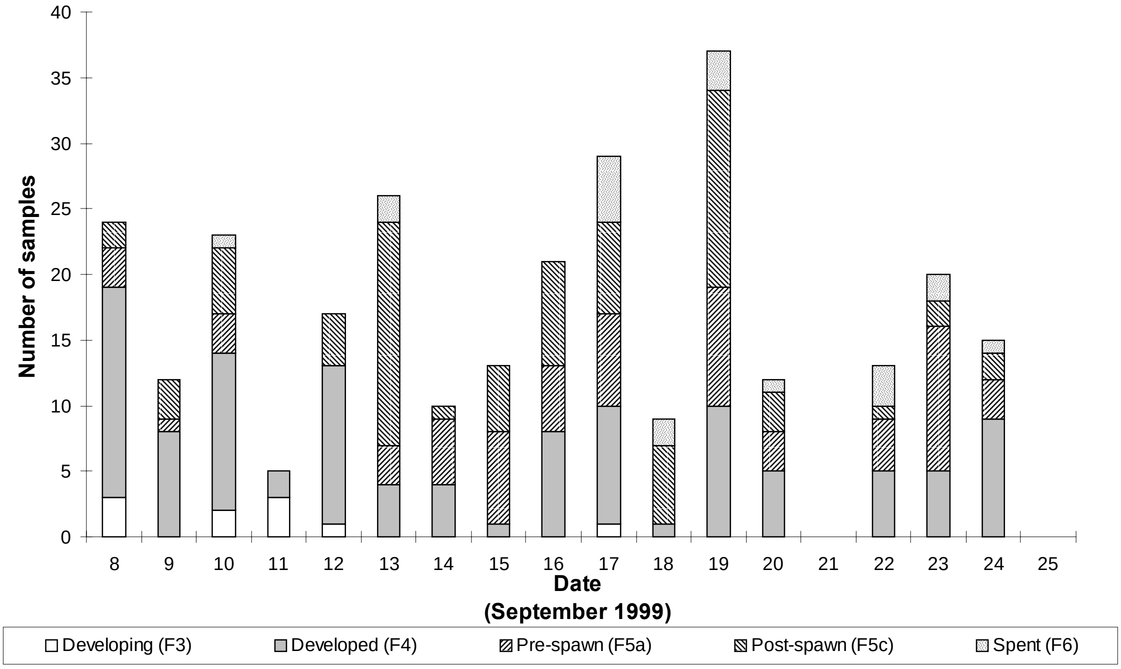


Figure 4.15 Number of *S. commerson* ovaries within each development stage from the north Kimberley region during September 1999. All samples were histologically processed.

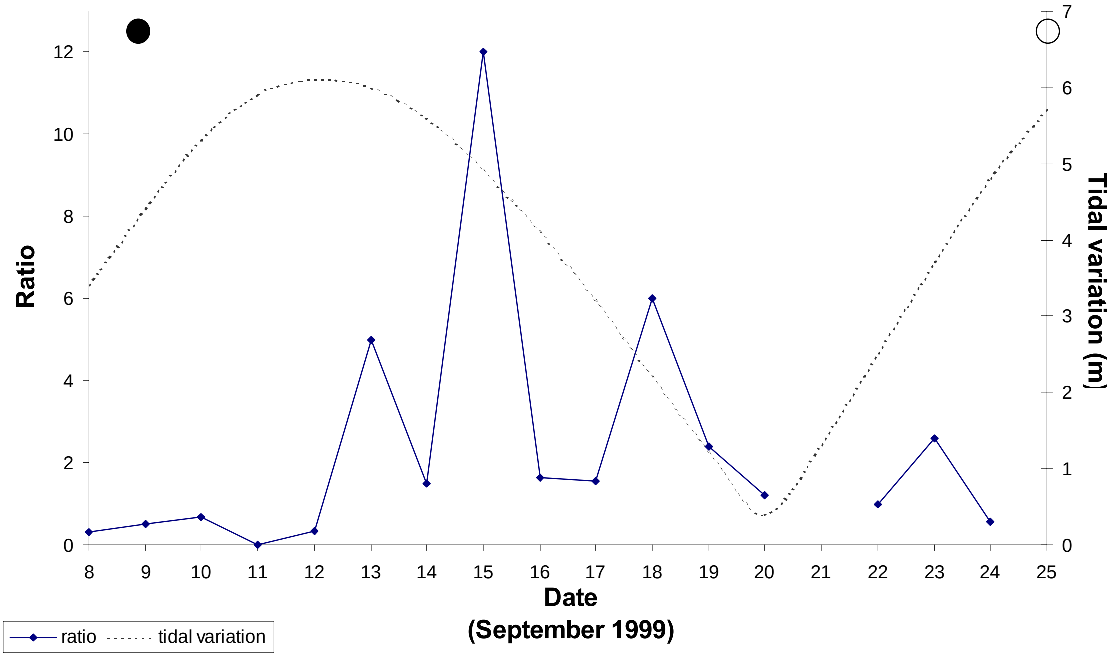


Figure 4.16 Ratio of spawning to non-spawning females in the north Kimberley region during September 1999. Curve showing tidal variation during the sample period is overlaid, along with dates of the new (●) and full moon (○).

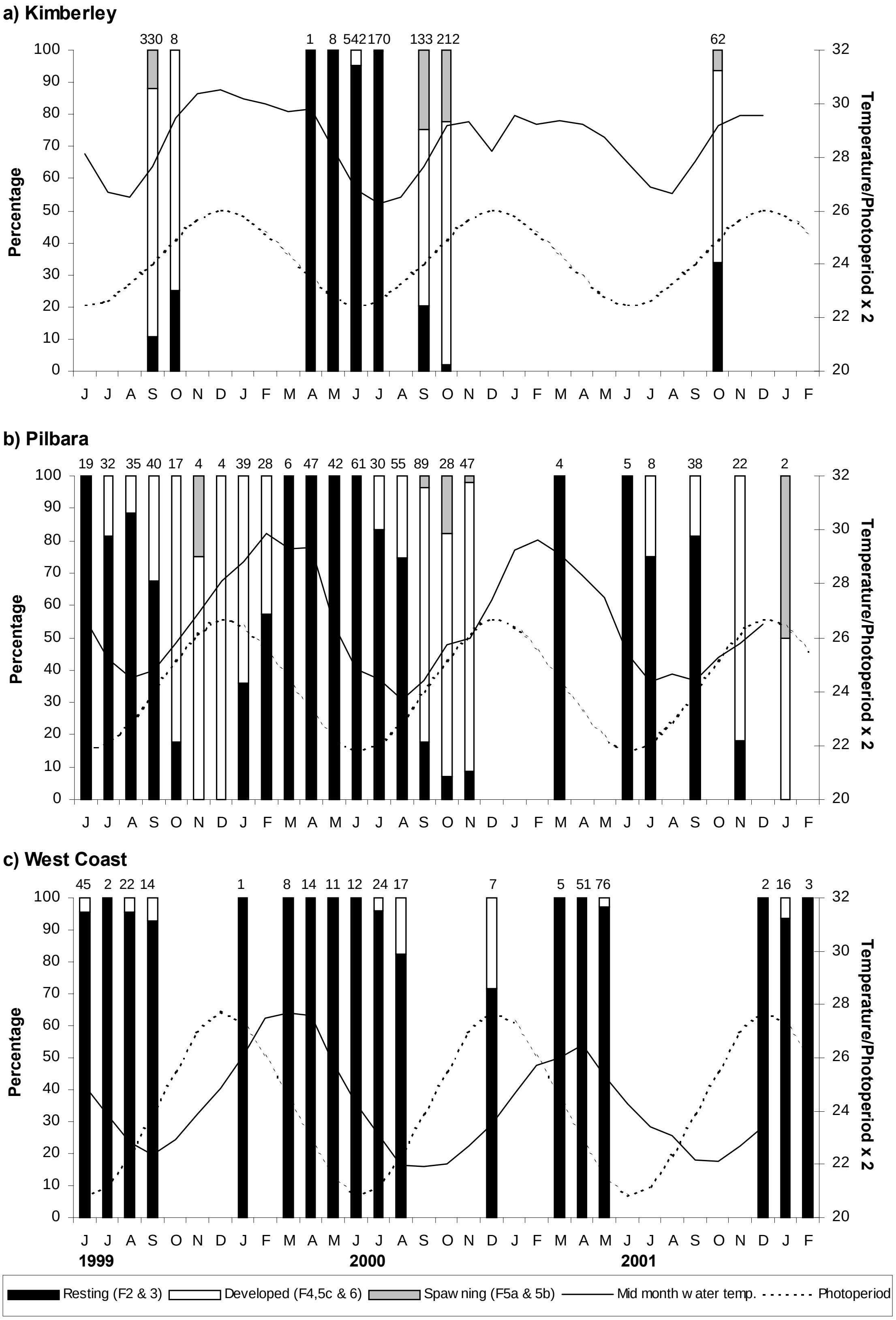


Figure 4.17 Annual cycle of *S. commerson* reproduction within each region, as indicated by macroscopically staged ovaries. Data for sea surface temperature and photoperiod are overlaid (units for photoperiod are in hours and multiplied by 2 on temperature scale). Sample sizes are shown above each column.

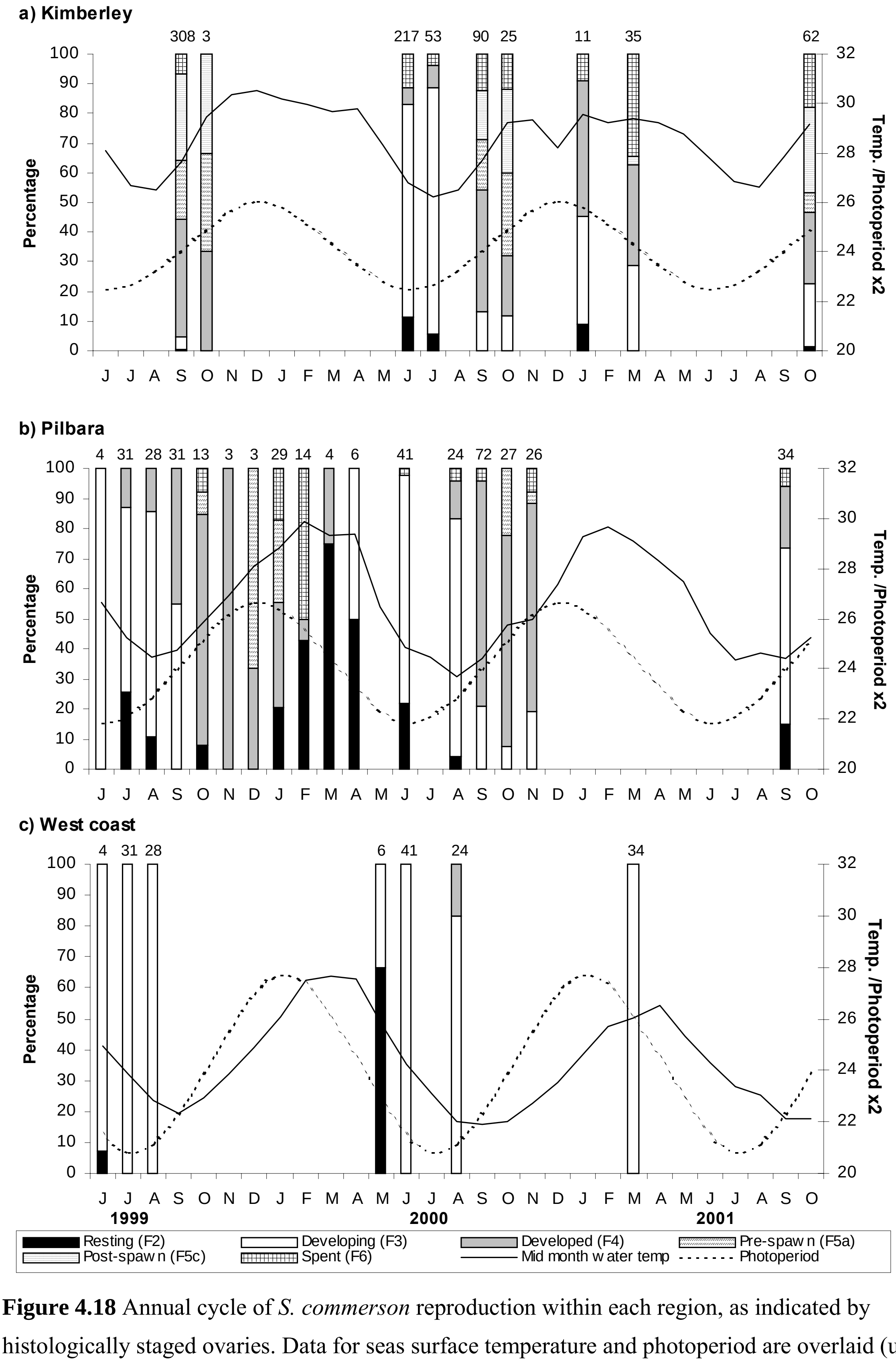
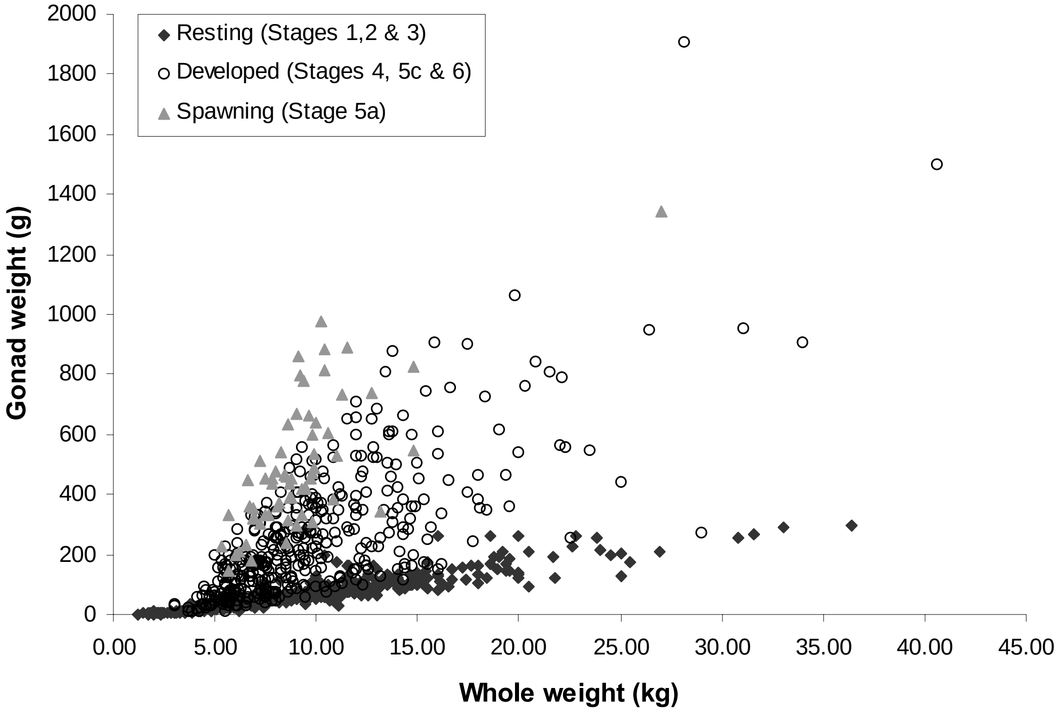


Figure 4.18 Annual cycle of *S. commerson* reproduction within each region, as indicated by histologically staged ovaries. Data for seas surface temperature and photoperiod are overlaid (units for photoperiod are in hours and multiplied by 2 on the temperature scale).

a) Ovary weight (N=893)



b) Teste weight (N=254)

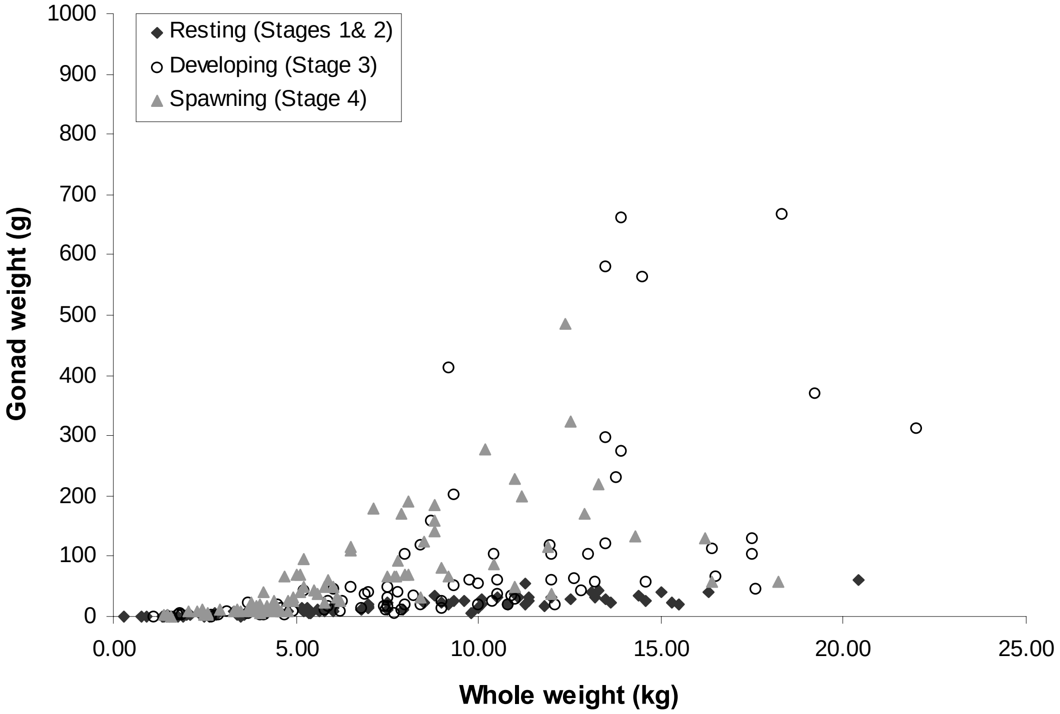
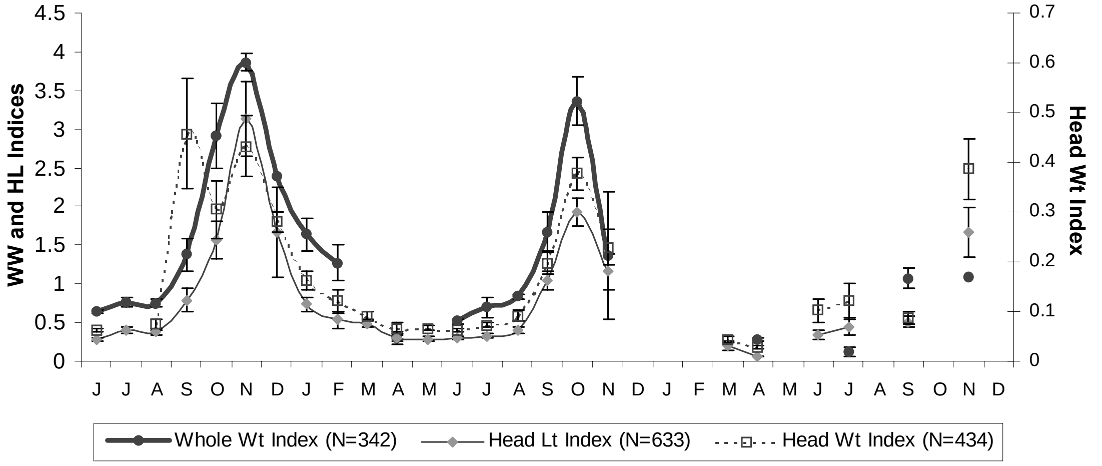
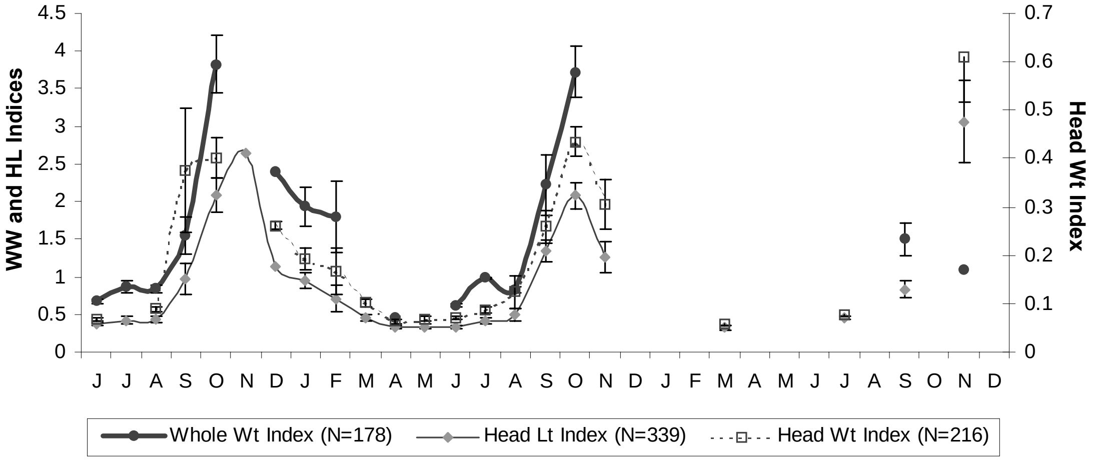


Figure 4.19 Relationships between gonad weight and whole weight for a) *S. commerson* females and b) males. Note different scales of charts.

a) Ovary indices-all data



b) Ovary indices - 9 to 18 kg Whole weight



c) Teste indices - 3 to 14 kg Whole weight

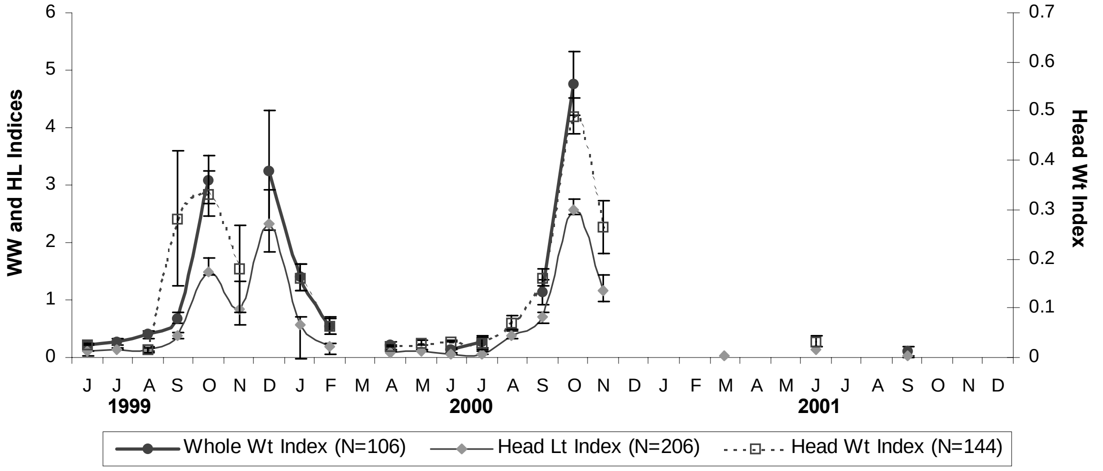


Figure 4.20 Annual cycle of gonad indices for *S.commerson* in the Pilbara region. Data shown for a) all females, b) females between 9-18kg whole weight, and c) males between 3-14kg whole weight.

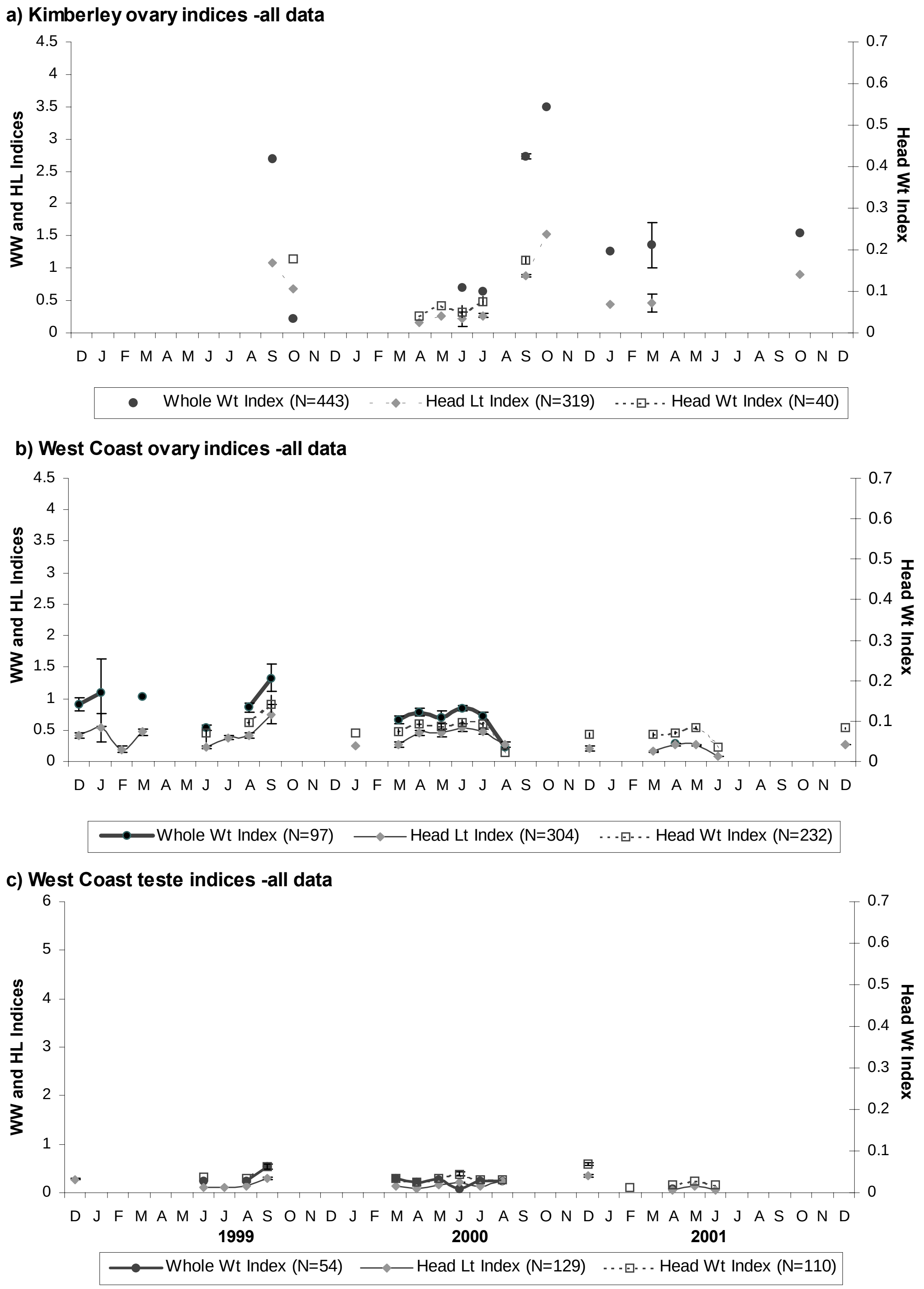


Figure 4.21 Annual cycle of *S. commerson* gonad indices for a) females from the Kimberley b) females from the West coast and c) males from the West coast region. Data for fish of all weights is included.

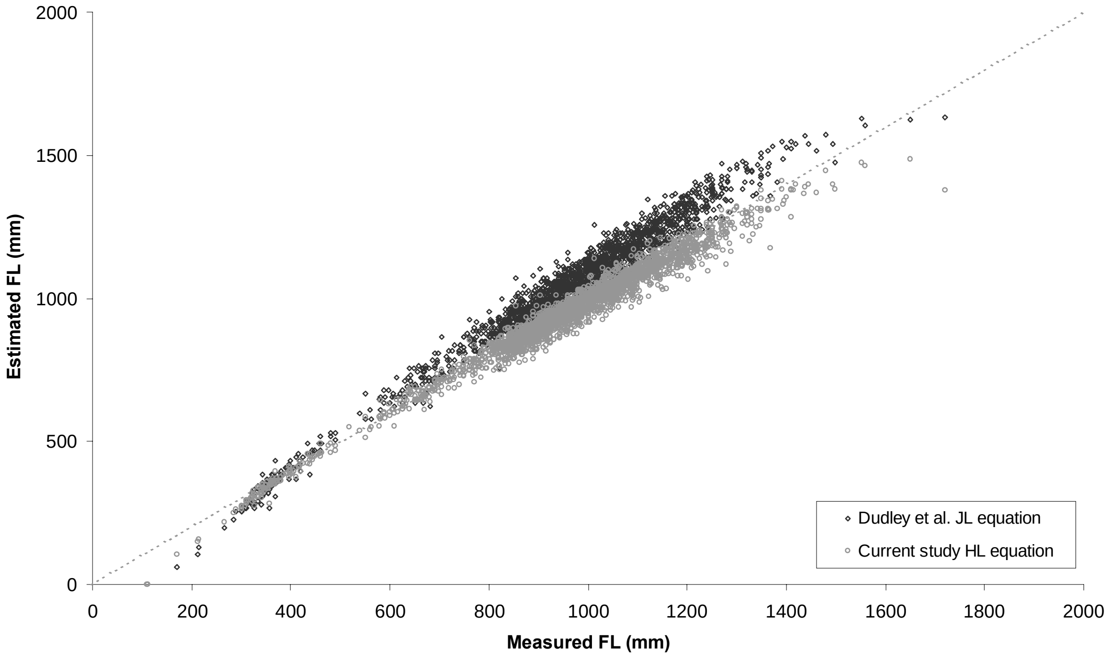


Figure 4.22 Comparison between estimated FL from the current study HL based equation and JL based equation given by Dudley *et al*. (1992) with measured FL for all *S. commerson* in the current study. Dashed line is the line of parity.

4.2 Discussion

S. commerson exhibited subtle spatial differences in morphological characteristics along the WA coast. This was also the case in QLD waters (McPherson 1992), although fish in the north of QLD tended to be heavier than in the south, whereas in WA the reverse was true. In WA at least, these regional differences may reflect different environmental regimes since most *S. commerson* do not appear to make lengthy long-shore migrations (Newman *et al.* In Prep.) as has previously been thought (e.g. Donohue *et al.* 1982, commercial fishers). Rather, evidence such as the rare capture of *S. commerson* from depths up to 50 m during the non-reproductive season, when they are not present in large numbers on the coast, suggest that most of the population move between coastal and offshore waters in time with reproductive activity. The other alternative is that the population remain in the coastal area all year round but become widely dispersed and economically unviable during the non-reproductive period. However, discussions with fishers as well as research-sampling experience indicate that whilst some *S. commerson* are present in coastal waters throughout the year, the majority of the population are not (observations by spear-fishers are particularly relevant since they are independent of line captures).

Sex Ratios

Female biased sex ratios were a feature of king mackerel (*S. cavalla*) catches during reproductive and non-reproductive months, most likely because of sex specific behavioural or biological traits (Trent *et al.* 1981, Sturm and Salter 1989). Begg (1998) also noted that biases in school and spotted mackerel (*S. queenslandicus* and *S. munroi*) catches on the east coast of Australia may be due to sexual differences in growth and mortality. Biological traits in particular are likely to have resulted in the tendency towards female bias in catches of *S. commerson*, principally because females grow faster than males (McPherson 1992, Chapter 5) and dominate the larger size groups above 1000 mm FL. They therefore dominate the exploitable biomass of the fishery in which the legal minimum length is 900 mm TL (809 mm FL).

The slight bias towards males during the main spawning period in the Kimberley region indicate that behavioural traits may also affect the composition of catches of *S. commerson* at this time. For instance, the rarity of actively spawning females in samples during the present study and in QLD based studies indicates they either move away from the reefs or stop feeding when spawning (Munro 1942, McPherson 1993). In contrast, spawning males were more common in the catch, thus resulting in a shift in bias towards male. Similar biases towards males were also found in catches of *S. queenslandicus, S. munroi* and *S. semifasciatus* during their respective spawning seasons in QLD and NT waters (Cameron and Begg 2002). This was thought due to sex-specific schooling or gill net selectivity with these species. Sex or size specific schooling may also affect sex/size distribution within catches of *S. commerson*, since it was noted during fishing sessions that similar sized fish were often caught within a short time period or dominated on a particular reef.

Reproductive biology and development

Classification of *S. commerson* ovaries into developmental stages was straightforward apart from the presence of cortical alveoli stage oocytes in some immature ovaries. As these oocytes were used to identify the onset of reproductive development in mature ovaries, a new category (F1a; immature developing) was established to distinguish between immature and mature developing ovaries when they were present (Mackie and Lewis 2001). Otherwise, estimates of biological parameters such as the size at sexual maturity may be adversely influenced. Beaumariage (1973) also noted that oocyte development in the ovaries of immature king mackerel (*S. cavalla*) sometimes proceeded into the vitellogenic stage. However these oocytes were thought to undergo 'rejuvenilisation' back to earlier stages of development without being spawned. In *S. commerson* they are more likely to atrophy rather than remain viable, as witnessed in some immature ovaries. As a consequence of such atresia, yellow-brown bodies (melano-macrophage centres) were occasionally observed in immature ovaries, even though these structures are usually associated with spawning activity, and hence sexual maturity, in fishes (Ravaglia and Maggese 1995).

The testes of *S. commerson* were more difficult to classify because there were no clear transition between stages in testicular development, and maturation of sperm through to the spermatozoan stage can occur at all stages of testicular development. Milt (sperm in the central sperm sinus or vas deferens) was also common in *S. commerson* testes, but was often more viscous than the milt released by running ripe males and was therefore unlikely to be immediately spawned. In other *S. commerson* the spermatozoa were still in crypts within the germ tissue or in efferent sinuses that were not open to the central sinus. These fish were unlikely to have spawned but may nevertheless be classified as spawning males given the relatively large amount of late stage sperm in their testis. The uncertainty in staging male gonads is further reason for using the development of ovaries for describing reproductive cycles in *S. commerson*.

To minimise the uncertainty in staging testes, criteria used to distinguish spawning from non-spawning male *S. commerson* included the volume as well as the location of the spermatozoa (Mackie and Lewis 2001). The presence of spermatozoa regardless of maturation class or season was also noted in the testes of congeners *S. cavalla* (Sturm and Salter 1989), *S. maculatus* (Schmidt *et al.* 1993) and *S. munroi* (Begg 1998), as well as cobia, *Rachycentron canadum* (Brown-Peterson *et al.* 2002). Brown-Peterson *et al.* (2002) note that traditional systems of classifying of testes based on abundances of sperm type (particularly spermatozoa) may not accurately reflect testicular development in a range of teleost species. The new classification system these authors used in their study of cobia, based on changes in the germinal epithelium and spermatogonial proliferation, is also likely to be more relevant for describing the development of *S. commerson* testes.

Minor atresia was regularly observed throughout the year in *S. commerson* ovaries. Significant atresia (> 50% of latest stage oocytes) was generally only common at the end of the spawning period as fish resorbed unspawned oocytes prior to entering the resting stage. Hunter and Macewicz (1985) also note that this is a normal occurrence at the end of the annual reproductive cycle of many fishes with indeterminate fecundity. Occasionally though, the gonad of an individual *S. commerson* underwent significant gonadal atresia at other times of year. For example, this occurred in the ovary of one particular female, apparently as a result of stress and injury since it was badly wounded near the tail and probably could not swim freely. This underweight female (22 kg WW for a TL of 1587 mm), had a resting ovary with large numbers of yellow-brown bodies whilst the ovaries of all other females in the same sample were reproductively developed. Significant atresia amongst groups of females was also noted at times other than at the end of the spawning season. These mass atretic events indicate that development of *S. commerson* gonads is sensitive to exogenous factors such as extremes of water temperature, as has been found in other species of fish (Lam 1983). Dickerson *et al.* (1992) further note that the prevalence of atresia in chub mackerel (*Scomber japonicus*) may show that females pass through more than one cycle of oocyte maturation, spawning and atresia within a season, and that spawning cycles are synchronised between schools rather than for the stock as a whole. This may also be the case for *S. commerson* since at times there were noticeable differences in the sexual development and size of fish found on particular reefs in the north Kimberley region.

Ontogenetic development and size at sexual maturity

Histological evidence shows that *S. commerson* has a gonochoristic life history, with the gonad differentiating into an ovary or testis at around 300-400 mm FL. However, the capture of two abnormally large juveniles (ca. 1200 mm FL) shows that this process may be delayed or not occur at all. These large juveniles might be expected to be relatively large for their age because they have put little energy into reproduction. This was not the case for one which, at seven years of age was of similar size to other fish of that age. The other was just two years old - not old for an immature fish (Chapter 5) - showing this fish had an unusually rapid growth rate for this species.

Earlier development of the testis relative to the ovary was noted in *S. maculatus* (Schmidt *et al.* 1993) and *S. cavalla* (Beaumariage 1973) in US waters. In the present study this was also apparent from the differentiation of the juvenile *S. commerson* gonad. The size of the smallest mature male (491 mm FL) was also less than that of the smallest mature female (641 mm FL) and less than the size of the smallest mature *S. commerson* in Omani waters (650 - 700 mm FL; Kingfish Task Force 1996), providing further evidence of spatial differences in developmental patterns for this species.

Females in QLD waters may also reach sexual maturity at a larger size than those in WA waters (smallest = 790 mm FL; McPherson 1993). Consequently, legal minimum lengths for *S. commerson* in WA should be set independently from those in other areas. Data from the present study show that the current minimum length (900 mm TL) for this species in WA is appropriate as it is close to the size at which 50% of females reach sexual maturity. In contrast, > 90% of the male population will be sexually mature by the time they reach the fishing size limit. This sex-specific difference in fishing mortality is one likely reason for female biased sex-ratios described above, with possible consequences under heavy fishing pressure of diminished egg production and selection for slower growing females. Ultimately, this may lead to a reduced reproductive output and reduced differences in growth rates between the sexes. Although the poor survivorship of released *S. commerson* brings to question the usefulness of a size limit, it nevertheless acts as a deterrent because many commercial fishers tend to avoid areas where smaller individuals are known to aggregate.

The reasonable fit of data points to the maturity curve developed for female *S. commerson* in the present study suggests that the estimated size at maturity is appropriate throughout much of the WA coast. However, regional differences in various body weight and length regressions indicate that there may be some spatial variation. Finucane *et al.* (1986) also found that the estimated size at maturity for *S. cavalla* varied between areas. Further research is therefore needed to examine regional variation in this parameter for *S. commerson* along the WA coast.

Reproductive cycle and spawning

The large size of *S. commerson* testes (up to about 5% of body weight), apparent ability to store sperm and relatively small size at which males attain sexual maturity implies a surplus of sperm in the spawning population. This suggests sperm competition between males, with spawning groups comprised of multiple males and females. The more limited production of oocytes further indicates that females are the limiting factor in terms of reproductive output and may control the timing and extent of spawning in this species.

Spatial and seasonal spawning patterns

Spawning activity of *S. commerson* exhibits a southerly decline, with little or none occurring south of North West Cape within the period of this study. Discussion with fish processors and fishers suggests, however, that limited spawning may possibly occur during some years in the Carnarvon area. Certainly, the known southern extent of spawning along the west coast (approx. 22º S) is less than that reported for *S. commerson* on the east coast, where spawning may occur as far south as Bundaberg (approx. 25º S; McPherson 1981). The Leeuwin Current, a warm water current flowing southwards down the WA coastline extends the southerly range of many tropical species (Caputi *et al.* 1996), and may also influence the southern spawning range of *S. commerson*. Thus in years when the Leeuwin Current is stronger the southerly extent of spawning may be increased.

It is likely that there are spawning hotspots for *S. commerson* along the WA coast. The main spawning reefs found during the present study extend northwest between 12.5 and 15º S in the north Kimberley region. Spawning by this species in QLD waters was also concentrated on certain reefs, particularly at about 19º S (Munro 1942, McPherson 1993). In the Kimberley region mackerel fishing is concentrated on the hotspots during the spawning period, whereas earlier in the season when the fish are less reproductive, fishing activity is concentrated further south between about 16 and 20º S. The difficulty of catching *S. commerson* in the south Kimberley region during the reproductive period (from September onwards) suggests that they are no longer there in large numbers and little spawning takes place in that area. Evidence for this was obtained during a sampling trip in 2001 to assess the utility of the daily egg production method to estimate the spawning biomass of *S. commerson* (Chapter 7). During this trip few fish were caught in the south Kimberley region, and none were in spawning condition, whereas many of those captured a few days later in the northern grounds had recently or were about to spawn. Fish in the southern area may therefore migrate to spawning grounds located elsewhere, such as in the north Kimberley, where they mix with other spawning populations that are otherwise temporally and spatially discrete. This has also been found among populations of king mackerel, *S. cavalla,* in US waters (Broughton *et al.* 2002). Alternatively, these fish may remain within the same area of coastline but move offshore to spawn on reefs located in deeper waters, or onshore into locations such as King Sound where numbers of *S. commerson* have previously been observed during the reproductive months. This onshore - offshore movement of fish is supported by otolith isotope data, which showed that *S. commerson* captured in mid and north Kimberley locations do not mix to any significant degree (Newman *et al. In Prep*.).

Catches of spawning females in the Pilbara region were also spatially aggregated, although relatively few were collected compared to the Kimberley region. This may be partially due to the later commencement of spawning in the Pilbara region, since inclement weather often reduces fishing time during the spring/summer spawning period. The effect of weather is further compounded by the fact that fishers tend to target offshore reefs at this time as fish become less abundant on inshore lumps. Given the fairly limited long-shore movement of *S. commerson* along the WA coast (Newman *et al.* In Prep.), the greater abundance of mackerel on deep reefs during the spawning period again suggests that many are moving further offshore to spawn. It is therefore possible that the lack of spawning fish south of North West Cape may also be due to the movement of fish away from the coast before they become reproductively active. Certainly, the annual range of SST in the Gascoyne region (*ca*. 22-28° C) overlaps with the preferred range of temperatures for spawning of fish in the north (*ca.* 25.5-28.5° C in the Pilbara region), and it seems unusual from an evolutionary perspective that there would be nonspawning adults residing in these waters. Sampling of *S. commerson* found in offshore waters of the Gascoyne region after the finish of the seasonal coastal fishery is therefore essential as the spawning status of these populations has important management implications.

Water temperatures were considered important in the movement patterns of *S. commerson* in waters of Oman (Kingfish Task Force 1996) and in an early study of this species along the WA coast (Donohue *et al.* 1982). The present study showed that spawning occurred within a SST range of about 3° C, with the earlier commencement of spawning in the Kimberley region reducing the differences in the SST regime of spawning between the two northern regions. Timing of the spawning period for this species may also vary with location on the east coast of Australia, and be earlier in the north (McPherson 1981). In the Torres Strait, which is about 3-5º to the north of the north Kimberley grounds, the spawning period was protracted, extending from August right through to March. In contrast, spawning between Lizard Island and Townsville (equivalent in latitude to the south Kimberley grounds) may occur from October to early December (McPherson 1981), and is thus more comparable to spawning in WA. Although restricted to October and November, spawning was also recorded in southern waters between Gladstone and Bundaberg (McPherson 1981), which is equivalent in latitude to the Gascoyne region of WA where no spawning was found. Schmidt *et al.* (1993) also note that Spanish mackerel (*S. maculatus*) in US waters spawned during late spring/summer months (May to August), indicating similar patterns to *S. commerson* in Australia.

The influence of water temperature on gametogenesis, spawning and gonad atresia has been shown to be important in many species of fish, and may act in unison with photoperiod (Lam 1983). Beaumariage (1973) considered that photoperiod was an important cue in the development king mackerel (*S. cavalla*) gonads in Florida, and initial yolk formation occurred as the photoperiod exceeded 13 hrs. However, photoperiod is likely to have less influence on reproduction in species that spawn in higher latitudes because the amplitude of the cycle is reduced (Lam 1983). This may be the case with *S. commerson* along the WA coast, which spawn during photoperiods that barely reach 13 hrs and vary around 1.75 to 2 hrs compared to approximately 4 hrs of variation experienced by *S. cavalla*.

Better understanding of spawning by *S. commerson* along the WA coast will require more detailed information on water movements, water temperatures and offshore topography (particularly in the north). Further biological information (particularly of fish in deeper waters) is also required, as is fine-scale movement data of mackerel, using techniques that permit greater temporal resolution of the elemental composition of otoliths.

Potential batch fecundity

Batch fecundity of *S. commerson* has not previously been recorded and similar data is rare for other *Scomberomorus* species. Fecundity data for *S. commerson* from the Indian Peninsula by Devaraj (1983) are not comparable, because this data were apparently estimated from diameters and weights of all oocytes > than 0.25 mm. This does not provide an estimate of batch or annual fecundity in multiple spawning species such as *S. commerson*, because oocytes of this size will be both vitellogenic and previtellogenic (Mackie and Lewis 2001), and new batches of vitellogenic oocytes are likely to be matured throughout the spawning season (Hunter *et al.* 1985). For the same reasons, estimates of fecundity by Finucane and Collins (1984) for *S. regalis*, and by Finucane *et al.* (1986) for *S. cavalla* (both species considered serial spawners by the authors) are not comparable with the estimated batch fecundity of *S. commerson*, as in both cases counts of eggs ≥ 0.2 mm diameter were used.

Spawning fraction

Estimates of spawning frequency based on the macroscopic staging of ovaries with hydrated oocytes were relatively low (5.8 days) compared to the 2.9 days for the same samples analysed histologically. This is due to the inability to macroscopically identify migratory nucleus oocytes, which comprised 53.9% of the histologically staged, pre-spawning (F5a) ovaries, and are part of the spawning batch (Macewicz and Hunter 1993). Further, it is impossible to identify fish that have spawned on more than one occasion using macroscopic criteria, resulting in a further underestimate of spawning fraction and frequency.

Spawning fraction and frequency have also been estimated from the proportion of ovaries with POFs (Hunter and Macewicz 1985). Use of this method requires histological examination of all ovaries because macroscopic examination is not reliable for detecting post-spawning ovaries (Mackie and Lewis 2001). It also requires the sampling of ovaries containing new POFs, since old POFs persist in the ovary for at least 24 hrs after spawning (as also suggested for *S. commerson* in QLD waters; McPherson 1993) and do not permit differentiation between spawning events. Sampling must therefore be undertaken in the afternoon to obtain ovaries with new POFs, although this may result in underestimates of spawning fraction because of the inability to catch spawning females. Further, sampling should occur after all fish have finished spawning, which may not happen until after dusk when *S. commerson* are usually less catchable and fishing is not practical. Ovaries with hydrated/migratory nucleus stage oocytes obtained in the mid to late morning period prior to spawning will therefore provide a more reliable estimate of spawning fraction. Sampling at this time should reduce the underestimate of macroscopic staging since most oocytes will have become hydrated, and they will also be suitable for estimates of batch fecundity.

S. commerson in QLD waters may spawn with similar frequency to those in WA (every 2 – 6 days; McPherson 1993). McPherson also considered that daily spawning may be possible for some females in QLD, as was shown for about a third of the spawning females during the present study. This increases the incidence of spawning for females, although there was little evidence to suggest that any spawned on more than two consecutive nights. If females spawn consistently every third day or so during the peak spawning period (*ca*. 4 months duration) the potential number of spawns over this time is about 40. Since about a third of spawning females also spawn on consecutive days this total could be considerably more. A 10 kg female with an average batch fecundity of about 750 000 eggs therefore has the potential to produce about 30 million eggs over the spawning period. However this figure may be significantly reduced if individual spawning success is influenced by social, environmental and biological factors.

Diel spawning pattern

S. commerson spawn during the mid to late afternoon period in the Kimberley region. Few samples were obtained at or after dusk because fish are usually uncatchable at this time; nevertheless, spawning at dusk is prominent among pelagic spawning species that inhabit tropical reefs (Thresher 1984) and cannot be discounted for *S. commerson*. Spawning in the afternoon is uncommon and may be linked to the large tidal cycles and strong currents in the north of WA, as suggested for snapper (*Lutjanus vitta*) that also spawn in the afternoon in the Pilbara region (Davis and West 1993). Numerous explanations for the timing and location of spawning in fishes have been proposed in the literature, including decreased predation and increased dispersion of eggs (Shapiro *et al.* 1988). Dispersal of eggs and larvae may be of particular importance in the stocking of downstream populations, but more detail on environmental parameters and spawning patterns are needed to elucidate the strategies employed by *S. commerson*.

McPherson (1993) determined that maturation and ovulation of oocytes in the ovaries of female *S. commerson* in Queensland waters occurs over 24 - 36 hours. Our data suggest that this process is quicker for female *S. commerson* in the Kimberley region, with the whole cycle of final oocyte maturation, ovulation and spawning completed within a 24 hour cycle. It is certain that spawning does occur in the afternoon, with the bulk of fish probably spawning sometime between late afternoon and the early hours of darkness, as suggested for *S. commerson* in Queensland (Munro 1942). However, it is impossible to say when the incidence of spawning peaks, when it is completed, and when final maturation of the new batch of oocytes commences because of the lack of night samples. Certainly, maturation of the oocytes is underway by sunrise and is probably completed in all spawning ovaries by mid to late morning to allow for ovulation prior to spawning in the afternoon. The timing of these events may also be influenced by environmental factors such as currents and water temperature (Lam 1983).

Management

An important aim of biological studies of exploited species is to provide advice on susceptibility to overfishing and measures that may assist in preventing or reversing this. Seasonal or spatial closures are a possibility in the case of *S. commerson* because they aggregated at known reefs. Such closures may be of particular benefit in the north Kimberley region to reduce disruption to the spawning population. However, protection of spawning fish may be less relevant in the Pilbara region where much of the catch is taken prior to spawning. The effectiveness of such measures requires more information on the movement of fish between reefs and should also consider the economic impact to fishers who catch a substantial proportion of their annual catch during the reproductive period. The ability to properly enforce these measures will also need to be considered. Further assessment of the contribution by populations south of 27° S to the generation of new offspring is also essential in order to determine their reliance on recruits generated by populations to the north. Although generally of fairly limited commercial value, these southern populations are of considerable recreational importance and appropriate resource allocation between fishing sectors should be considered in their management.

Future monitoring of *S. commerson* will require cost-effective collection of samples. Hence the search for a means of estimating body length from head parameters because heads are the easiest and cheapest option for doing so. Their usefulness is further enhanced if the gonads are still attached, since the length data can then be structured by sex and the head to gonad ratio is as good an indicator of reproductive activity as the conventional gonadosomatic index. Furthermore, because they contain the otoliths, age of the fish can also be obtained. The model for estimating FL of fish in the Kimberley region proved to be most suitable for estimating lengths of fish throughout WA. Whether it is appropriate for fish outside of WA will need to be confirmed, although a comparison with a model derived for fish in Oman by Dudley *et al.* (1992; Figure 4.22) suggests that spatial differences may occur in the relationship between head and body parameters. Finally, information gained from the present study supports the recent changes in the size limit from 750 to 900 mm TL as this concurs with the estimated size at which 50% of the female population has reached sexual maturity.

5.0 Age and growth

M. Mackie and P. Lewis

5.1 Results

Between May 1998 and June 2002 a total of 3781 sagittal otolith pairs were collected from *S. commerson* within the three regions of Western Australia and the western Northern Territory (Table 5.1). Of these, 2973 were weighed and measured before those of 2220 adult and 68 juveniles were sectioned for analyses. Total length (TL) of fish from which otoliths were sectioned ranged from 62 to 1780 mm, with 1278 lengths obtained from females, 842 from males and 98 from fish of unknown sex.

Description of S. commerson sagittae

The sagittal otolith of *S. commerson* is an elongate, fragile structure with a slightly concave distal surface. It has a long, narrow rostrum, relatively short antirostrum and fairly straight ventral margin that angles downwards at the posterior to a rounded or angular point (Figure 5.1). The edges are generally smooth or have fine growth reticulations. The sulcus acusticus is relatively broad at the posterior margin but narrows anteriorly towards the junction of rostrum and antirostrum. An alternating series of opaque and translucent zones were discernable towards the posterior margin of dried whole otoliths when viewed with reflected light. Striae (McPherson 1992) radiating lengthways from the focus were also evident within translucent zones posterior of the core. These striae were generally present up to the third and occasionally to the fifth translucent zone within the posterior margin of whole otoliths.

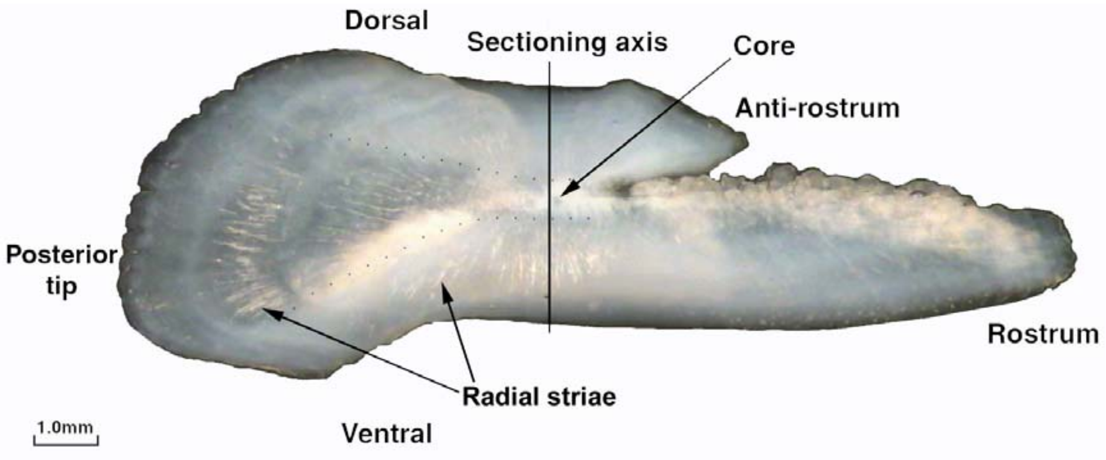


Figure 5.1 Whole right sagittal otolith of *S. commerson* showing orientation, features, location of the core, sectioning axis, radial striae, and outline of sulcus acusticus (dots).

In cross section the otoliths of juvenile fish exhibited a concentric series of regularly spaced microincrements (Figure 5.2a), each comprising an opaque and translucent zone. Generally, the region around the primordium of the otolith containing the first 30 microincrements was opaque and required a higher light intensity for the rings to be clearly visible. The outer microincrements were usually faint but could be clarified by lowering the light intensity and adjusting the phase contrast platform of the microscope to give more contrast.

Annuli were a feature of the internal structure in otoliths of adult fish. Within the otolith cross section the radial striae generally extended for 3-4 months of growth (based on microincrement counts). This was often followed by a marked change in the deposition of the otolith material that resulted in a 'bump' in the ventral margin between about the 110th and 150th microincrements. This also coincided with a change in the relationship between body length and the number of microincrements (see age and growth analyses below), and was often associated with a false (secondary) annulus (Figure 5.2b). The true (and first primary) annulus followed soon after. This first annulus was generally broader and less distinct than subsequent annuli and was often difficult to identify. This was particularly the case in otoliths less than two years old which did not yet have the distinct annuli structure of older fish. In these younger fish the measurements from microincrement analyses were therefore important in determining the thickness and structure of the otolith sections at 1 year of age. In some otoliths this pattern of closely associated true and false annuli continued for numerous years. In other otoliths they appeared to have fused into one broad opaque zone, which could be 3-4 times wider than the translucent zone.

5.1.1 Validation of otolith increment periodicity

Microincrements

The periodicity of microincrement deposition was not validated as part of this study. Nevertheless, the consistency in the width of these increments within the otolith indicates that they are deposited with a regular periodicity. As microincrements in *S. maculatus* (Peters and Schmidt 1997) and *S. niphonius* (Shoji *et al* 1999a) have been shown to be formed on a daily basis, this was also assumed to be the case in *S. commerson* otoliths.

Annuli

- *Calcein marked otoliths*

One hundred and eighty one *S. commerson* (112 in the Dampier region and 69 in the Shark Bay region) were tagged and injected with calcein solution before this component of the study was halted due to the low tagging rate and the low recovery rate of those that were successfully tagged and injected. The low tagging rate was due to a high loss of hooked fish to sharks, the amount of time taken to revive each tagged fish, and the low abundance of mackerel when the study was conducted at Dampier (see Lewis and Mackie 2002 for details).

The tagged and injected fish covered a wide size range, including many juveniles from the Dampier region (Figure 5.3). To date only two of these fish have been recaptured from the Shark Bay region, however, for both of these the time at liberty was less than one month. As such the tagging component provided no validation to date of the periodicity of annulus formation in *S. commerson* otoliths.

- *Marginal increment analyses*

A complete monthly series of otoliths for marginal increment analyses (MIA) was achieved in the Pilbara region, although in all regions an annual cycle in the predominance of each category was evident (Figure 5.4). Otoliths within each category were present throughout the year. Those with category 2 margins (1-50% of previous translucent zone) were most common. In the Pilbara region otoliths with opaque (category 1) margins were most abundant in December and January (Figure 5.4b**)**, those with category 2 margins (1-50% of previous translucent zone) present from February to July, and those with category 3 margins (51-100% of previous translucent zone) present from August to November. This logical progression of each category (each peaking for 2-6 months of the year) appears to be repeated in the Kimberley (NT samples included) and west coast regions, although in the latter region the cycle appears to be a month or two in advance (Figures 5.4a and c).

The annual cycle of margin categories in the Pilbara was also evident in the otoliths of *S. commerson* within pooled age groups of 1-2 yo, 3-5yo and 6yo+ age groups (Figure 5.5 a**,** b and c). The annual cycle was clearest for fish within the 3-5yo age groups, in which otoliths with opaque margins were most common from December to March, those with category 2 margins from April through to August, and those with category 3 margins from September through to November. However, the pattern was less defined than for 1-2 yo and 6yo+ age groups. In the 1-2yo age group there were relatively few otoliths with opaque margins whereas those with category 2 margins dominated. However, the reverse was true for the older fish in the 6yo+ age group.

Comparison of margin categories between sexes (age groups pooled) indicated that otoliths of females have a clearly defined pattern in the progression of each category through the year (Figure 5.6a**,**b). The pattern in margin categories of male otoliths is less distinct although an annual periodicity of annuli is nevertheless evident and there is some suggestion of an opaque band forming in May.

Formation of the opaque zone in fish from the Pilbara region mainly occurs during the time of year when water temperatures are rising (Figure 5.7). This was completed in most otoliths by the time water temperatures had peaked in 2000 (February), with the period of decreasing temperatures coinciding with the appearance and growth of the new translucent zone. By August, when water temperatures were lowest in 2000, the translucent zone of many fish was relatively broad, and as water temperatures began to increase again so did the number of otoliths that were forming an opaque zone.

5.1.2 Analyses of the precision between counts and the readability of otoliths

Juvenile otoliths

Otoliths from 72 *S. commerson* ranging in fork length from 58 to 781 mm were successfully sectioned, mounted and read for microincrement counts. The method used, although time consuming (up to 2 hrs to process each section), located the primordium of the otolith in 95% of these sections. The double counts of 63 of the 72 (87.5%) otoliths were within 10% of each other, whilst a third count of the remaining nine otoliths were within 10% of a previous count. The calculated index of average percent errors (APE; Beamish and Fournier 1981) between the initial two microincrement counts was 2.9%.

Adult otoliths

- *Sectioned otoliths*

At the completion of the first two readings, 4 (0.3 %) of the sectioned *S. commerson* otoliths were rejected as being unreadable (Table 5.2). In one case this was due to an abnormal structure in the otolith, and when the other otolith of the pair was sectioned it could be read successfully. For the remaining 2211 otolith sections the agreement between the initial two counts of annuli by the primary reader was 76.8%, which increased to 79% for the adjusted final age. The 456 sectioned otoliths for which the ages differed were re-examined and an additional 15 otoliths were rejected when none of the three readings agreed. Overall only 20 sectioned adult otoliths (0.9%) were rejected as being unreadable or of indeterminable age whereas most otoliths had fair or good readability (categories 2 or 3; Table 5.2). There were relatively minor and inconsistent differences between the readability of male and female otoliths, however otoliths from the Kimberley region were noticeably harder to read than those from the other regions.

The APE between the two initial counts of annuli and between the adjusted ages (see below) were 4.4% and 3.7%, respectively. The test of the symmetry (Hoenig *et al.* 1995) indicated a significant difference between the two annuli counts (Chi-squared =49.7, df=30, *P*=0.015) but not between the adjusted ages (Chi-squared =41.4, df=33, *P*=0.17). Further investigation of the source of bias, based on tests of symmetry for select age groups, revealed that the counts for fish less than 9 years were biased by a tendency for the first count of annuli to be higher than the second (Chi-square =35.0 , df =13 , *P* =0.0001). No bias was evident in the counts for fish greater than 8 years (Chi-square =14.7 , df =17 , *P* =0.6).

The bias in ageing of younger fish was due at least in part to a variation in the interpretation of the marginal increment categories between the two readings. Otoliths that were allocated to marginal increment category 2 in reading 1 were allocated to category 0 in reading 2 and subsequently had an additional annulus counted. However, as most of these cases occurred during the period of opaque zone formation, the subsequent adjustment of the counts to determine the final age of each fish allowed for this difference in interpretation of the margin.

Of the 207 randomly selected otoliths aged by the secondary reader there was only 46% agreement with the ages assigned by the primary reader. The calculated APE for adjusted ages was 11.9% and the test of symmetry showed a significant difference (Chi-squared =43.41, df=28, *P*=0.035). Further testing showed that the difference was significant for fish ≤ 5yo (Chi-squared =25.31, df=13, *P*=0.02) and not significant for fish > 5yo (Chi-squared =11.2, df=11, *P*=0.45). This was due to the secondary reader counting more annuli than the primary reader. Exclusion of the readings by the second reader for otoliths with a low readability index only marginally increased the agreement between the readers to 51.8% but removed the significant difference in the symmetry.

- *Whole otoliths*

Two hundred and ninety two otoliths were selected for assessment of the ageing of whole *S. commerson* otoliths. Criteria for selection was otolith-section readability, with 92, 100 and 100 from Readability Categories 2, 3 and 4, respectively. Of these, 285 (97.6%) were successfully aged, with 75.1% agreement between the ages assigned by the two whole otolith readings. The APE was 3.8% and the test of symmetry showed that there was no significant difference between the ages of the two readings. These results were similar to those for the sections of these otoliths, in which 96.6% were successfully sectioned and aged, 75.5% of the two readings provided the same age, the APE was 4.4% and the test of symmetry was non-significant.

Fifteen otoliths (5.1%) of the 292 otoliths could not be aged by either the whole or sectioning method. For the remaining 277 otoliths there was 61.0% agreement between the adjusted ages assigned by the two methods, an APE of 6.3% and the ages were not significantly different (Paired t-test; t=0.247, P=0.805, df=276). The test of symmetry indicated a significant difference between the two ageing methods (Chi-square=71.57, df=41, *P*=0.003), particularly in the ageing of fish less than 4 years old (Chi-square=40.9, df=11, *P*=0.001). However there was no apparent bias in the ageing of these fish (Figure 5.8). Subsequent comparison of the marginal increments (MI) assigned to each otolith by the two ageing methods showed only 44.4% agreement and the test of symmetry indicated a significant difference (Sum=53.7, df=3 *P*=0.001). This was due in part to differences in interpretation of the otolith margin of sectioned and whole otoliths, leading to dissimilar marginal increment categories and hence different age estimates for each otolith (Figure 5.9). Although there appears to be a bias in the ageing of fish older than 12 years (Figure 5.8), the test of symmetry for these fish was not significant because of the low numbers in this age group (n = 25). The median difference between ages determined from whole and sectioned otoliths was 0 for females (range – 3 to 3) and 0 for males (range – 4 to 2.5).

The readability of otoliths when read whole and sectioned could not be compared by region because too few otoliths from the Kimberley region were represented in the fair and good (3-4) readability categories. This reflects the general pattern of decreased readability of otoliths from the Kimberley region compared to those from other regions. Comparison of readability categories given to whole and sectioned otoliths generally showed good agreement, although a greater number of otoliths with poorly readable sections were easier (fair) to read whole (Table 5.3).

Examination of the agreement between whole and section ages within each readability category indicated that as readability increases the % agreement also increased (Table 5.4). This trend was particularly evident for whole otoliths, where only 33% of those with poor readability were given the same reading as sectioned otoliths, in contrast to 79% for whole otoliths with good readability.

5.1.3 Age and growth analysis

Assuming daily periodicity of microincrements in *S. commerson* otoliths, the small juvenile and immature fish aged from counts of otolith microincrements ranged from 23 to 204 days (Table 5.5). Birthdate for most of these was subsequently back-calculated to between November and January, although several of the older juveniles appear to have been born in

July and August (Figure 5.10). The smallest male aged from counts of microincrements was 284 mm FL and 80 days old, and the smallest female was 396 mm FL and 122 days old. Two unusually large juveniles were also collected. These measured 1170 and 1251mm FL, and were aged at 2 and 7 years, respectively.

The age distributions of male and female *S. commerson* aged from annuli overlapped considerably. However, males dominated the older age classes as only 10 of the 37 fish aged 15 years and over were female (Figure 5.11a-c). The maximum age of fish in southern waters also appears to be greater than in the north (Table 5.5). In the Kimberley region the oldest fish was 12.5 years, and 80% of fish were less than 5 years, whereas in the Gascoyne and Pilbara the oldest fish were 18.5 and 22 years (Figure 5.2c), with 5.1 and 3.8% of fish greater than the Kimberley maximum age, respectively.

Relationships between otolith and body parameters and age

A summary of the otolith length and weight data obtained for *S. commerson* during this study are provided in Table 5.6. These otoliths increased in weight and length with body weight and length, in a linear manner when comparing weight – weight or length – length parameters, and curvi-linear when comparing weight – length parameters (the latter linearised by log-log transformation; Table 5.7**,** Figures 5.12a-c and 5.13a-c). The relationship between fork length and the three otolith parameters (length, antirostrum length, and weight) exhibited increasing variance with body size, but was less variable than the relationship between whole weight and the otolith parameters. Coefficient of determination (r^2) values indicate that the otolith parameter which explained most of the variability in body parameters was otolith weight (95% or more using log-log transformed data; Table 5.7).

Both otolith weight and length increase in a non-linear manner with age (Figure 5.14a-c). Length of the otolith increases rapidly in young fish until the otolith is about 9 mm long (6 mm antirostrum length) but then slows and becomes highly variable with increasing age. The otoliths of females exhibit greater growth than those of males after about 2 years and an otolith length of about 16 mm. After this age the otoliths of male fish grow very little in length. Otolith weight appears to be the single best otolith parameter for predicting age, as it shows least variability and continues to increase over the lifetime of the fish. Again, there is significant variability between sexes after about 2 years and an otolith weight of about 0.07 g.

The (transformed) age of male *S. commerson* from the Kimberley and Pilbara regions were most accurately described using a combination of head length (HL) and the cube root of otolith weight ($\sqrt[3]{OW}$), whereas age of females from these regions were best described using a combination of the cube roots of whole and otolith weights (Table 5.8, Appendix 5, Table A5.1). The model describing these relationships is:

$$\text{Age (yrs)} = \frac{b}{1-1.3b},$$

where for

i) Kimberley females $b = \sqrt{-0.479 + (0.0478 \times \sqrt[3]{WW}) + (0.95 \times \sqrt[3]{OW})}$

ii) Kimberley males $b = \sqrt{-0.3400 + 0.00167HL + (0.97 \times \sqrt[3]{OW})}$

iii) Pilbara females $b = \sqrt{-1.1208 - 0.00071HL + (0.86 \times \sqrt[3]{OW}) + (0.131 \times \sqrt[3]{WW})}$

iv) Pilbara males $b = \sqrt{-0.2939 + 0.00204HL + (0.63 \times \sqrt[3]{OW})}$

and HL = head length (mm), OW = otolith weight (gm), and WW = whole weight (kg).

The fact that head length and otolith weight provide the best estimation of male age is fortuitous since future research of *S. commerson* is likely to be based on samples of heads and gonads. For this reason the head length and otolith parameters that best described age of females were also determined. As with males, these proved to be head length and the cube root of otolith weight for females in both regions (Table 5.8, Appendix 5, Table A5.2). The r^2 values of these models indicate a loss in explanation of variation in the data of 0.8% and 4.2%, for females in the Kimberley and Pilbara region respectively, compared to models based on all parameters. The regressions describing this relationship is:

$$\text{Age (yrs)} = \frac{b}{1-1.3b},$$

where for

i) Kimberley females $b = \sqrt{-0.1469 + 0.00058HL + (0.99 \times \sqrt[3]{OW})}$

iii) Pilbara females $b = \sqrt{-0.2045 + 0.00065HL + (1.07 \times \sqrt[3]{OW})}$

The estimated ages derived from the above regressions appear to model growth of *S. commerson* well (Appendix 5, Figure A5.1). New regression equations to describe transformed age from HL and $\sqrt[3]{OW}$ were subsequently developed for males and females within the two regions (Table 5.9a). A composite predictor variable was then derived from the two parameters in order to simplify the regression equation. This composite variable was weighted by the ratio of the constants for the two parameters (for simplification a mid-weighting of 600 was used), to arrive at the final model to estimate age (Table 5.9b):

$$\left(\frac{age}{(1+1.3age)}\right)^2 = a + (b(HL + 600 * \sqrt[3]{OW})) + \varepsilon,$$

where a and b are constants and ε is residual error. Thus,

$$\text{Age (yrs)} = \frac{b}{1-1.3b},$$

Where, for

i) Kimberley females $b = \sqrt{-0.1047 + (0.0011 \times (\mathrm{HL} + 600 \times \sqrt[3]{\mathrm{OW}}))}$, ± 0.0330 SE

ii) Kimberley males $b = \sqrt{-0.3403 + (0.0017 \times (\mathrm{HL} + 600 \times \sqrt[3]{\mathrm{OW}}))}$, ± 0.0360 SE

iii) Pilbara females $b = \sqrt{-0.1592 + (0.0011 \times (\mathrm{HL} + 600 \times \sqrt[3]{\mathrm{OW}}))}$, ± 0.0414 SE

iv) Pilbara males $b = \sqrt{-0.3120 + (0.0016 \times (\mathrm{HL} + 600 \times \sqrt[3]{\mathrm{OW}}))}$, ± 0.0369 SE

As shown in Table 5.9, the single parameter models fitted the growth curves for *S. commerson* well (Appendix 5, Figure A5.1). However, some estimates were clearly erroneous, for instant giving negative ages or ages in excess of 60 years. Further, when the otolith section and estimated ages given to each fish were compared large discrepancies were obvious, particularly for fish in older age groups where the data was limited (Appendix 5, Figure A5.2).

Growth models from length-at-age

Juvenile growth was most rapid up to 300 – 500 mm FL, when the average daily growth rate (estimated from FL/age) was greatest at 3 – 4 mm/day (Figure 5.15). Juveniles captured in March and April had the fastest average daily growth (4.2 mm/day), whereas those of similar size captured in June tended to have grown at a slower rate. After about 500 mm FL the average daily growth rate had decreased substantially to between 2 – 2.5 mm/day. The curvi-linear relationship between fork length and age of juvenile fish indicate that growth slows noticeably at around 100 days, just prior to the marked change in deposition of otolith material (Figure 5.16).

Growth after the first year declines considerably, and after 5 years is very slow (Figure 5.17). The von Bertalanffy growth model provided a good fit to the data for each sex and region up to this age but not in older fish. The parameters of these models are shown in Table 5.10. Because of the notably lower maximum age of fish in the Kimberley region, the von Bertalanffy curve and associated parameters for male and female length at age data from this region were compared separately from the other regions. Comparison of similar data for males and females from the Pilbara and west coast regions indicated that males had similar growth characteristics but females had a different L_∞ (Table 5.11). However, as this significant result is probably due to insufficient samples from the west coast region (particularly of older fish; Figure 5.17), the data for these regions were nevertheless pooled for each sex. Subsequent comparisons of von Bertalanffy curve and parameters between the males and females within the Kimberley region and the combined west coast/Pilbara region show significant differences in the fitted curves for each sex. In the Kimberley region this was due to differences in the combination of L_∞ and K (driven mainly by differences in L_∞), whereas in the west coast/Pilbara region the difference was solely due to L_∞ (Table 5.11).

Age at sexual maturity

The mean length at which 50% of females reached sexual maturity (data for all regions combined) was 809 mm FL ± 9.8 SE (898 mm TL), and 50% of males was 628 mm FL ± 13.8 SE (706 mm TL; Chapter 4). Using the inverse of the von Bertalanffy growth model described above, the estimated mean age at 50% sexual maturity of females in each region was 1.4 years. Similarly, the mean age at 50% sexual maturity of males in each region was 0.8 years.

Age-length keys

Age – FL, age – HL, age – otolith weight, and FL – HL keys are provided in the Appendices (Appendix 5, Tables A5.3 – A5.6). The keys for prediction of age may be a useful supplement to the multiple regressions given above, although there is much variation in the predicted values. This is particularly the case for older age groups in which sample sizes were limited.

Mortality

Total mortality (Z) estimated from the catch curves were consistently higher for females than males, and much higher in the Kimberley region than in the Pilbara and west coast regions (Table 5.12). These data suggest an overall Z of ≈ 0.50 yr^{-1} in the Kimberley region and ≈ 0.24 yr^{-1} in the Pilbara and west coast regions. The catch curves indicate that *S. commerson* were fully recruited into the fishery in each region by ≈ 2 years of age (Figures 5.18-20a-c).

Natural mortality (*M*) estimated using the Hoenig (1983) equation were not much less than *Z* (≈ 0.35 yr^{-1} in the Kimberley region and 0.20 yr^{-1} in the Pilbara and west coast regions; Table 5.13). Estimates of *M* from the Pauly (1980) equation and the modified version of the Pauly equation described by Brey (1999), suggest that *M* is considerably higher than either the Hoenig and *Z* estimates (generally between 0.8 and 1.0 yr^{-1}; Table 5.13; see also Appendix 5, Table A5.7). However estimates using the derived values of both *K* and L_∞ are lowest (≈ 0.5 yr^{-1} for the Kimberley region and 0.34 yr^{-1} for the Pilbara and west coast regions).

Table 5.1 Regions and locations from which otoliths were collected between 1998 – 2002 for the study of *S. commerson* age and growth in Western Australia.

Region	General Location	Otoliths collected	No. weighed & measured	Otoliths sectioned
North. Territory	Bathurst Island	24	24	22
	Timor Box	71	71	28
	Coburg Peninsula	62	61	60
		157	156	110
Kimberley	Holothurian Bank	113	110	64
	Cape Voltaire	804	720	272
	White Island	219	86	66
	Cape Leveque	216	181	126
	Broome	57	37	15
		1409	1134	543
Pilbara	Port Hedland	424	315	348
	Dampier	584	420	464
	Onslow	309	241	152
	Exmouth	179	154	140
		1495	1129	1102
West Coast	Shark Bay	325	255	294
	Geraldton	320	278	211
	Perth	28	20	27
		669	551	530
Overall		**3781**	**2973**	**2288**

Table 5.2 Percentage of sectioned *S. commerson* otoliths within each readability category.

			Readability Categories (percentages)				
			1	**2**	**3**	**4**	**5**
Area	**Sex**	N	(unreadable)	(poor)	(fair)	(good)	(excellent)
Kimberley	Female	265	0.75	14.3	67.2	17.0	0.75
	Male	275	0	15.3	74.6	10.2	0
Pilbara	Female	622	0	3.7	52.4	42.4	1.5
	Male	372	0	4.3	62.9	31.5	1.3
West coast	Female	314	0	5.4	61.5	31.5	1.6
	Male	157	0	0.6	61.2	37.6	0.6
Overall	Female	1201	0.17	6.5	58.0	34.0	1.3
	Male	804	0	7.3	66.6	25.4	0.7

Table 5.3 Comparison of the readability of whole and sectioned *S. commerson* otoliths. Percentages are shown in brackets.

	Whole Readability			
Section readability	**Poor**	**Fair**	**Good**	**Total Number**
Poor	28 (35.4)	48 (59.5)	4 (5.1)	79
Fair	16 (16)	54 (54)	30 (30)	100
Good	9 (9.2)	36 (36.7)	53 (54.1)	98

Table 5.4 Analysis of the effect that otolith readability has on comparisons of ages given to whole and sectioned *S. commerson* otoliths. Data has been divided by readability categories given to a) whole and b) sectioned otoliths.

	Age (yr)			**Ageing method comparison results**	
Readability category	**Avge**	**Min.**	**Max**	**% agreement**	**APE**
(a) whole otoliths					
Poor	4.3	0.5	19	32.65	12.2
Fair	4.5	1.0	17.5	59.12	6.9
Good	6.1	1.5	17	79.3	1.7
(b) sectioned otoliths					
Poor	2.8	0.5	10.5	50.6	10.1
Fair	4.5	1.5	17.5	66	6.0
Good	6.9	2	19	64.3	3.55

Table 5.5 Age, growth and length data of *S. commerson* aged from counts of microincrements and annuli. The microincrements were assumed to be deposited daily.

	Sex		
	Juvenile	**Female**	**Male**
Microincrements			
n	60	7	5
Min FL (mm)	58	396	284
Max FL (mm)	563	770	781
Avge FL (mm)	359.0	599.9	464.0
SD FL (mm)	98.2	143.2	226.9
Min age (days)	23	122	80
Max age (days)	204	391	325
Avge age (days)	104.0	255.6	171.8
SD age	30.8	101.3	122.9
Min growth (mm/day)	2.5	2.0	2.2
Max growth (mm/day)	4.2	3.6	3.8
Avge growth (mm/day)	3.5	2.5	3.1
SD growth (mm/day)	0.4	0.6	0.8
Adjusted annual age			
n		1273	837
$\text{Max}_{\text{Kimberley}}$		12.5	11.0
$\text{Max}_{\text{Pilbara}}$		18.0	22.0
$\text{Max}_{\text{west coast}}$		17.5	18.5

Table 5.6 Otolith parameters for juvenile, female and male *S. commerson*.

	Min. Oto Wt (g)	**Max. Oto Wt (g)**	**Avg. Oto Wt (g)**	**Min. Oto Lt (mm)**	**Max. Oto Lt (mm)**	**Avg. Oto Lt (mm)**
Juvenile	0.00065	0.08549	0.0109	2.35	9.35	7.03
Female	0.01084	0.21178	0.0645	7.09	22.03	14.44
Male	0.00657	0.15379	0.0569	5.45	18.18	13.71

Table 5.7 Relationships between otolith and body parameters of female and male *S. commerson*. WW; whole weight (kg). FL; fork length (mm). OW; otolith weight (g). OL; otolith total length (mm). OAR; length of otolith to the antirostrum (mm).

Dep. Var.	**Ind. Var.**	**n**	**Equation**	**r^2**	**Residual SE**
WW_{fem}	OW	995	Ln(WW) = 6.253 + (1.460 x Ln(OW))	0.9526	0.2128
WW_{male}	OW	823	Ln(WW) = 6.087 + (1.431 x Ln(OW))	0.9576	0.2085
WW_{fem}	OL	992	Ln(WW) = -8.112 + (3.854 x Ln(OL))	0.9485	0.2311
WW_{male}	OL	818	Ln(WW) = -8.015 + (3.791 x Ln(OL))	0.9477	0.2323
WW_{fem}	OAR	1012	Ln(WW) = -6.632 + (3.813 x Ln(OAR))	0.9422	0.2222
WW_{male}	OAR	838	Ln(WW) = -6.698 + (3.822 x Ln(OAR))	0.9396	0.2231
FL_{fem}	OW	1132	Ln(FL) = 8.331 + (0.496 x Ln(OW))	0.9516	0.0735
FL_{male}	OW	955	Ln(FL) = 8.270 + (0.484 x Ln(OW))	0.9486	0.0760
FL_{fem}	OL	1126	FL = -168.629 + (83.533 x OL)	0.9158	66.85
FL_{male}	OL	948	FL = -161.167 + (81.403 x OL)	0.9138	62.67
FL_{male}	OAR	1158	FL = -148.344 + (117.703 x OAR)	0.9193	63.01
FL_{fem}	OAR	975	FL = -161.017 + (117.246 x OAR)	0.9116	60.63

Table 5.8 Results of Best Subsets Regression analyses to determine the parameters which most accurately described age a) using all otolith and body parameters and b) using just head length and otolith parameters. CRootWW; cube root of whole weight. CRootOW; cube root of otolith weight. Refer to Appendix 5, Tables A5.1 and A5.2 for details.

Sample	**Best predictive variables**	**Adj. r^2**	**Model error**
a)			
$\text{Kimberley}_{\text{Female}}$	CRootWW ; CRootOW	78.1	0.0321
$\text{Kimberley}_{\text{Male}}$	Head length ; CRootOW	77.6	0.0361
$\text{Pilbara}_{\text{Female}}$	Fork length ; CRootWW ; CRootOW	85.4	0.0362
$\text{Pilbara}_{\text{Male}}$	Head length ; CRootOW	91.1	0.0365
b)			
$\text{Kimberley}_{\text{Female}}$	Head length ; CRootOW	77.3	0.0327
$\text{Pilbara}_{\text{Female}}$	Head length ; CRootOW	81.2	0.0410

Table 5.9 Results of regressions to predict transformed age, $\left(\frac{age}{(1+1.3age)}\right)^2$, using a), two parameters, HL and $\sqrt[3]{OW}$, and b), a single composite parameter (HL + 600*$\sqrt[3]{OW}$). Also shown is the ratio of $\sqrt[3]{OW}$ to HL for each of the two parameter regressions, from which the weighting factor (600) used in the composite parameter was derived.

	Intercept	**HL**	$\sqrt[3]{OW}$	$\sqrt[3]{OW}/HL$	**HL + (600*$\sqrt[3]{OW}$)**	**SE of estimate**	**Adj. r^2**
a) Two parameter model							
$\text{Kimberley}_{\text{Female}}$	-0.1465	0.0006	0.9879	1688.7	-	0.0327	0.7730
$\text{Kimberley}_{\text{Male}}$	-0.3396	0.0017	0.9746	584.2	-	0.0361	0.7765
$\text{Pilbara}_{\text{Female}}$	-0.2041	0.0007	1.0725	1636.4	-	0.0410	0.8123
$\text{Pilbara}_{\text{Male}}$	-0.2875	0.0020	0.6180	303.0	-	0.0366	0.9141
b) Single parameter model							
$\text{Kimberley}_{\text{Female}}$	-0.1047	-	-	-	0.0011	0.0330	0.7691
$\text{Kimberley}_{\text{Male}}$	-0.3403	-	-	-	0.0017	0.0360	0.7779
$\text{Pilbara}_{\text{Female}}$	-0.1592	-	-	-	0.0011	0.0414	0.8091
$\text{Pilbara}_{\text{Male}}$	-0.3120	-	-	-	0.0016	0.0369	0.9127

Table 5.10 Parameters of the von Bertalanffy growth curve fitted to length-at-age data for *S. commerson*. Lengths are of fork length in mm.

	Kimberley			**Pilbara**			**West coast**		
	M	**F**	**both**	**M**	**F**	**both**	**M**	**F**	**both**
L_∞	1067.23	1218.77	1150.83	1155.27	1259.03	1208.53	1139.77	1204.93	1167.36
K	0.847	0.646	0.711	0.692	0.631	0.670	0.761	0.661	0.722
t_0	-0.211	-0.262	-0.250	-0.293	-0.285	-0.277	-0.214	-0.259	-0.228
n	336	324	660	344	417	761	121	156	277
SD	69.37	69.37	77.52	76.52	85.40	85.91	76.52	85.40	86.67

Table 5.11 Conclusions of likelihood ratio tests comparing the von Bertalanffy growth curve and associated parameters fitted to data for sexes between and within regions. Each test determined whether increased model complexity (more parameters) significantly improved the simplest base model. Kimb; Kimberley region. Pilb; Pilbara regions. WC; West Coast region. M; male. F; female. Pooled; data for Pilbara and west coast pooled. Note that data for all juveniles (mostly caught from the Pilbara region) were added to each data set prior to analyses as these develop into either males or females. As this juvenile data has only been added once to the data for males and females when pooling Pilbara and west coast regions the total n for pooled data is less than sum of data for Pilbara and West coast males and females. ns; not significant, sig; significant.

H_0 tested	**Data set compared**			
	Kimb M v Kimb F	**Pilb M v WC M**	**Pilb F v WC F**	**Pooled M v Pooled F**
One curve	base model	base model	base model	base model
Different L_∞	sig	ns	sig	sig
Different K	ns	ns	ns	ns
Different t_0	ns	ns	ns	ns
Different L_∞ & K	ns	ns	ns	ns
Different L_∞ & t_0	ns	ns	ns	ns
Different K & t_0	ns	ns	ns	ns
Different curves	ns	ns	ns	ns
Total n	660	465	573	904

Table 5.12 Estimates of total mortality (Z, yr^{-1}) from catch curves (using data from unbiased samples).

	Female (n)	Male (n)	Combined
Kimberley	0.45 (180)	0.43 (202)	0.50
Pilbara	0.26 (114)	0.16 (88)	0.23
West Coast	0.27 (182)	0.16 (109)	0.24

Table 5.13 Estimates of natural mortality (M, yr^{-1}) from the empirically derived equations of Hoenig (1983) and Pauly (1980), and the modified version of Pauly's equation by Brey (1999). Estimates of L_∞ and K used in the Pauly equation were obtained from the present study and from the empirical equations of Froese and Binohlan (2000). K derived from the present study and L_∞ from Froese and Binohlan were used in the Brey equation. Refer to Appendix 5, Table A5.7 for details. Note that the Hoenig equation was converted to a geometric mean regression as suggested in the addendum of Hoenig (1983).

	L_∞ and K from present study	L_∞ from L_{max}, K from present study	L_∞ from L_{max}, K from t_{max}	Brey	Hoenig
Kimberley	1.00	0.82	0.54	0.98	
Kimberley$_{Female}$	0.92	0.78	0.54	0.92	0.32
Kimberley$_{Male}$	1.13	0.97	0.48	1.15	0.37
Pilbara	0.92	0.84	0.37	0.89	
Pilbara$_{Female}$	0.88	0.81	0.37	0.85	0.20
Pilbara$_{Male}$	0.95	0.90	0.34	0.94	0.16
West coast	0.90	0.89	0.32	0.81	
West coast$_{Female}$	0.84	0.85	0.32	0.77	0.20
West coast$_{Male}$	0.93	0.96	0.34	0.89	0.20

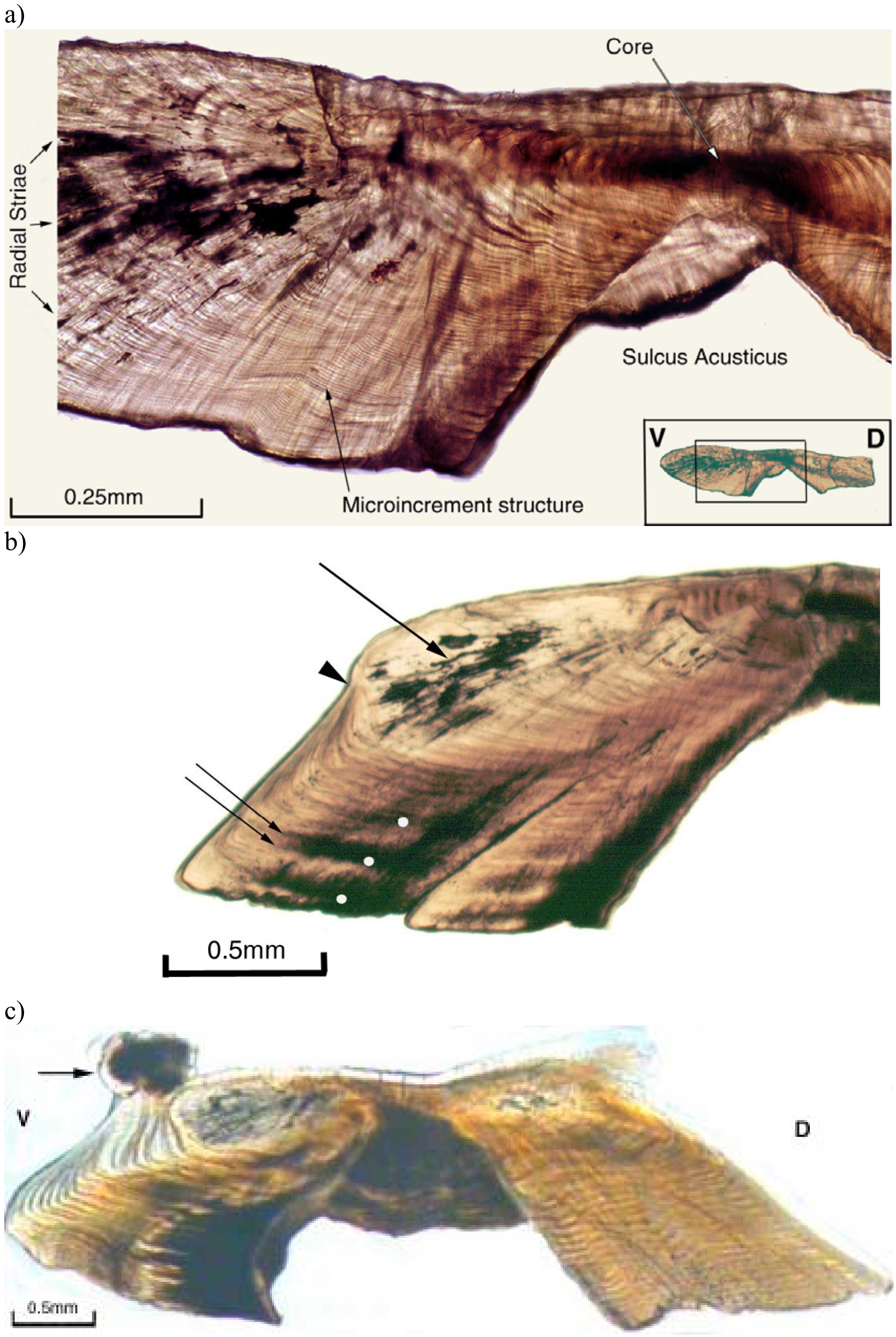


Figure 5.2 Section views of *S. commerson* otoliths giving orientation (V-ventral, D -dorsal) showing a) juvenile otolith with core, radial striae, and regular pattern of microincrements, b) ventral portion of an adult with three annuli (white dots) showing radial striae (large arrow) preceding the ventral bump and associated broad secondary opaque zone (arrow head), and parallel pair of secondary and primary annuli (small arrows), c) the oldest fish (a male) collected during the study, with 22 annuli. Note the abnormal outgrowth on the ventral surface (arrow).

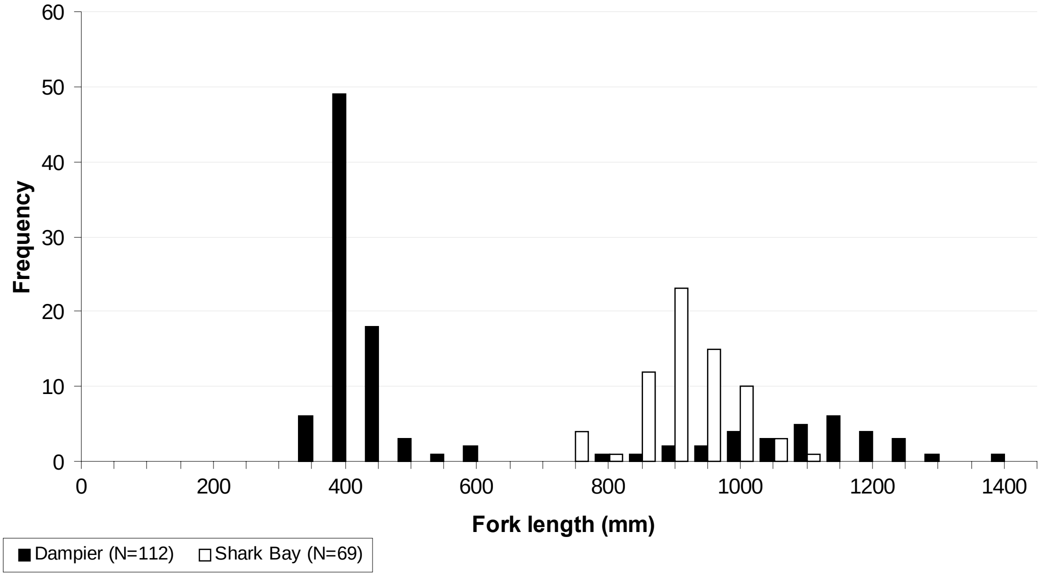
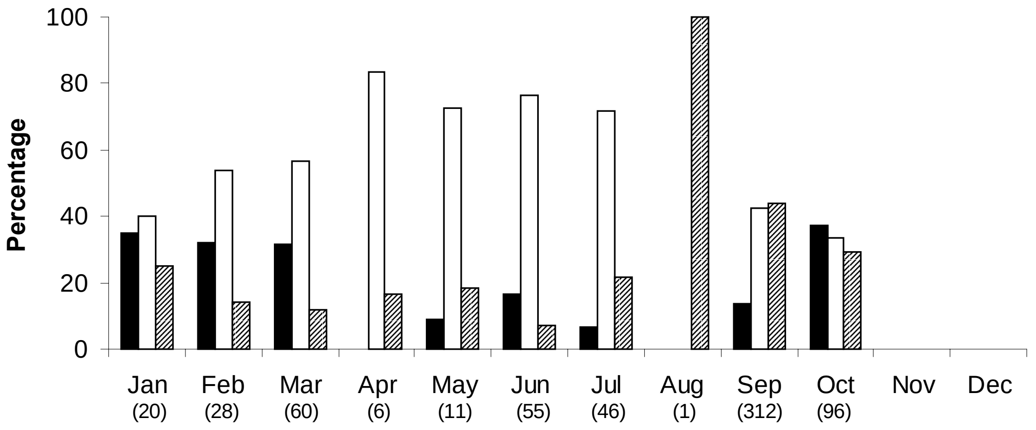
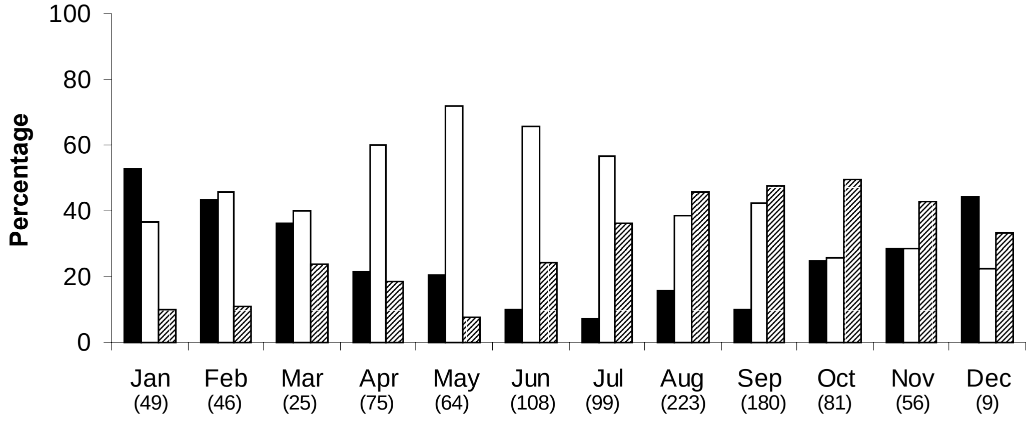


Figure 5.3 Frequencies of 50mm FL groups for *S. commerson* tagged in the Dampier and Shark Bay regions.

a) Kimberley region



b) Pilbara region



c) West coast region

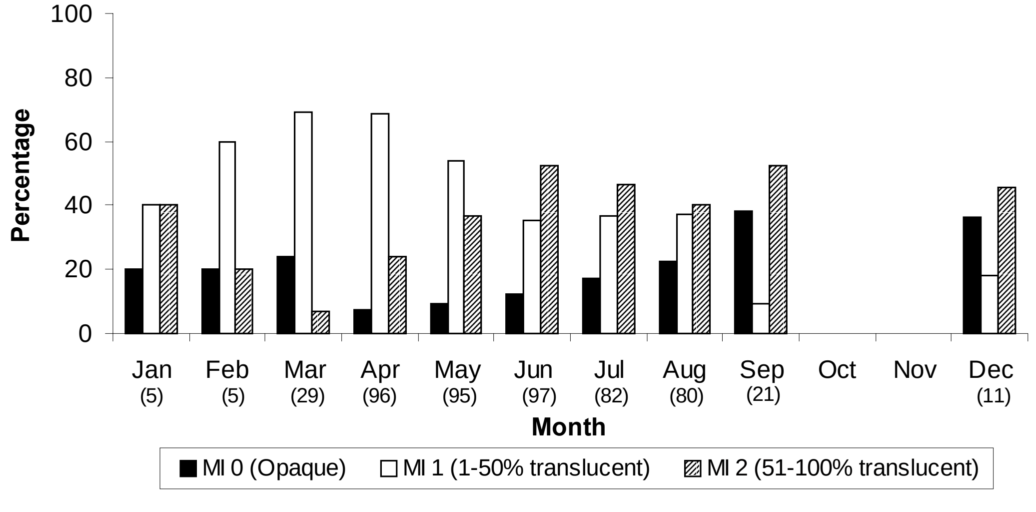


Figure 5.4 Monthly percentages of each otolith marginal increment category for *S. commerson* from a) Kimberley, b) Pilbara, c) west coast regions. Data pooled by sex and age-class with the number of samples for each month given in brackets.

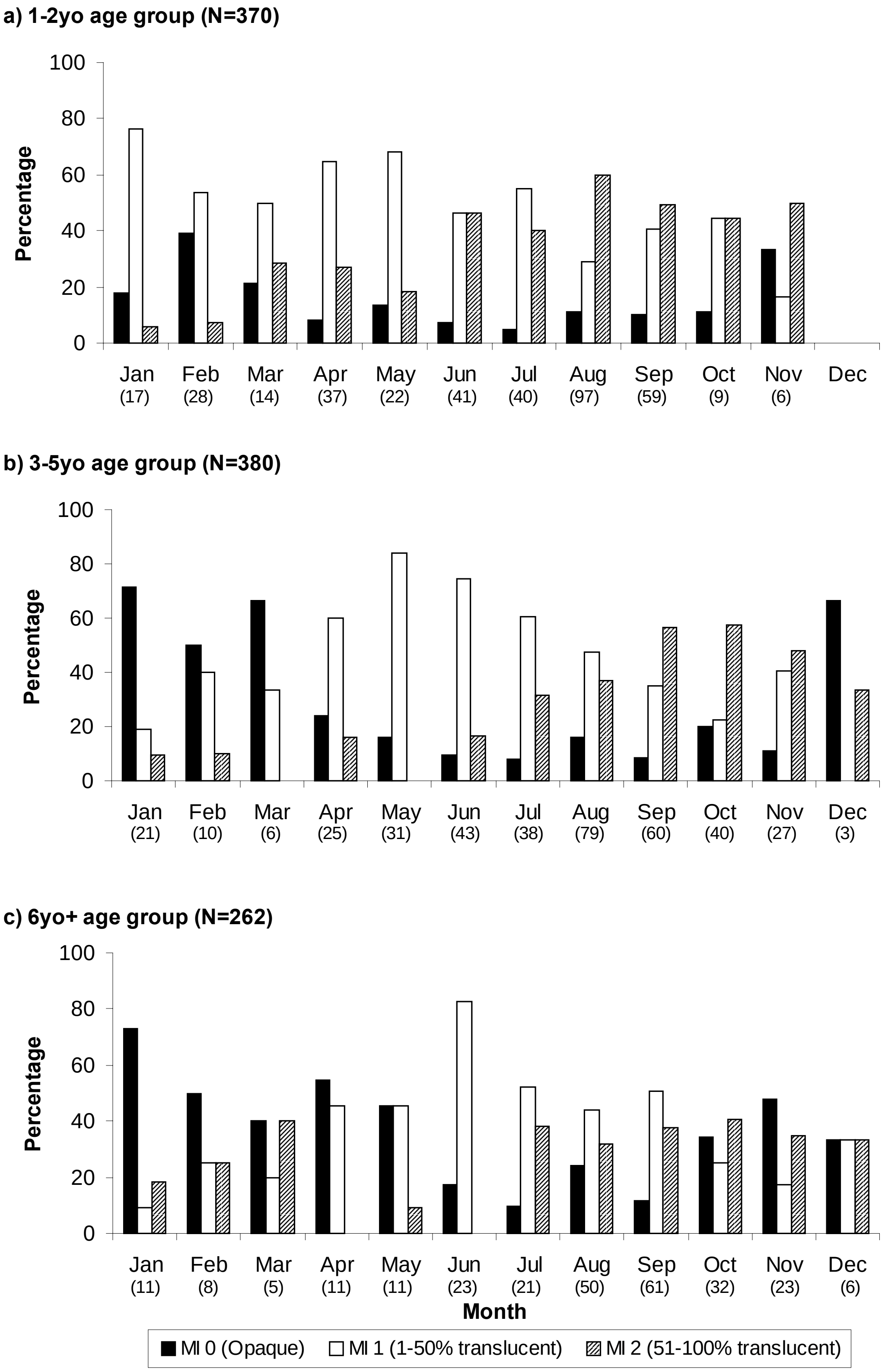
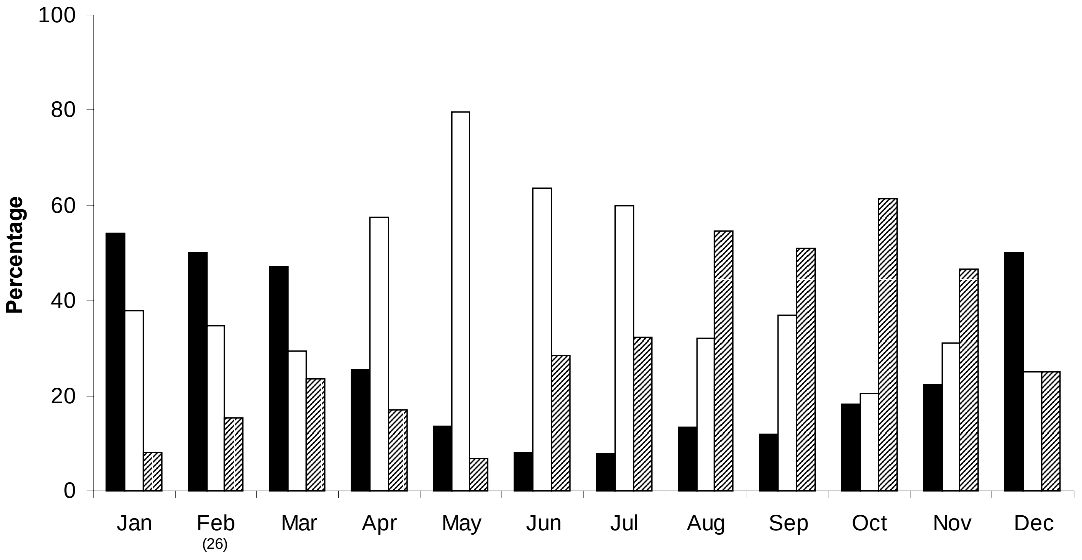


Figure 5.5 Monthly percentages of each otolith marginal increment category for *S. commerson* within a) 1-2 year age-classes, b) 3-5 year age-classes, and C) 6+ year age-classes from the Pilbara region. Data for each sex pooled with the number of samples for each month given in brackets.

a) Pilbara Females



b) Pilbara Males

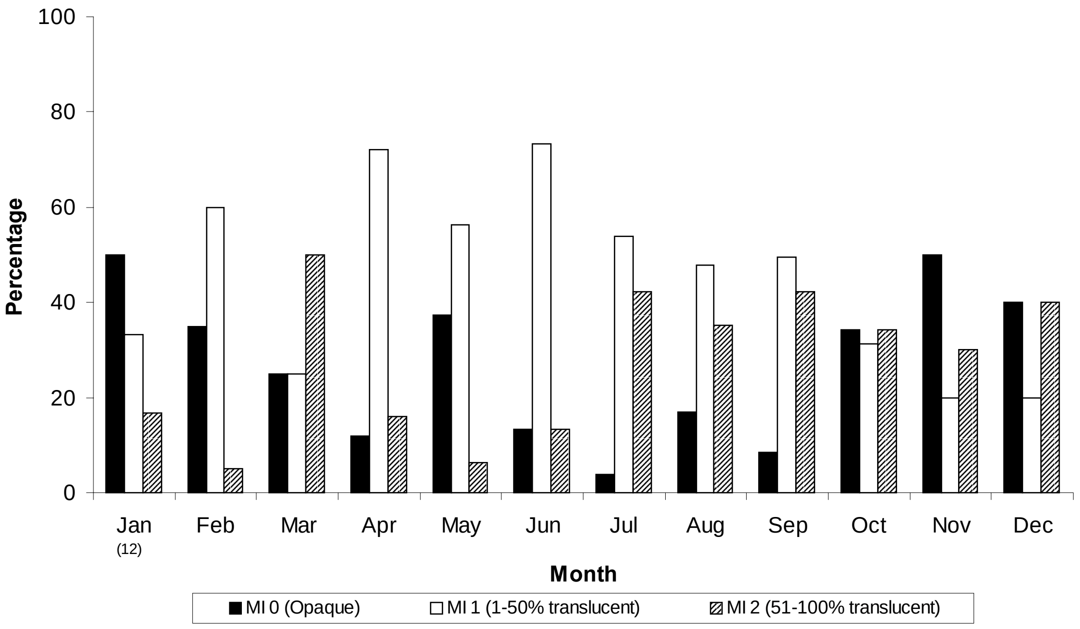


Figure 5.6 Monthly percentage of each otolith marginal increment category for *S. commerson* a) females and b) males from the Pilbara region. Data for each age-class pooled with the number of samples for each month given in brackets.

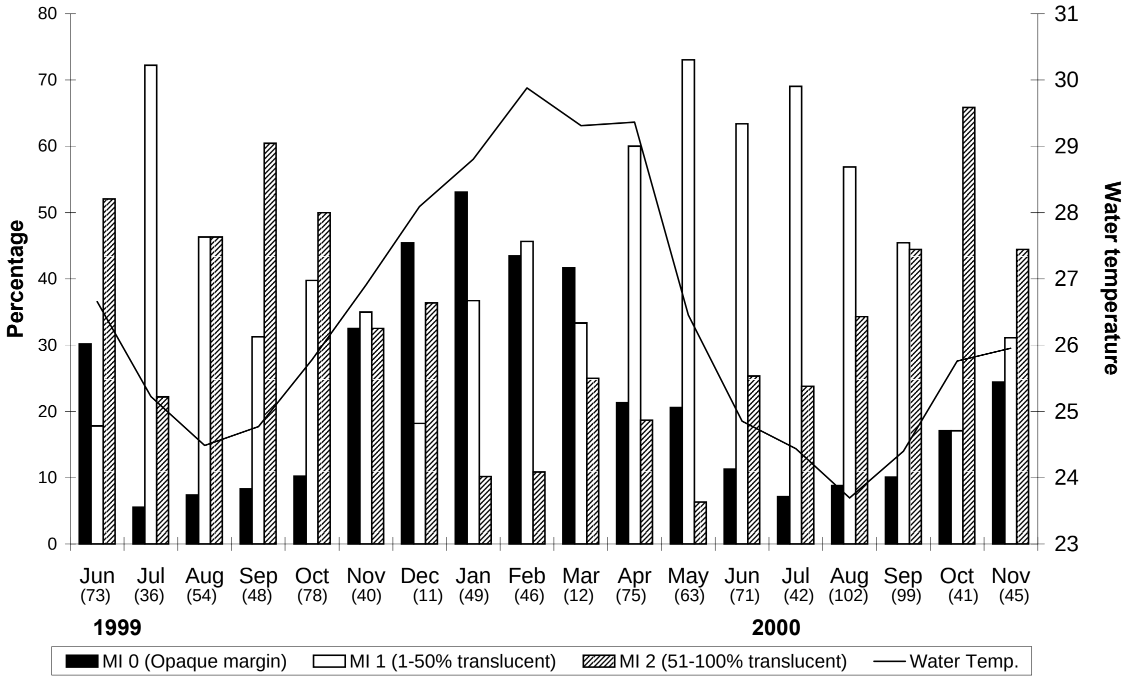


Figure 5.7 Monthly cycles of otolith marginal increment categories for *S. commerson* from the Pilbara region between June 1999 and November 2000 with mid month water temperature. Marginal increment data pooled by sex and age-class and the number of samples for each month is given in brackets.

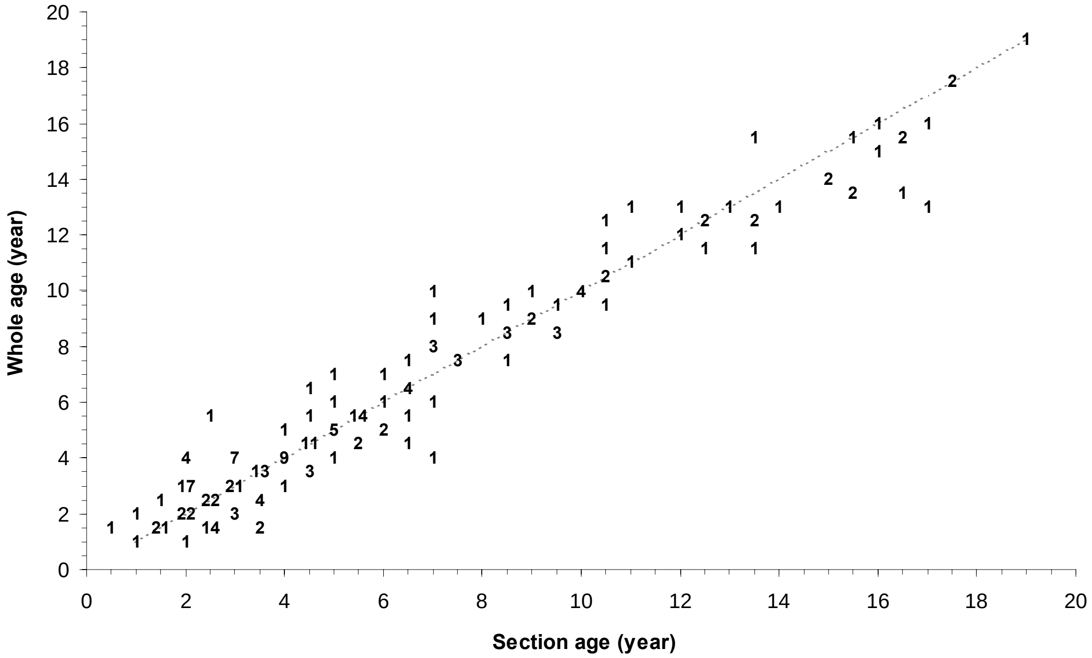
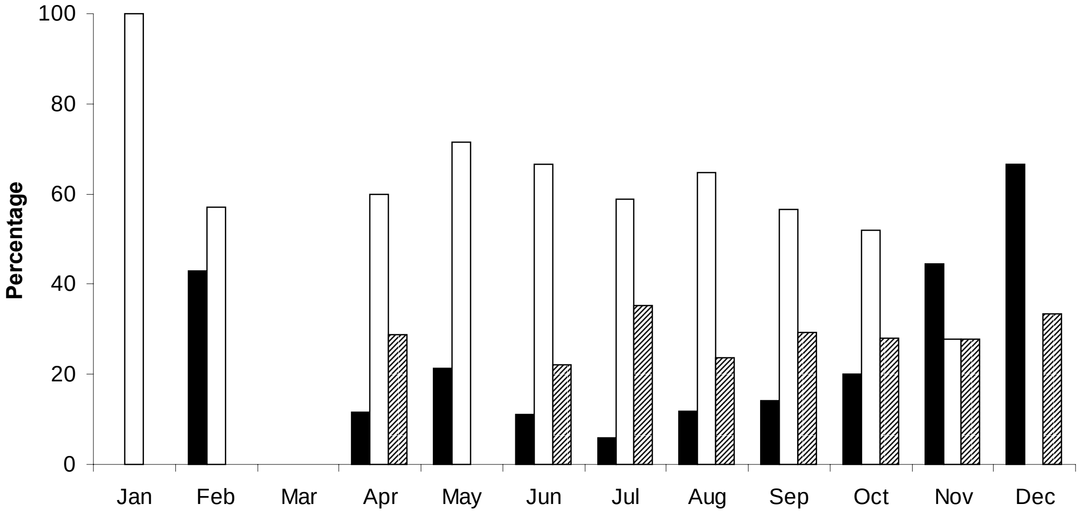


Figure 5.8 Comparison of the adjusted ages given to each whole and sectioned *S. commerson* otolith, with equal ages indicated by the fitted line and sample sizes given for each data point (n = 277).

a) Sectioned otolith marginal increment



b) Whole otolith marginal increment

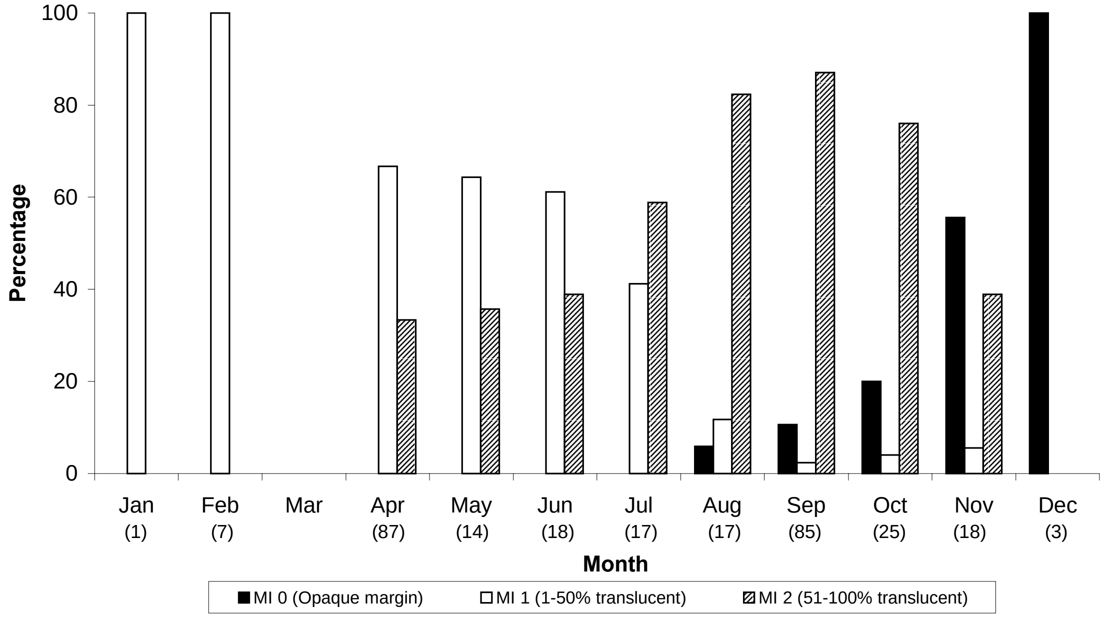


Figure 5.9 Monthly percentages of each marginal increment category for *S. commerson* from a) sectioned and b) whole otoliths. Data pooled by sex, region and age-class with the number of samples for each month given in brackets. The same otoliths were used in both graphs.

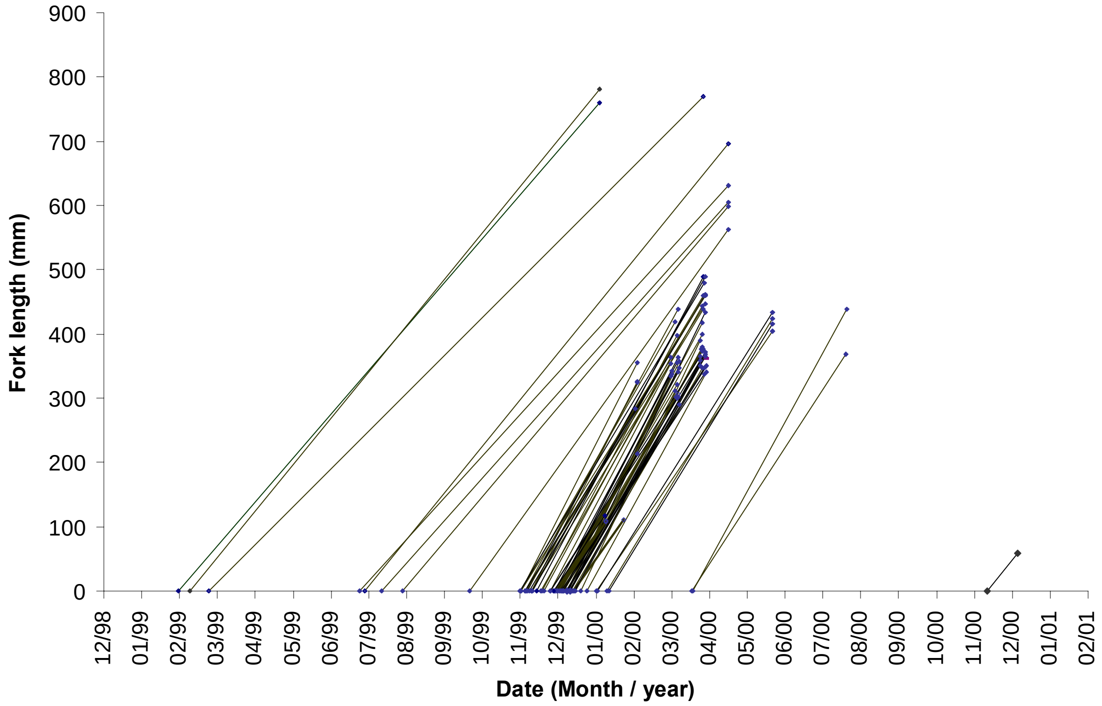
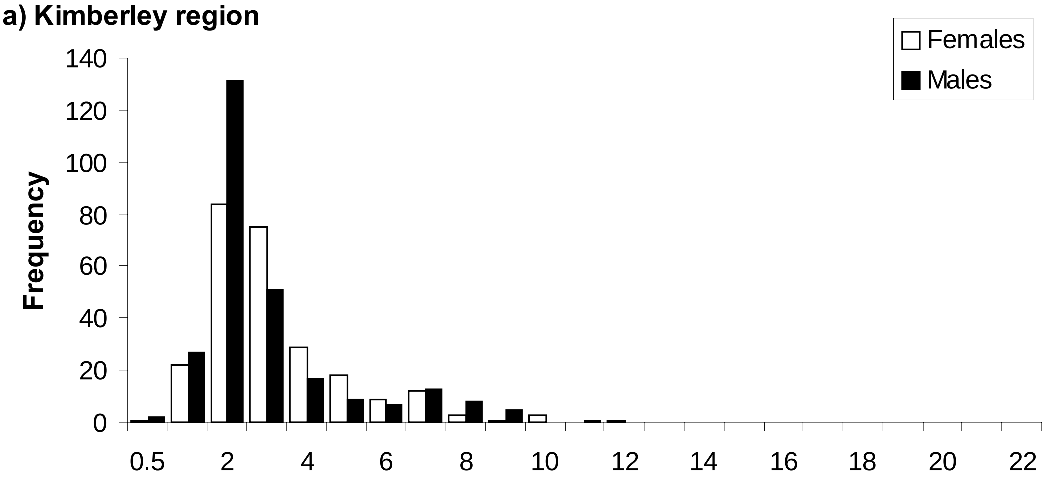
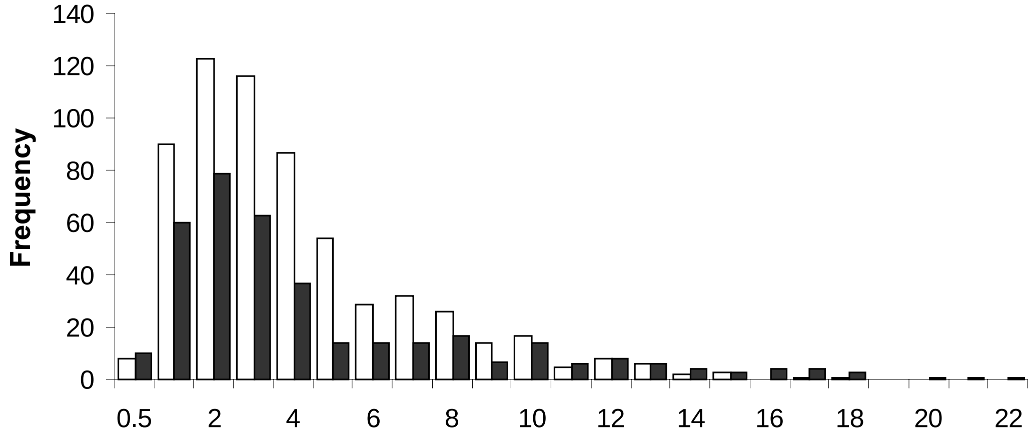


Figure 5.10 Back calculated birth dates of *S. commerson* aged from microincrement counts showing date of capture and fork length (N=74).

a) Kimberley region



b) Pilbara region



c) West coast region

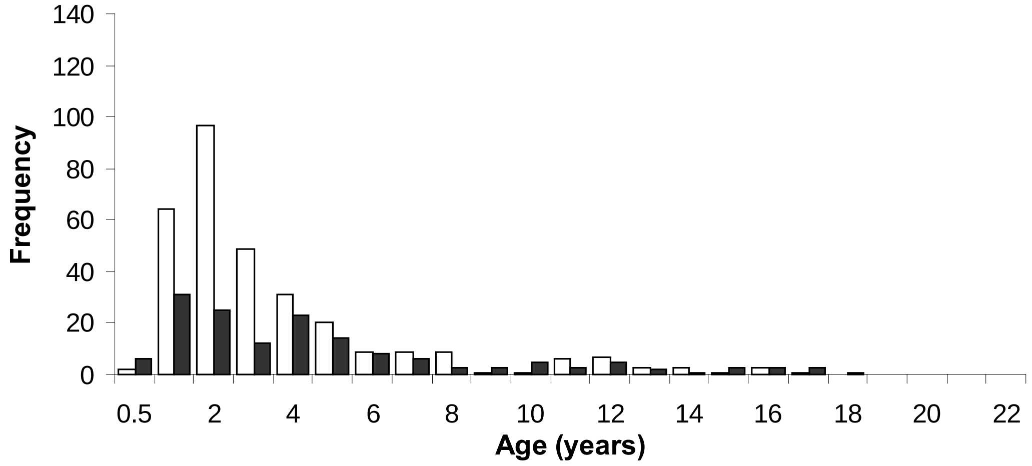


Figure 5.11 Age frequency distributions of female and male *S. commerson* for a) Kimberley, b) Pilbara and c) West coast regions.

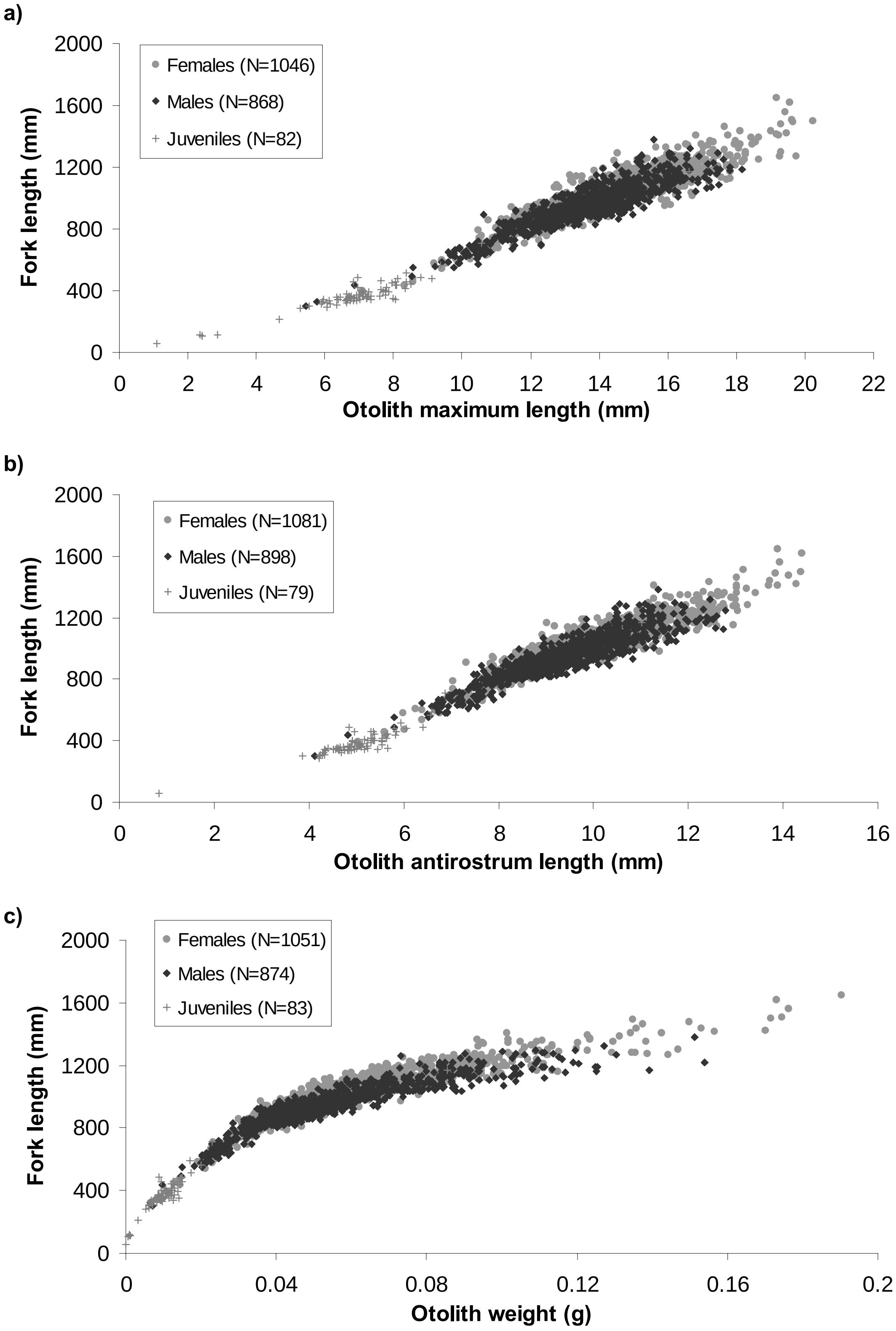


Figure 5.12 Relationship between fork length and a) maximum otolith length, b) otolith length to the antirostrum, and c) otolith weight. Data pooled for each region.

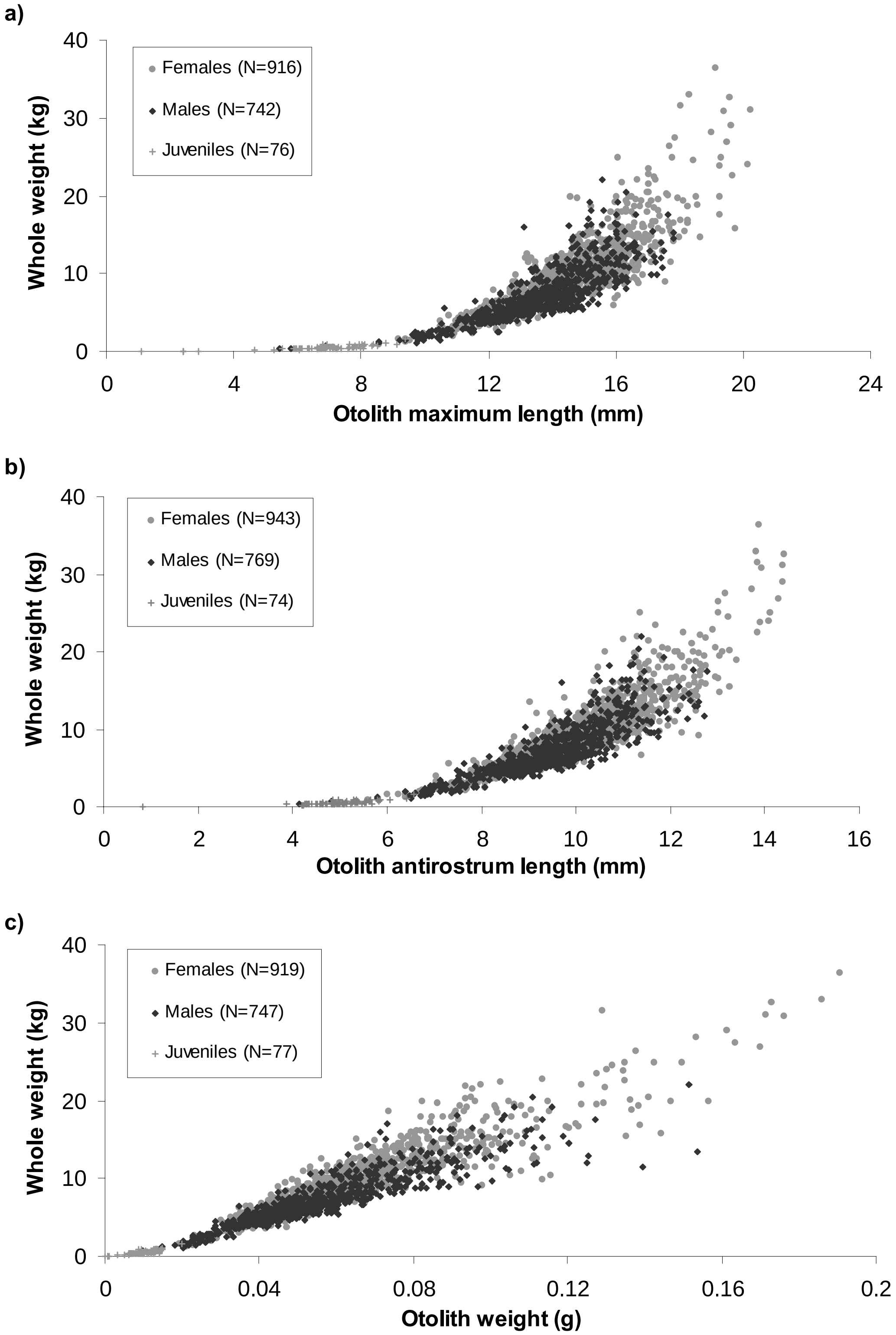


Figure 5.13 Relationship between whole weight and a) maximum otolith length, b) otolith length to the antirostrum, and c) otolith weight. Data pooled for each region.

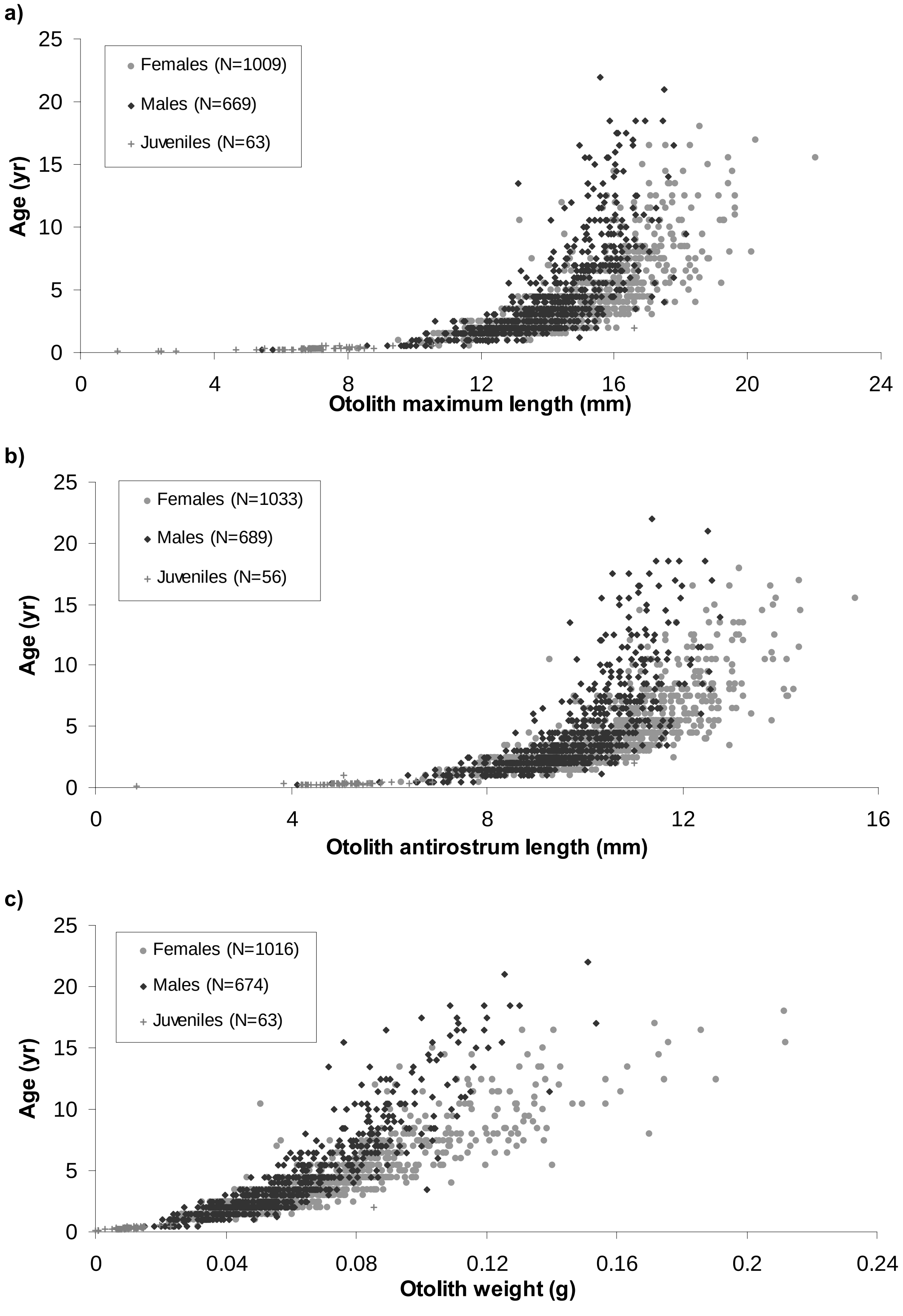


Figure 5.14 Relationship between adjusted age and a) maximum otolith length, b) otolith length to the antirostrum, and c) otolith weight. Data pooled for each region.

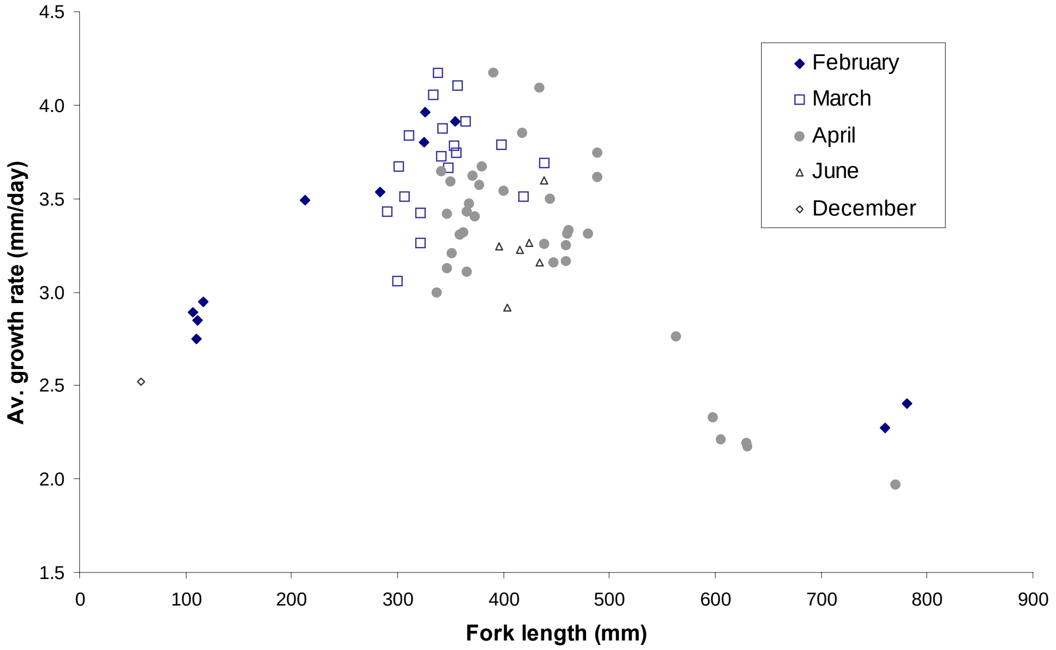


Figure 5.15 Average growth rate of juvenile *S. commerson* by month of capture. The length divided by otolith microincrement count was used to estimate average growth since birth of each fish.

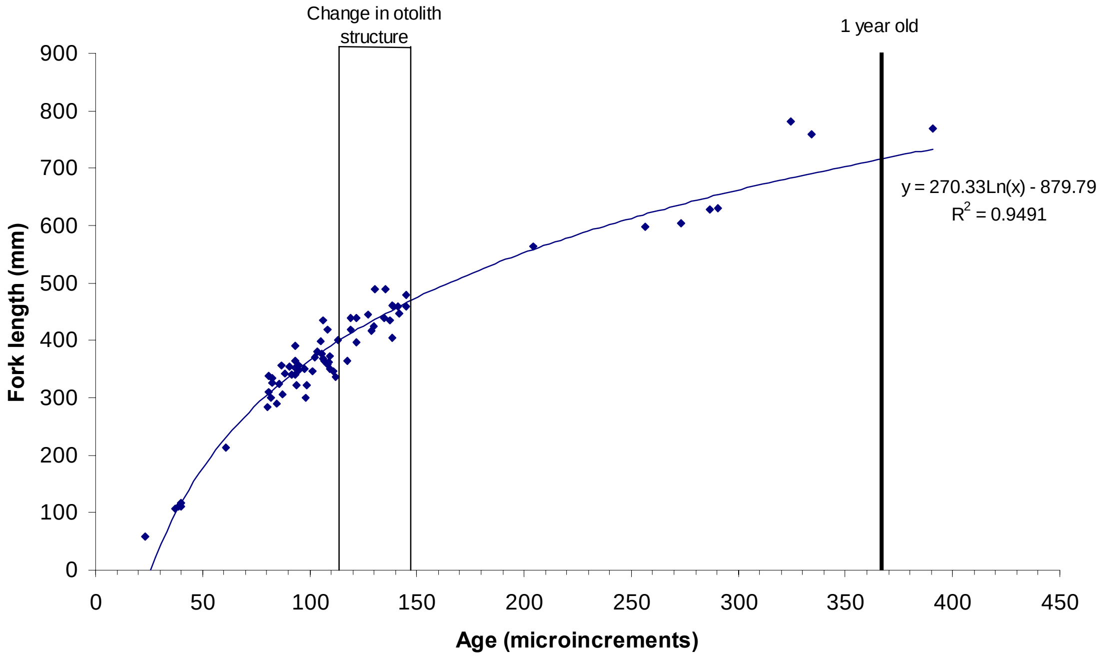


Figure 5.16 Length at age of young *S. commerson* based on counts of otolith microincrements with log regression line fitted by MS excel. The rectangle indicates the range of ages during which the ventral bump at the change in growth of the otolith was formed and 1 year is indicated.

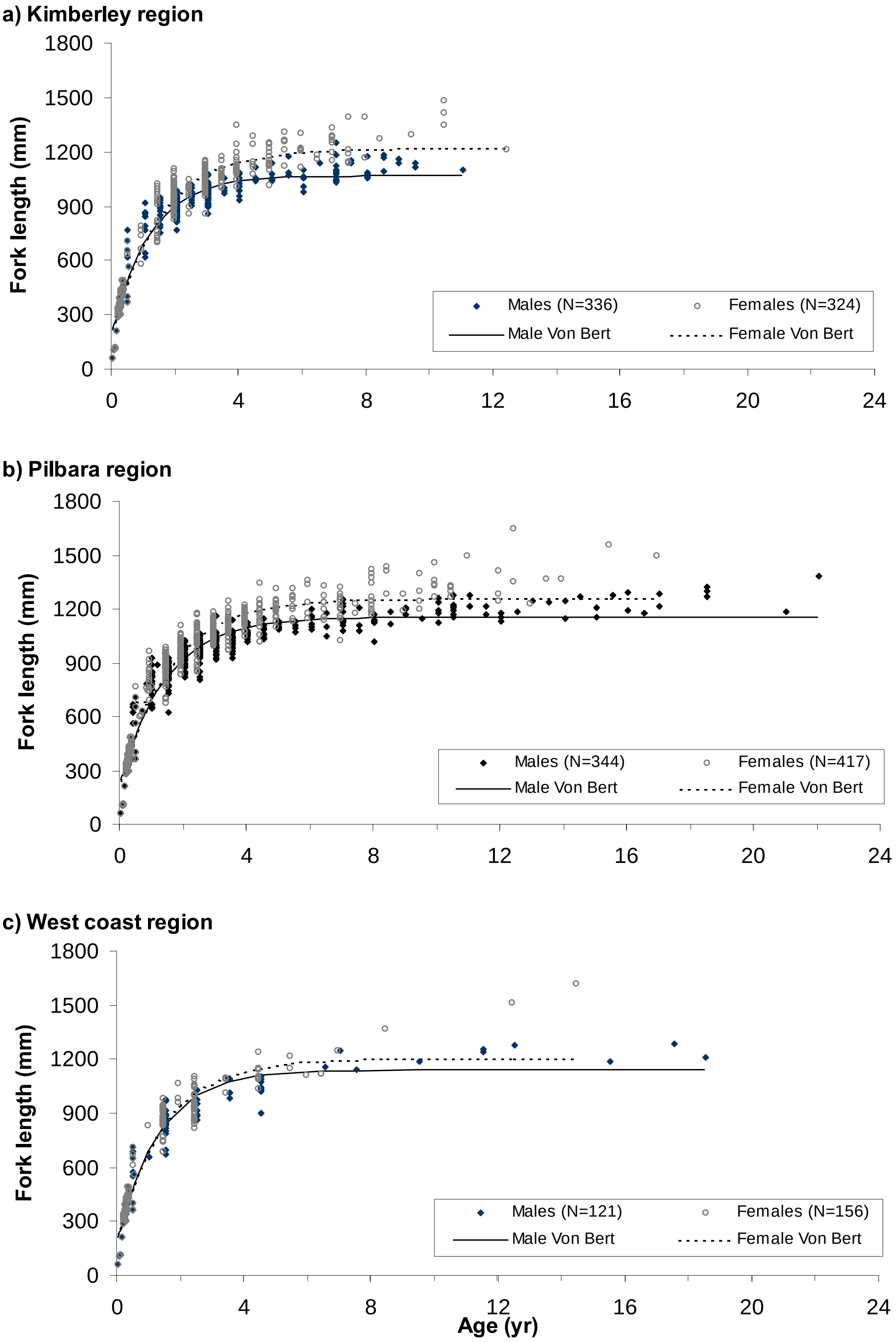
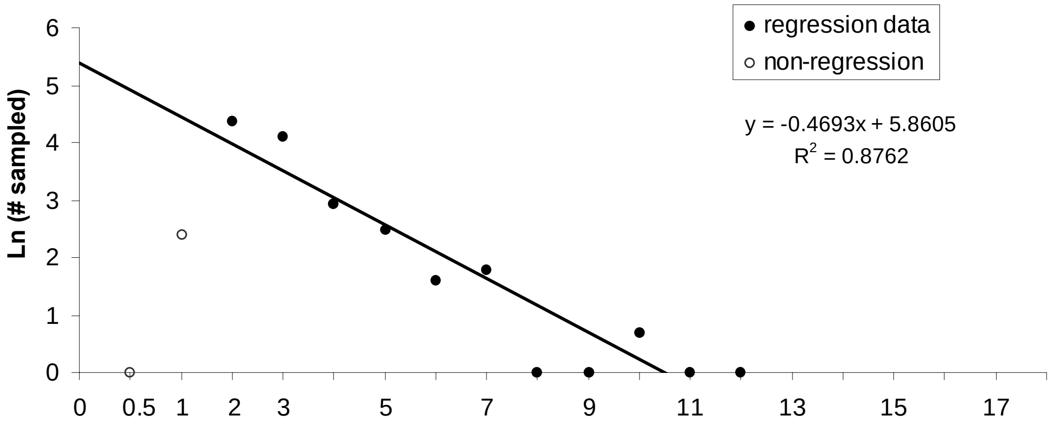
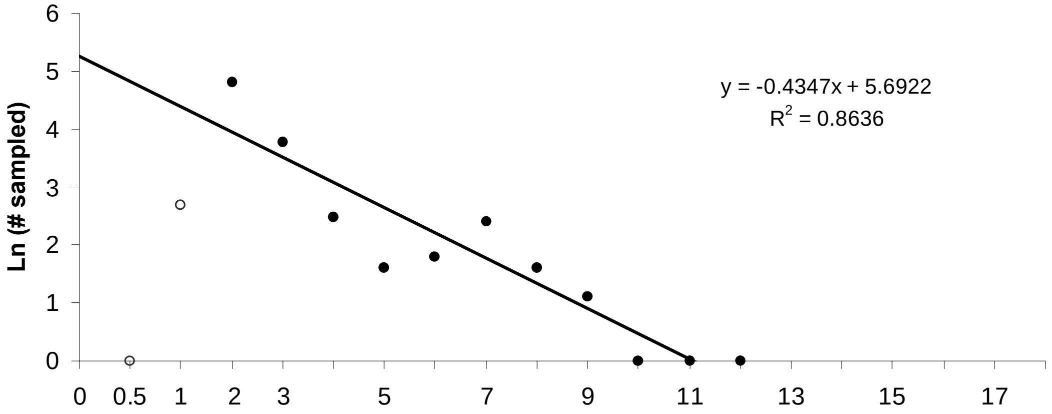


Figure 5.17 Length at age of *S. commerson* based on counts of annuli and microincrements (converted to annual ages). Von Bertalanffy growth functions fitted to the data are also shown.

a) Kimberley females



b) Kimberley males



c) Kimberley combined

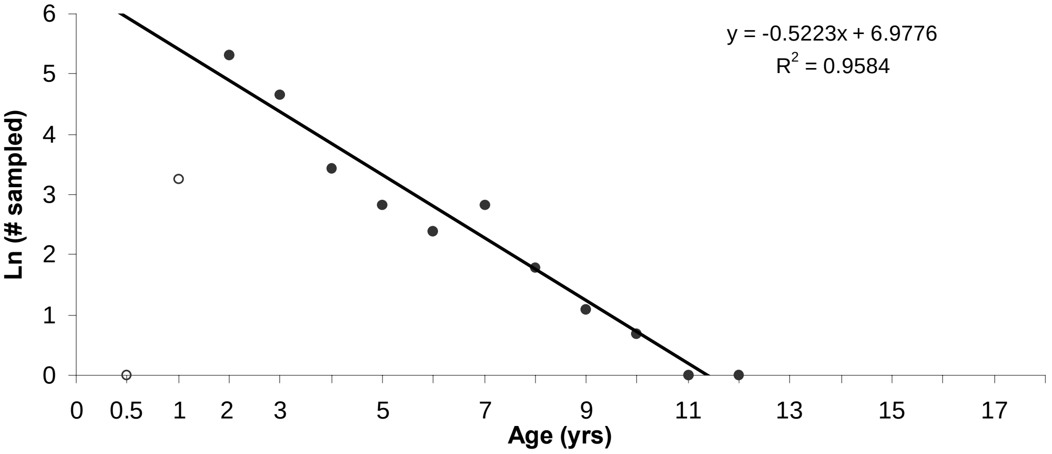
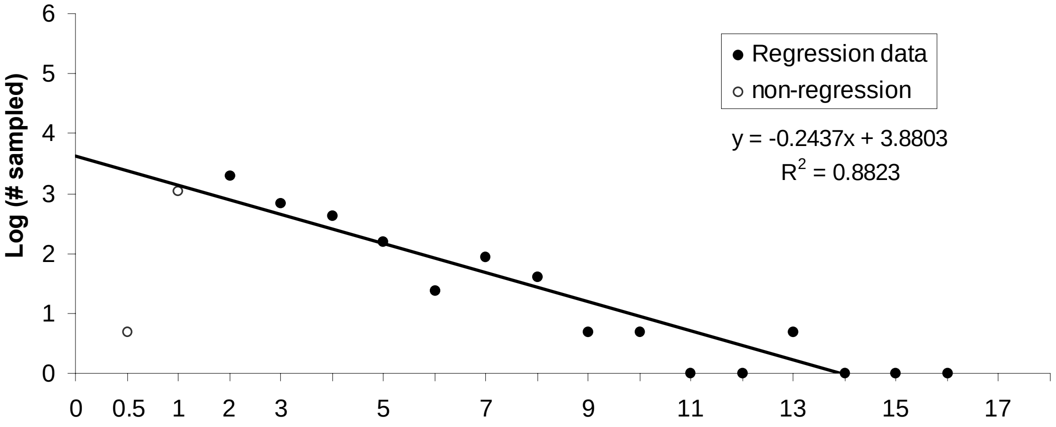
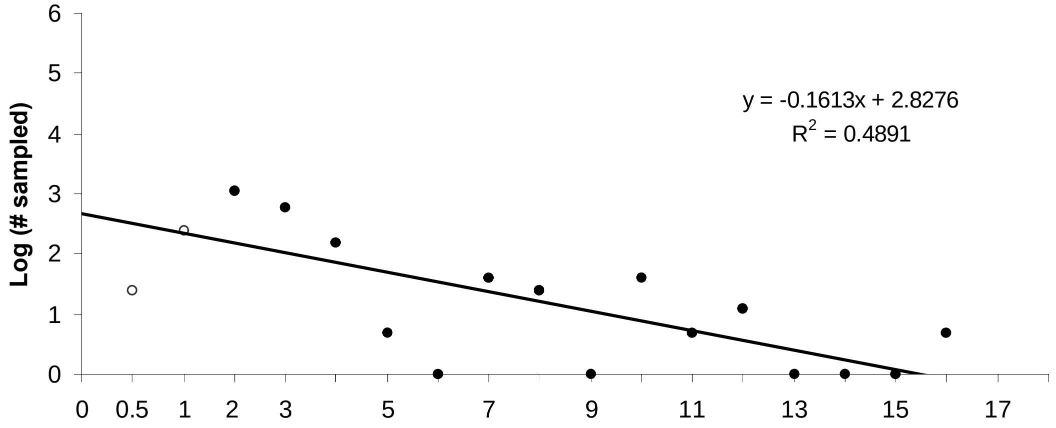


Figure 5.18 Log transformed number of *S. commerson* in each age group from unbiased Kimberley samples, with fitted regressions used to estimate total mortality (*Z*). Data indicated by hollow circles were not included in regression analyses. Regression equations and coefficient of determination values are also shown.

a) Pilbara females



b) Pilbara males



c) Pilbara combined

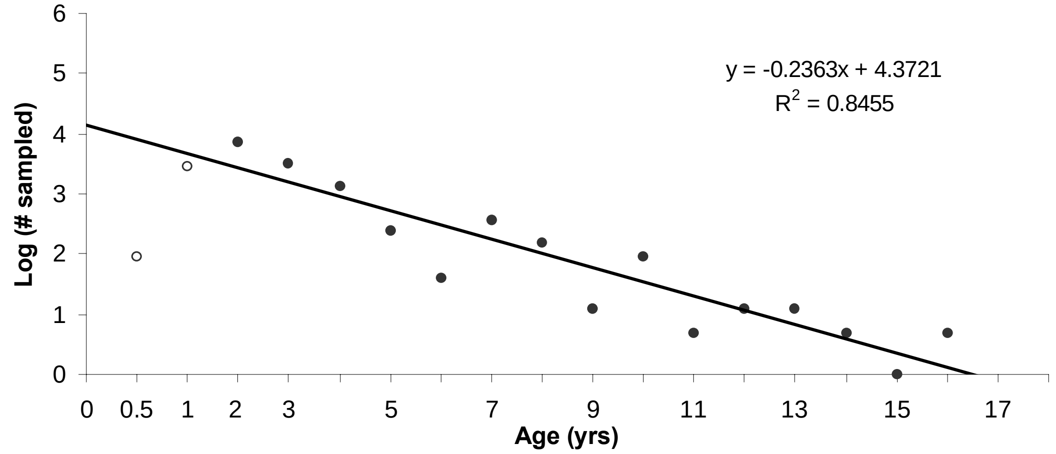
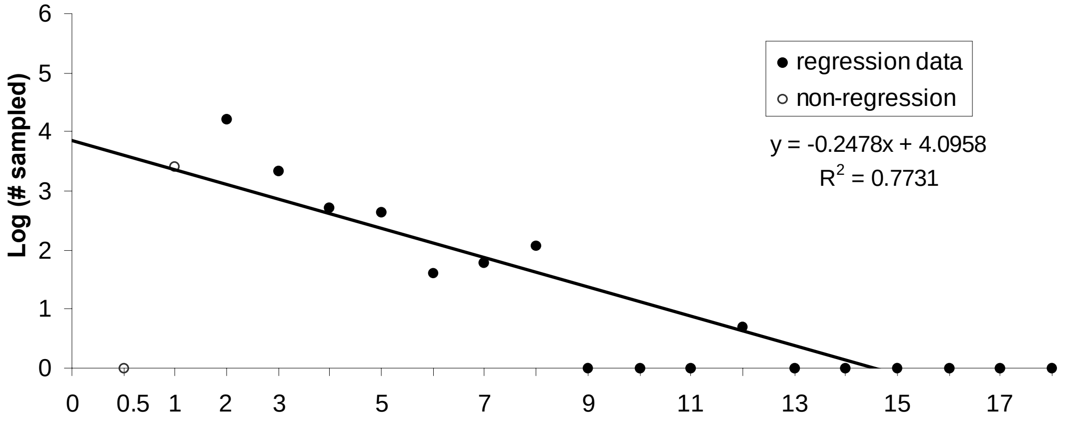
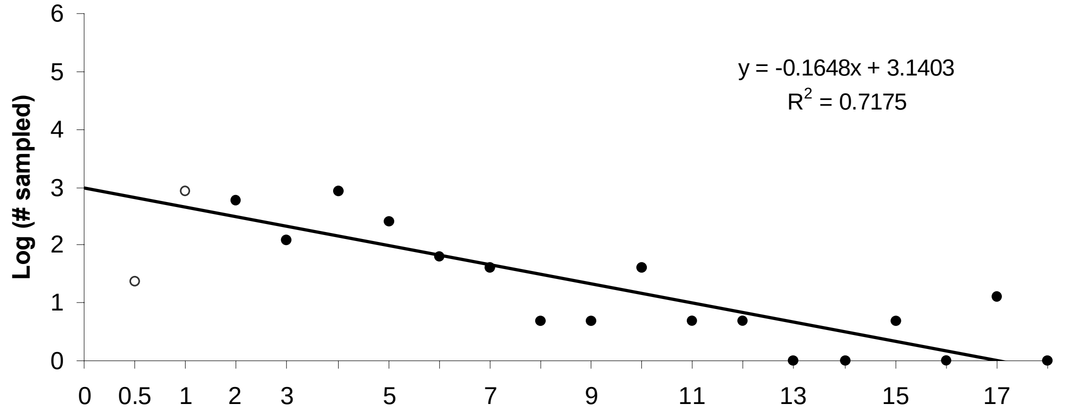


Figure 5.19 Log transformed number of *S. commerson* in each age group from unbiased Pilbara samples, with fitted regressions used to estimate total mortality (*Z*). Data indicated by hollow circles were not included in regression analyses. Regression equations and coefficient of determination values are also shown.

a) West coast females



b) West coast males



c) West coast combined

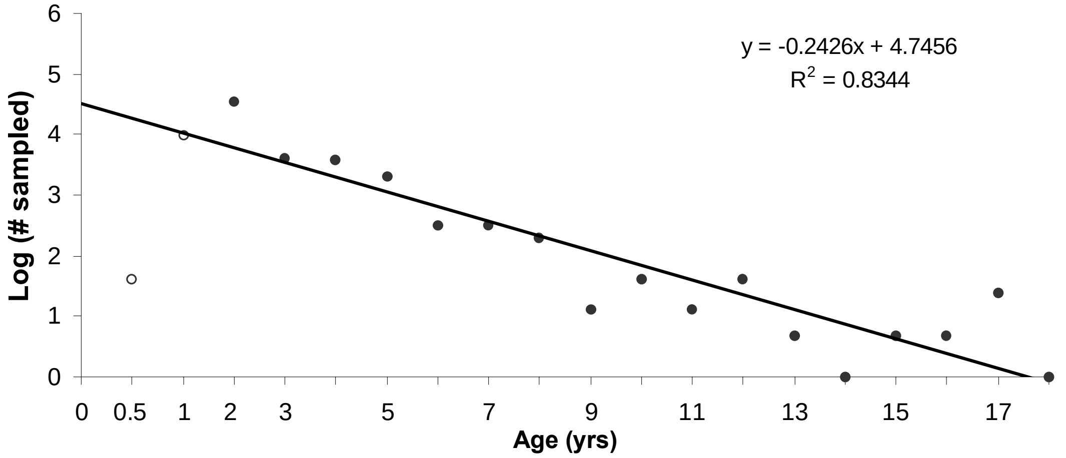


Figure 5.20 Log transformed number of *S. commerson* in each age group from unbiased west coast samples, with fitted regressions used to estimate total mortality (*Z*). Data indicated by hollow circles were not included in regression analyses. Regression equations and coefficient of determination values are also shown.

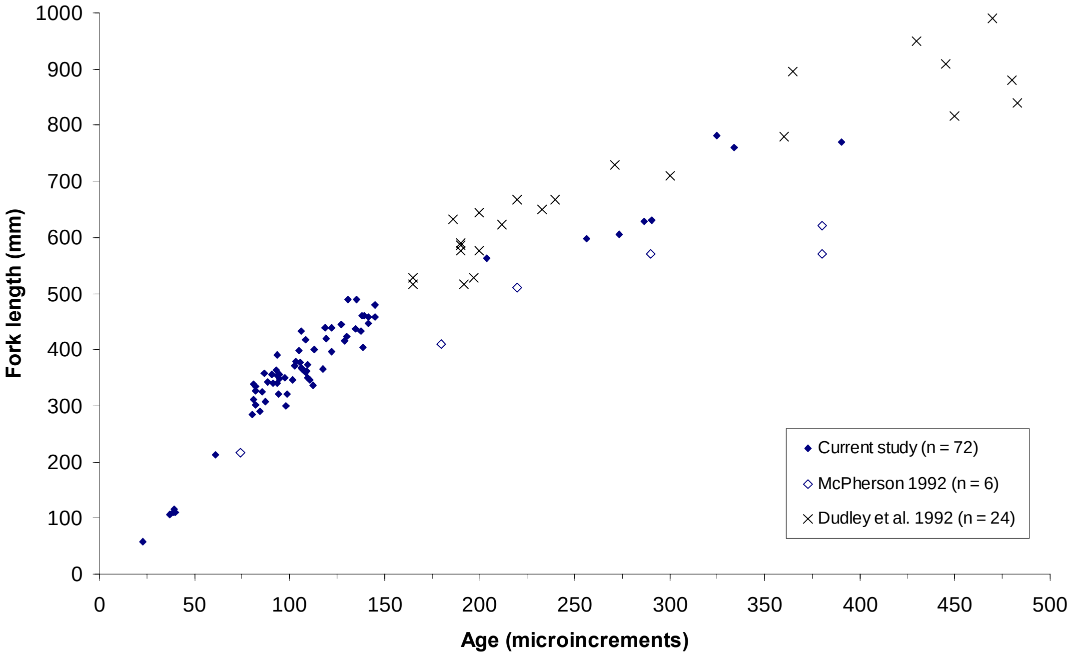


Figure 5.21 Length at age of young *S. commerson* based on counts of otolith microincrements. Data is from the present study, McPherson (1992), and Dudley *et al*. (1992).

5.2 Discussion

Validation and formation of annuli

Determination of the periodicity of annuli formation from chemical marking of the otoliths was not possible because of difficulties associated with the capture and release of *S. commerson*. Other tagging studies involving this species have also resulted in a low recapture rate. For instance, in the Game Fish Tagging Program run by NSW Fisheries only 35 (1%) of 3537 *S. commerson* that were tagged and released between 1989 and 2002 have subsequently been recaptured (K. Thompson, *pers. comm.*). As a consequence the periodicity of annuli were validated from the seasonal development of the otolith margin – a less reliable method (Campana and Thorrold 2001) but the only other means by which validation has been attempted to date for this species. Previous studies have concluded that the otoliths of *S. commerson* may form one or two annuli per year. The present study indicated that they form on an annual basis, although sometimes with the formation of a secondary annulus. McPherson (1992) and Govender (1994) also note the formation of a narrow secondary opaque zone in *S. commerson* sagittae, between January and May in Queensland waters and during May in South African waters, which corresponds with the timing of this secondary zone in WA. Although these secondary zones are usually identifiable as such, the implications of including them in counts are significant, thereby requiring care in the interpretation of otoliths of this species.

Buckworth (1998) and Govender (1994) were unable to validate the temporal periodicity of annuli within *S. commerson* otoliths by MIA due to difficulties in obtaining samples throughout the year. This was also a problem during the present study because of the seasonal nature of the fishery and could only be achieved in the Pilbara region. McPherson (1992) was able to validate the annual formation of annuli from the distinct peak in the percentage of whole otoliths with opaque margins and from MIA made from measurements of whole otoliths. These validations were made separately for age classes 1 to 3, whereas the present study provides validation for a wider (but pooled) range of otolith age groups. The distinct peak in the percentage (> 80%) and July – October occurrence of otoliths with an opaque margin in *S. commerson* from Queensland (McPherson 1992), differ from the pattern in WA where the percentage of otoliths with opaque margins in 1 – 2 year old fish never surpassed 40% and was greatest between November and February. However, otoliths with opaque margins were also collected outside this period, perhaps due to misinterpretation of the margin of some (particularly older) otoliths, but also because of the frequent formation of the double opaque zone. The higher incidence of otoliths with opaque margins in older fish may also be due to a longer period of formation than in the otoliths of younger fish. Otoliths with an opaque margin were also found during eleven months of the year in samples of king mackerel (*S. cavalla*) from the United States (Johnson *et al.* 1983).

The seasonal pattern of annulus formation was less distinct in the otoliths of male *S. commerson* than it was in female otoliths. Otolith growth is the result of interactions between endogenous and/or exogenous cycles of somatic growth rate and/or protein and aragonite metabolism, and the ecology, behaviour and physiology of each fish (Brothers 1982, Fowler 1995). Consequently, as with the isotope characteristics of the otolith, the formation of the annuli is likely to be affected by the environment in which the fish has lived. Differences between the sexes in the pattern of deposition may therefore reflect differences in movement patterns, as has been suggested for *S. commerson* in WA waters from analysis of parasitic fauna (Lester *et al.* 2001).

Formation of the opaque zone in otoliths has been linked to spawning activity in the king mackerel, *S. cavalla* (Sturm and Salter 1990). However, a review of fish species (including *S. cavalla*) by Beckman and Wilson (1995) suggested that there was no clear association with spawning and opaque zone formation. With *S. commerson* there is good correlation between the peak in opaque zone formation and the main spawning period from October to January (Chapter 4), which in turn is associated with increasing water temperatures, a parameter thought likely to be important in otolith growth (Beckman and Wilson 1995). Whether the temperature and other environmental influences act directly on the otolith or indirectly through their impact on other physiological processes remains unknown (Fowler 1995).

Although the temporal periodicity of the microincrements in *S. commerson* otoliths has not been validated, those of S. *maculatus* (Peters and Schmidt 1997) and *S. niphonius* (Shoji *et al.* 1999a) have been shown to be formed on a daily basis. Daily periodicity of *S. commerson* microincrements is supported by the fact that most juveniles appear to have been hatched during the peak spawning time, as estimated by back calculating from the date of capture. However, some appear to have been hatched in July and August when few ovaries would have been reproductively active (Chapter 4). Nevertheless, the year in which these fish were captured resulted in a significantly large cohort of recruits, as shown by the jump in catches of appropriately sized fish into the fishery in subsequent years, and was also reported by recreational fishers and observed by research staff. Therefore, it is possible that favourable conditions did result in a spawning, by some fish at least, in the winter months.

Assignment and reliability of ages

Quality and standardisation of *S. commerson* age determination was a primary focus of the present study. As such the methods and problems associated with the collection, preparation and interpretation of *S. commerson* sagittal otoliths have been documented (Lewis and Mackie 2002). Location of the first annulus from analysis of microincrements was also considered important due to initial confusion over interpretation of the inner pattern of zonation. This was particularly the case with timing of the distinctive ventral 'bump' that was evident in sections when otolith growth was altered, and was initially surmised to occur at one or two years (rather than at six months as later determined). Indeed, identification of the first annulus was the most significant problem encountered when reading *S. commerson* otoliths. Assignment of final ages was made using criteria that allowed for individual variation in the timing of opaque zone formation and thus improved the resolution of the length-at-age data.

The criteria used to adjust ages improved the agreement, APE and tests of symmetry between counts compared to comparisons between unadjusted counts. The APE of 3.7% was low compared to that recorded for *S. commerson* from the NT (6-7%), although the otoliths of these NT fish were difficult to read since the modal readability was two (using a scale similar to that used during the present study; Buckworth 1998). Otoliths of fish from the Kimberley region (similar latitude to the NT) also tended to be more difficult to read than those of fish from the more southern regions, suggesting latitudinal differences possibly related to water temperatures since the otoliths of warm water coral reef fish species often vary in clarity and readability (Fowler 1995).

The tests of symmetry also highlighted the importance of improved experience in reading *S. commerson* otoliths because biases were detected in the initial reading of younger fish by the primary reader. This was due to misinterpretation of the margin during the first reading, although it would not have been of consequence since the adjustment of ages to allow for variations in the appearance of the opaque zone reduced the effect of this bias. The relatively low agreement between age estimates by the primary and secondary readers also highlighted the influence of experience on interpretation of the ring structures, particularly of otoliths with poor readability.

Juvenile growth

The growth rate of juvenile *S. commerson* was most rapid up to about 300 mm FL (c.a. 80 days) before it levelled off and then decreased after about 500 mm FL (c.a. 160 days). Although Dudley *et al.* (1992) did not obtain *S. commerson* in this age range, they note from data for older fish that growth was also most rapid in Omani waters during the first 3 to 5 months of life. A plot of data presented by Dudley *et al.* (1992) and McPherson (1992) shows that growth of juvenile *S. commerson* from Oman and WA follow a similar trajectory, whereas juvenile growth may be less in Queensland waters (Figure 5.21). Early growth of *S. commerson* may vary with water temperature as shown for other fish species (Pepin 1991), and thus show temporal and spatial variation. This could also cause differences in growth rate between fish hatched early and late in the reproductive season, as indicated in the present study and also for *S. cavalla*, in which fish hatched early in the spawning season had faster growth rates that fish hatched later in the spawning season (Johnson *et al.* 1983). A decrease in water temperature during winter may also be a causal factor in the sudden drop in growth rates, change in otolith growth and formation of the broad secondary opaque zone in the otoliths that occurs after the fish are approximately six months old.

Adult growth

Continuance of rapid growth by *S. commerson* in WA for the first two years concurs with data from Oman, where this species may reach 700 – 800 mm FL at one year and 1000 – 1100 mm at two years (Dudley *et al.* 1992). Faster growing fish may reach these lengths (or more) in

WA, although even by two years the range in FL varies by about 300 mm and the growth of females is starting to increase above that of the males. Differences in growth rates are also reflected in differences in the age at which sexual maturity are obtained, with most males maturing before they are one year old and females when they are around one and a half years of age. Faster growth by female *S. commerson* occur throughout the waters of northern Australia (McPherson 1992, Buckworth 1998). Sexual differences in growth also occur in the related *S. munroi*, *S. queenslandicus*, and *S. semifasciatus* in Queensland waters (Begg and Sellin 1998, Cameron and Begg 2002), and *S. cavalla* and *S. maculatus* in southern United States waters (Peters and Schmidt 1997, DeViries and Grimes 1997), although the sex with the greatest growth rate and/or asymptotic length differ among species.

The von Bertalanffy growth function has been commonly used to model *S. commerson* growth (see Govender 1994), although only McPherson (1992) and Buckworth (1998) have previously fitted the model separately to each sex. The parameters estimated for *S. commerson* in WA waters indicate a relatively low L_∞ and correspondingly high K compared to other studies, in which these values were generally > 1300 mm FL and 0.2 – 0.4, respectively (Govender 1994). Data for Australian waters also show variation (Table 5.14), due in part to differences in data and the peculiarities of the VBGF. For instance, the data for the present study provides a better fit of growth by younger fish than did other studies (as indicated by the t_0 value) because more samples and accurate ages were obtained for fish less than a year old. However, the VBGF did not provide a good fit to the data for the older, less abundant fish, and therefore underestimates the asymptotic length for *S. commerson* in WA. This is indicated by the fact that in all three regions of WA the estimate of L_∞ was less than the average length of the ten largest fish in the samples (Table 5.14), which may also be used as an approximation of asymptotic length (King 1995). Nevertheless, when forced through zero the estimated L_∞ for male and female *S. commerson* in the NT are similar to those for the adjacent Kimberley region (Table 5.14), indicating similar growth trends. Buckworth (1998) also noted the poor fit of the VBGF to data for NT *S. commerson*, and it is likely that an alternative model to the von Bertalanffy growth function may provide a better description of growth in this species.

Female *S. commerson* have previously been shown to attain a larger body size and age than males (McPherson 1992, Buckworth 1998). As in the Kimberley region, where the oldest fish was a 12.5 year old female, the oldest fish in Queensland waters was a 14 year old female (McPherson 1992), and the oldest fish in NT waters was 11 years of age (with no apparent difference between the sexes; Buckworth 1998). Dudley *et al.* (1992) also suggested that this species reached a maximum age of 10 or more years in Oman. The maximum ages and tendency for males to dominate the older age groups in the Pilbara and west coast regions are therefore in contrast to previous studies of this species. However, *Scomberomorus cavalla*, which like *S. commerson* is a larger member of this genus, also reach over 20 years of age (Collins *et al.* 1987, DeViries and Grimes 1997), and fish of a given species that inhabit colder waters tend to have greater longevity (and, to a lesser extent, larger body size) than those in warmer environments (Beverton 1986).

Prediction of age

The subjective and time-consuming task of interpreting otolith annuli has led to investigation of alternative methods of ageing fish, with otolith weight typically shown to be a more accurate predictor of age than other parameters (e.g. Pawson 1990, Fletcher 1991, Worthington *et al.* 1995). Otolith weight (OW) was the best single predictor of length, weight and age of *S. commerson* during the present study because it incorporates ontogenetic changes in the deposition of otolith material. This is in contrast to otolith length which slows considerably as the fish ages and changes occur in the deposition of otolith material. Buckworth (1998) similarly noted that OW showed promise as a predictor of age for *S. commerson* in the NT, although considerable care was required in the removal of otoliths as these are easily broken in this species.

The combination of OW and head length (HL) provided the best fit to the length at age data for males, whereas whole weight and OW (plus FL) were better overall for females. This provides further evidence of how the growth of males and females differ. The use of HL and OW to describe growth of females incurred a minor loss of accuracy and is more advantageous for future cost-effective monitoring. However, whilst HL and OW provided a good fit to the growth curves for *S. commerson*, there were considerable errors in some of the point estimates of age. This is probably due to individual variability in OW or HL, since the estimates of age are best for younger age groups in which body parameters generally exhibit less variability. It is also likely that HL is the main source of error since body parameters vary more with age than otolith weight.

Further analyses are therefore required before the age of *S. commerson* individuals can be reliably obtained by means other than otolith annuli counts. The answer may lie in identifying head and otolith measurements that are outside objective criteria prior to their use in identifying age. Other body parameters could also be included in analyses as a check of the validity of age estimates. For instance, use of FL to show that fish of a certain size could not possibly be a certain age. However, the use of more parameters in estimating age may considerably complicate the data gathering process and significantly reduce sample numbers. Finally, it will be necessary to regularly recalibrate the relationship between body dimensions and otolith parameters with ages obtained from counts of otolith annuli.

Whole versus sectioned otoliths

Of six previous studies on the age and growth of *S. commerson* using otoliths, five were based on analysis of whole and one on sectioned otoliths. In the latter study whole otoliths were more difficult to interpret than sectioned otoliths although neither method produced good results (Buckworth 1998). Dudley *et al.* (1992) also concluded that whole otoliths of *S. commerson* were not suitable for ageing and subsequently sectioned and aged a small number of otoliths (24 for microincrement and 14 for annuli counts) to supplement their length data for growth analyses. In contrast, McPherson (1992) read otoliths whole (apart from seven sectioned for microincrement counts), finding most could be reliably aged. The present study concurs with McPherson (1992) in showing good agreement between repeat counts of the whole otoliths, although noting that the reader was more familiar with the structure of *S. commerson* otoliths sections by the time whole otoliths were examined. Whole otoliths with good readability also provided results that were generally similar to those obtained from sections, and the overall difference between estimated ages was zero. Nevertheless, with less readable otoliths there were significant differences between ages of sectioned and whole otoliths, due mainly to differences in interpreting the otolith margin and ring structure, with the first few bands generally clearer in whole otoliths whereas the opposite was true for otoliths with more numerous bands. The results therefore show that whole otoliths have potential for ageing *S. commerson* inhabiting WA waters, although ideally only those with good readability should be utilised, thereby impacting the number of useable otoliths from each region.

Age-length keys

Age-length keys have been widely used to estimate age distributions of populations, but can give poor or misleading data if the sample from which the key is developed is not representative of the population (Kimura 1977). They are nevertheless an important component in the stock assessment of king mackerel (*S. cavalla*) in US waters (http://www.gulfcouncil.org/newslet/nlet0902.pdf). The keys developed for *S. commerson* are probably sufficiently representative of the population but suffer from low sample sizes and therefore should be used with caution since some age classes are likely to be biased (particularly older age groups). It may be possible to test and then adjust for such biases using patterns in the distribution of other data within the key and from ages estimated using other means. If this is done these keys will be a useful adjunct to other means for estimating ages, although they should be validated regularly for changes in the age structure of the population through time.

Mortality

Estimates of mortality are fundamental to stock assessments yet are difficult to determine. Usually total mortality (Z) is easier to estimate than its fishing (F) and natural (M) mortality components (King 1995). In contrast, M is one of the most difficult parameters of all to determine because of the confounding effects of recruitment, F, and M, and the difficulty in obtaining the data required to estimate it (Quinn and Deriso 1999, Vetter 1988). As such, M is usually estimated indirectly using parameters such as K and L_∞ that have been shown to be related to M. Fishing mortality is also difficult to estimate but is a crucial parameter in traditional management of fish populations, where biological reference points used in managing harvest rates often pertain to limits of F (see Chapter 7).

Few studies have estimated mortality for *S. commerson*, and reliability of methods used, and subsequent results, vary markedly (Table 5.15). Differing capture methods are also likely to result in different estimates of mortality (e.g gillnet versus troll lines; Collette and Nauen, 1983). Our estimates of Z are low compared to the few published values, although only Govender (1995) used age-based catch curves as in the present study. However, the analyses by Govender (1995) were based on the deposition of two rings per year and the Schnute growth function. The estimates of Z for South African fish were much higher than found in the present study (0.75 yr^{-1}) - possibly too high because of the lack of fish in older age classes (Govender 1995). Compared to other *Scomberomorus* species, our estimate is also generally low, although again the methods employed varied considerably (Table 5.15). Total mortality for *S. cavalla* in South Eastern US waters, a species which perhaps has the most similar age and growth characteristics to *S. commerson*, are most comparable (Johnston 1983).

The relatively high estimate of maximum age found for *S. commerson* in the Pilbara and west coast regions is likely to be the main reason for the correspondingly low values of Z. It is also possible that the relatively high value for Z in the Kimberley region is due to an underestimation of maximum age, since the gear used and locations fished by commercial fishers in this region could be biased against larger/older fish. Consistently higher Z of females in each region may reflect the slight female bias in overall sex ratios and faster female growth rate, making them more vulnerable to the fishery at a slightly younger age than males (as indicated in Table 2.3, Chapter 2). The particularly large intersexual differences in the Pilbara and west coast regions may be further evidence that larger fish are more vulnerable to the fishery in the Pilbara and west coast regions (because of the fishing gear used), since females dominate the larger size classes (Section 4.1.2).

Literature values of natural mortality for *S. commerson* vary 0.35 – 1.23, with most between 0.4 – 0.6 (Table 5.15). This range also applies to other species of *Scomberomorus*. In Australian waters, stock assessments in the NT and QLD have been based on an *M* of 0.34 (R. Buckworth, Fisheries Division, Dept. of Business, Industry & Resource Developt., *pers. comm.*), although this estimate has recently been revised to 0.4 for QLD waters (S. Hoyle, Southern Fisheries Centre, QLD Dept. of Primary Industry, *pers. comm.*). Estimates for *S. commerson* in WA waters derived from the Pauly (1980) equation are therefore relatively high, due mainly to the high estimate of *K* for fish in WA waters (noting that this is not considered an overestimate given the good numbers of smaller fish in our samples).

Reliability of the Pauly (1980) equation is suspect, and may provide misleading estimates of *M* (Vetter 1988). Furthermore, being based on a large number of species from a wide range of habitats and widely varying estimates of *M*, the equation has wide confidence intervals. Consequently, point estimates obtained from this equation (and its derivatives) are imprecise and likely to be inaccurate (N. Hall, Centre for Fish and Fisheries Research, Murdoch University, *pers. comm.*).

The most reliable estimates of *M* are therefore likely to be those derived from the Hoenig (1983) equation, although as this equation was derived from exploited stocks it is biased and provides an overestimate of *M* (S. Newman, WA Dept. of Fisheries, *pers. comm.*). However, because of the relatively old ages for *S. commerson* in the Pilbara and west coast regions these estimates are lower than those previously reported in the literature. There is therefore considerable uncertainty surrounding the estimates of *Z* and *M* for *S. commerson* in WA waters, highlighted by the fact that subtraction of Hoenig (1983) derived values of *M* from *Z* produce very low values for *F* (Table 5.16). These are much lower than values that YPR analyses (Section 7.1.2) suggest are optimal. Because of the sensitivity of fisheries models to *M* (Vetter 1988) and the importance of *F* in management of fishing activities, further assessment of mortalities is essential for *S. commerson* in WA waters. This was the impetus behind a recently commenced study to estimate *F* for this species in NT waters, using a novel tagging method that minimises post-release mortality (R. Buckworth, Fisheries Division, Dept. of Business, Industry & Resource Development., *pers. comm.*).

Table 5.14 Von Bertalanffy growth parameters for *S. commerson* in Australian waters. Data for McPherson (1992) was based on back calculated length-at-age data, all other data were calculated using actual length-at-age data. Avge largest; the average length of the largest ten fish used in growth curve analyses. All lengths are of fork length.

Sex	Area	L_∞	K	tzero	Avge largest	Reference
Male	QLD	1275.00	0.25	-1.72		McPherson 1992
Male	NT	1285.80	0.10	-9.80		Buckworth 1998
Male	NT*	1026.80	0.63			Buckworth 1998
Male	Kimberley	1067.23	0.85	-0.21	1163.2	Present study
Male	Pilbara	1155.27	0.69	-0.29	1293.6	Present study
Male	West coast	1139.77	0.76	-0.21	1205.7	Present study
Female	QLD	1550.00	0.17	-2.22		McPherson 1992
Female	NT	1515.60	0.12	-6.31		Buckworth 1998
Female	NT*	1216.10	0.52			Buckworth 1998
Female	Kimberley	1218.77	0.65	-0.26	1361.2	Present study
Female	Pilbara	1259.03	0.63	-0.29	1473.3	Present study
Female	West coast	1204.93	0.66	-0.26	1269.2	Present study
Both	NT	1217.90	0.24	-3.25		Buckworth 1998
Both	NT*	1130.50	0.57			Buckworth 1998
Both	Kimberley	1150.83	0.71	-0.25		Present study
Both	Pilbara	1208.53	0.67	-0.28		Present study
Both	West coast	1167.36	0.72	-0.23		Present study

* Data forced through zero.

Table 5.15 Mortality estimates for *S. commerson* and related species from previous studies.

		Mortality (year^{-1})					
Species/ Sex	**Region**	**Z**	**M**	**F**	**Method; References**	**C°**	**Reference**
S. commerson							
Combined	South Africa	0.75	0.5	0.25	Schnute growth curve to age length data, 2 bands/yr; Pauly 1980		Govender 1980
			0.45		“ “	22	
			0.48		“ “	25	
			0.51		“ “	28	
			0.55		“ “ ; Richter and Efanov 1977		
Combined	Oman		0.6 0.5	1.1	VBGF, Pauly 1980;Ricker 1975	25	Dudley *et al* 1992
Combined	Oman	1.21-1.38	0.35	0.86-1.45	Length converted catch curve Pauly 1983; Pauly 1980		Al Hosni & Siddeek 1999
			0.64	0.57-1.16	“ “ ; Averston & Carney 1975		
			0.77	0.44-1.03	“ “ ; Richter and Efanov 1977		
Combined	Yemen	0.44	0.38		Aged scales and length frequency		Edwards *et al* 1985
Combined	Oman		0.7		Length frequency Bertignac & Yesaki 1994		In Al Hosni & Siddeek 1999
Combined	Sri Lanka		0.48		Dayaratne 1989		“ “
Combined	India		0.78		Pillai 1994		“ “
Combined	Arabian Gulf			0.36	Kedidi 1993		“ “
Combined	Red Sea		0.46		Kedidi & Abushusha 1987		“ “
Combined	India	3.09 4.08	0.79		Length converted catch curve analysis, Pauly 1983	29	Yohannan *et al* 1992
Combined	Phillipines	1.49	1.23	0.17	Trawl fishery length converted catch curve Pauly 1984, Pauly 1980	27	Ingles & Pauly 1984
S. munroi							
Female	Queensland	1.167	0.689		Regression linearised catch age frequency; Ricker 1975		Cameron & Begg 2002
Male		1.079	0.660		“ “		
S. queenslandicus							
Female	Queensland	0.877	0.584		Regression linearised catch age frequency; Ricker 1975		Cameron & Begg 2002
Male		0.961	0.617		“ “		
S. semifasciatus							
Female	Queensland	0.482	0.382		Regression linearised catch age frequency; Ricker 1975		Cameron & Begg 2002
Male		0.492	0.389		“ “		
S. plurilineatus							
Combined	South Africa	0.73	0.45	0.28	Age Lt Special VBG, Schnute 1981; Pauly 1980; Punt 1992		Chale-Matsau *et al* 1999
		0.27			Monthly Length based, SLCA; Pauly 1980		
S. cavalla							
Combined	South Eastern U.S.	0.35			Convert length freq to age freq by age key; Heincke 1913		Johnston 1983
		0.34			“ “ ;Jackson 1939		
		0.42			“ “ ;Rounsefell & Everhart 1953		
		0.42			“ “ ; Beverton & Holt 1957		
		0.32			“ “ ; Robson & Chapman 1961		
		0.35			“ “ ; Regression		
Combined	Gulf of Mexico	0.794			Recapture growth rates by nonlinear solution Fabens 1966; Regression		Sutter *et al* 1991
		0.877			“ “		
		0.766			“ “		
Combined	Atlantic	0.658			“ “		
		0.49			“ “		
		0.582			“ “		
S. maculatus							
Combined	Carribean	0.7	0.5		Beach seine Walford plots fitted by eye to mean lt at age Vs age		
		0.99	0.63		Gill net “ “		
Combined	Atalantic			0.21	Not given		Desfosse *et al* 1999
S. niphonius							
	Seto Sea	0.75	0.31	0.44	Averaged catch curve; Estimated from life span		Nagai *et al*

Table 5.16 Fishing mortality (*F*) for *S. commerson* derived by subtracting natural mortality (estimated using the Hoenig (1983) equation) from total mortality (estimated using age based catch curves).

	Fishing Mortality (*Z* - *M*)
$\text{Kimberley}_{\text{Female}}$	0.06
$\text{Kimberley}_{\text{Male}}$	0.13
$\text{Pilbara}_{\text{Female}}$	0.00
$\text{Pilbara}_{\text{Male}}$	0.06
$\text{West coast}_{\text{Female}}$	0.04
$\text{West coast}_{\text{Male}}$	0.06

6.0 Diet

P. Lewis and M. Mackie

6.1 Results

Most *S. commerson* stomachs were empty (78.4%, N= 1200). Of the 331 stomachs that contained items, 10.6% contained fresh garfish or mullet that was probably the bait used in their capture and were excluded from further analysis. The remaining 296 stomachs either contained fish (85.8%), cephalopods (11.5%), fish and cephalopods (2.0%) or crustaceans (0.7%). Due to the degree of digestion only 44.9% of the fish items could be identified to family and of these only 59.6%, which were freshly consumed, could be identified to species. The range of families and species identified, along with the occurrence, size ranges and the overall percentages of the 8 general groupings are given in Table 6.1. This shows that *S. commerson* prey on a wide range of fish species from 19 families, and small pelagic fish (Atherinidae, Carangidae, Clupeidae, Exocoetidae, Engraulidae, Leiognathidae, Scombridae, Sphyraenidae) made up the largest percentage of identifiable prey items (30.0%).

The weight of stomach contents ranged from 1 - 1231grams. The relationships between prey length and gut content weight with *S. commerson* length (Figures 6.1 and 6.2) shows that fish are restricted in the size of prey they can consume and there is a tendency for individuals > 1100 mm FL to target and consume fish with lengths > 200 mm (particularly medium to large pelagic fish and reef associated fish). It was also evident that the stomachs of smaller *S. commerson* often contained just the tails of prey whereas the larger individuals seemed to take the prey in the middle, evident by the prey items often being in three clear pieces.

A number of unexpected items were discovered in the stomach contents of *S. commerson*, including half a snowpea and the broken off tip of a pectoral fin or tail from a *S. commerson*. The ends of the pectoral fins and tails often break off the landed fish as they thrash on the deck and presumably, like the snowpea, it had been washed overboard and consumed by this individual as it sank down. Other unusual prey items included a mantis shrimp (Stomatopoda), swimmer crab (Portunidae), small cuttlefish (Sepiidae), small triggerfish (Monacanthidae, TL = 22 mm), and pufferfish.

6.2 Discussion

As in previous studies of *S. commerson* diet (McPherson 1987, Williams 1964) the majority of stomachs were empty. This may be due to the tendency of the species to regurgitate its stomach contents while being captured (McPherson 1987, Williams 1964, *pers. obs.*) although this was not frequently noted in the present study. Structure of the digestive system, with numerous pyloric caecae, suggests a rapid digestion rate of prey in this species. This was also indicated by the advanced state of digestion of most prey in the stomachs of *S. commerson*, which hampered the identification of most fish beyond family or even digested fish. This would be expected given the rapid growth rate of this species (Chapter 5).

The occurrence of families identified in the stomachs of *S. commerson* is similar to that of McPherson (1987) and Williams (1964) who also found that pelagic fish (Clupeidae, Carangidae and Caesionidae) were well represented in the diet. The low numbers of reef-associated pelagic and demersal fish in the stomachs indicates that even though *S. commerson* are aggregating at reefs they are not actively targeting these reef associated species.

Cephalopods were also a common prey item, comprising 11.5%. However, more than half of these were collected on the same day and a further third were collected at the same locations in the Kimberley region, a month or two earlier. This suggests a high abundance of squid in the area that were being targeted by *S. commerson*. Commercial fishers in the Kimberley region also note that *S. commerson* had previously targeted large schools of squid that periodically appeared in northern waters.

The positive relationship between maximum prey size and stomach content weight with body length suggests that smaller individuals are restricted in the size of prey they can consume. There is some indication that individuals > 1100 mm FL may utilise a different feeding technique and select prey items > 200 mm in length. Nevertheless, the regular occurrence of small prey items and range of prey shows that the species is an opportunistic higher order predator. The presence of unusual items also indicates that this species has limited ability to stop and test items before consumption.

Table 6.1 Occurrence of prey items and group percentages. Note bait percentage is of all non-empty stomachs and remainder are with bait excluded.

Group **Common name**	**Family/Order**	**Species** (if known)	**N** **(N)**	**Size range**	**Group** **(%)**
Bait Items			**35**		**(10.6)**
Digested Fish Unidentified			**104**		**35.1**
Small pelagic			**89**		**30.0**
Unidentified			26		
Hardyheads	Atherinidae		1		
Yellow-tail scad	Carangidae	*Atule mate*	14	FL: 55-230mm	
Oxeyed scad	Carangidae	*Selar boops*	2	FL: 175-215mm	
Northern pilchard	Clupeidae	*Amblygaster sirm*	4	FL: 85-110mm	
Gold striped sardine	Clupeidae	*Sardinella gibbosa*	7	FL: 100-146mm	
Scaly mackerel	Clupeidae	*Sardinella lemuru*	15	FL: 130-160mm	
Longfin anchovy	Engraulidae	*Setipinna tenuifilis*	2	FL: 80-110mm	
Indian anchovy	Engraulidae	*Stolephorus indicus*	7	TL: 140mm	
Flying fish	Exocoetidae	*Cypselurus sp.*	2		
Ponyfish	Leiognathidae		2	FL: 65-85mm	
Blue mackerel	Scombridae		4	FL: 80mm	
Striped seapike	Sphyraenidae	*Sphyraena obtusata*	3	FL: 250mm	
Med/Large pelagic			**35**		**11.8**
Trevally	Carangidae		11	FL: 80-280mm	
Finny scad	Carangidae	Megalaspis cordyla	3	FL: 230-505mm	
Needleskin queenfish	Carangidae	*Scomberoides tol*	2	FL: 275mm	
Tuna and mackerel	Scombridae		18	FL: to 380mm	
Mackerel tuna	Scombridae	*Euthynnus affinis*	1	FL: 380mm	
Reef associated pelagic			**11**		**3.7**
Fusilier	Caesionidae		3	FL: 52-180mm	
Red-bellied fusilier	Caesionidae	Caesio cuning	4	FL: 150mm	
Randall's fusilier	Caesionidae	*Pterocaesio randalli*	1	TL: 220mm	
Damselfish	Pomacentridae		3	FL: 55-135mm	
Reef associated			**15**		**5.1**
Common grinner	Harpodontidae	*Saurida tumbil*	1		
Spotfin squirrelfish	Holocentridae	*Neoniphon sammara*	1		
Parrotfish	Scaridae		1		
Blue&yellow wrasse	Labridae	*Anampses lennardi*	1	TL: 270mm	
Blue bone tuskfish	Labridae	*Choerodon sp*	1	TL: 270mm	
Triggerfish	Monacanthidae		2	FL: 22-51mm	
Scribbled angelfish	Pomacanthidae	*Chaetadontoplus duboulayi*	1		
Rockcod	Serranidae	*Epinephelus sp.*	1	TL: 290mm	
Spinefoot	Siganidae	*Siganus sp.*	1	TL: 215mm	
Lizardfish	Synodontidae		1		
Pufferfish	Tetraodontidae		1		
Finespined pufferfish	Tetraodontidae	*Tyienus spinosissimus*	2	TL: 102mm	
Hairtail	Trichiuridae		1	TL: 400mm	
Digested fish & squid			**6**		**2.0**
Cephalopod			**34**		**11.5**
Squid	Loliginidae		33	TL: 95-160mm	
Cuttlefish	Sepiidae		1	Cuttle: 55mm	
Crustacean			**2**		**0.7**
Swimmer crab	Portunidae		1		
Mantis shrimp	Stomatopoda		1	TL: 75mm	

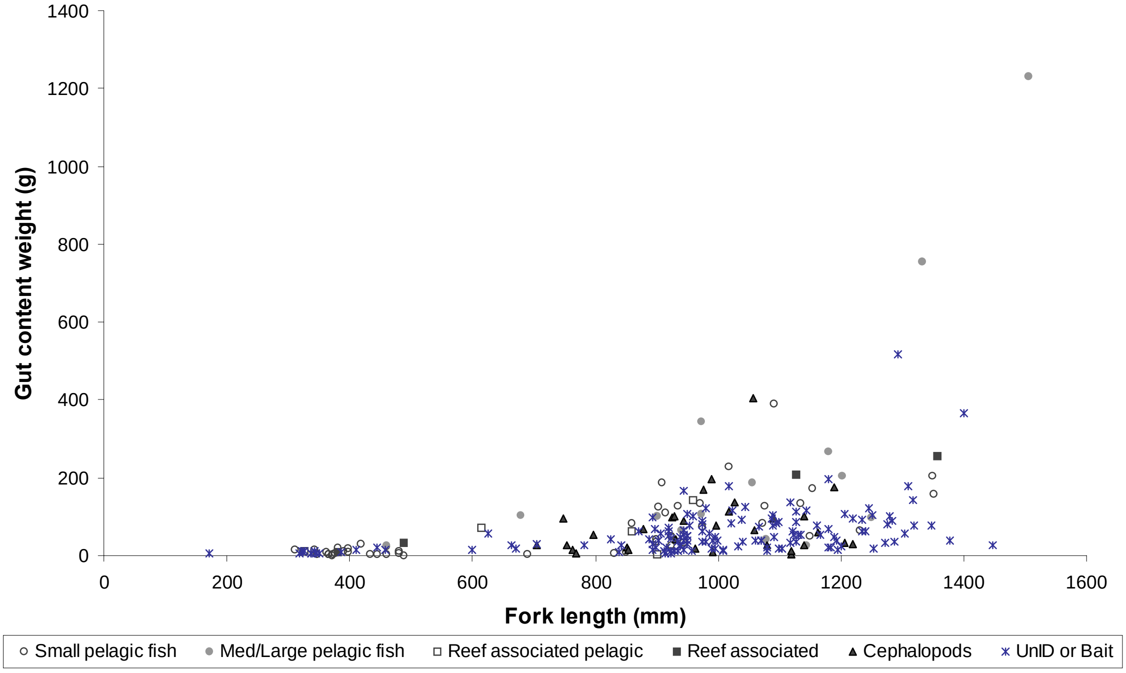


Figure 6.1 Weight of stomach contents in relation to the fork length of *S. commerson*, showing the 6 groups of prey items.

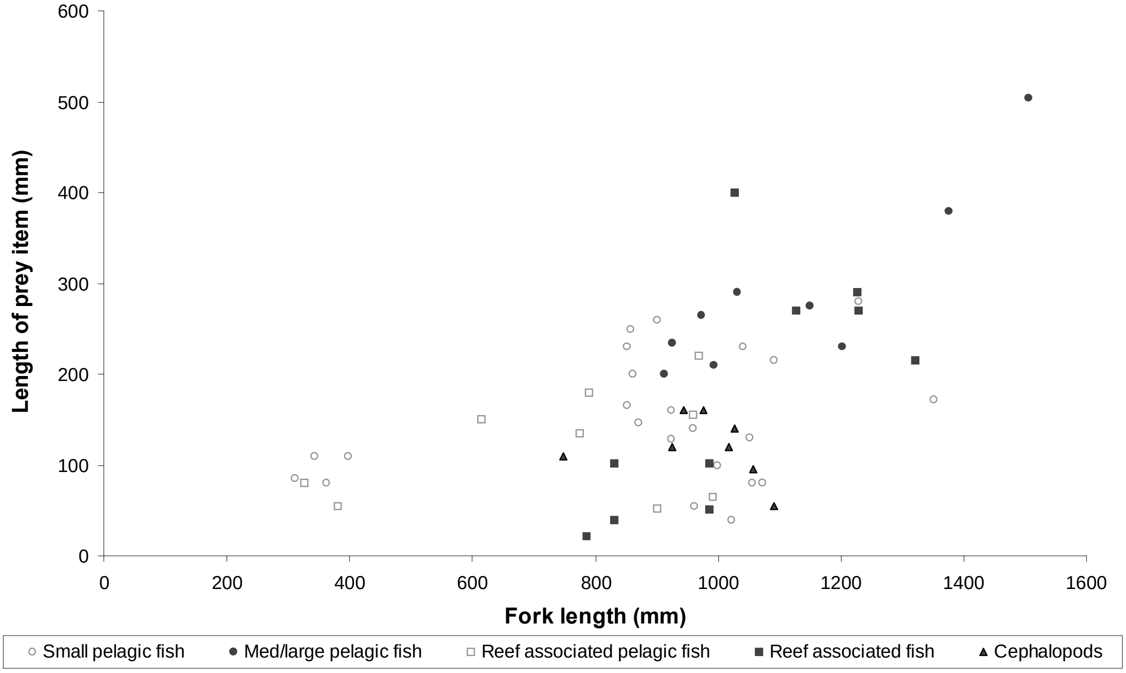


Figure 6.2 Length of prey items in stomach contents in relation to the fork length of *S. commerson*, showing the 5 groups of prey items.

7.0 Stock assessment

M. Mackie, P. Stephenson and P. Lewis

7.1 Results

7.1.1 Relationship between catch and effort

By acting as an index of abundance, catch-per-unit-effort (CPUE) data provides the key to fitting biomass dynamics models. However, when a lack of sufficient contrast in the CPUE data negates the possibility of successfully fitting these types of models it is still be instructive to examine the catch rate information. Therefore, before examining the results for the biomass dynamics models, we first determined whether or not any temporal trends in the level of effort exerted were influencing CPUE. To facilitate interpretation of the temporal data, annual data were grouped into 5- or 6-year intervals.

For each of the three regions there did not appear to be any obvious long term trends in CPUE that could be attributed to trends in effort (Figure 7.1). This was particularly clear for the Kimberley region where CPUE has remained constant regardless of the level of effort applied in the fishery. While the patterns for the Pilbara and the West coast regions show more scatter than for the Kimberly data, the longer term trends are, again, for stable CPUEs.

The consistent relationship between CPUE and effort, whereby CPUE has remained stable over a range of effort levels applied in the three fisheries, suggests that historic and current effort-levels by the line fishery for mackerel have not been sufficient to induce a response in the stock. In terms of using CPUE as an index of abundance, the stability of the CPUE-effort relationship means that trends in CPUE can be considered as indicators of the performance of the fishery, even in those cases were there is insufficient contrast to effectively fit a population model.

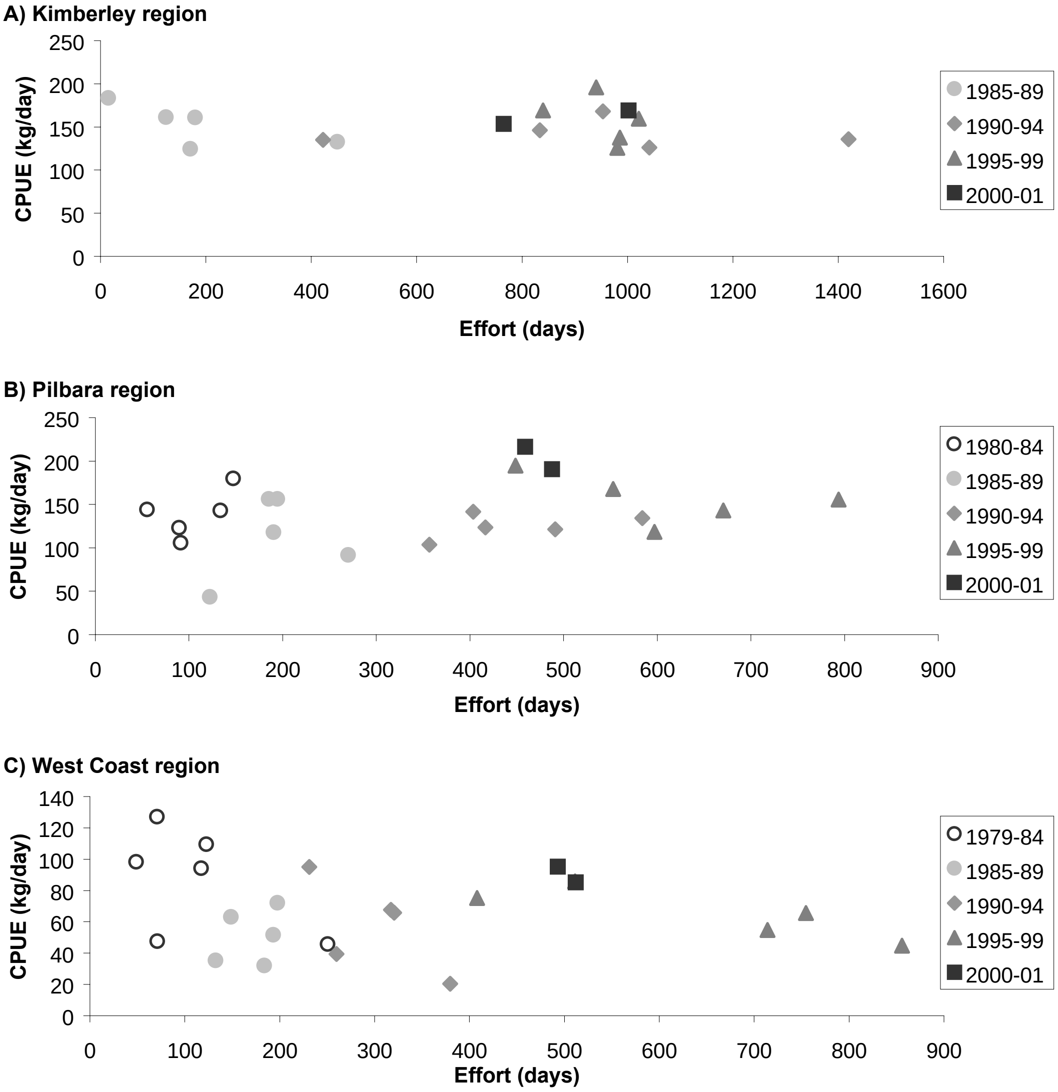


Figure 7.1 Relationship between catch per unit effort (CPUE) and effort for *S. commerson* in the three regions of Western Australia.

7.1.2 Biomass dynamic model

The models generally did not provide a good description of the data for each region, due mainly to the lack of temporal contrast in the catch and effort data (note that weighted data was used in each of the analyses – refer to Section 3.2.2.). The one exception was the data for the west coast region, which could be modelled using the Schaeffer (1954) form of the biomass dynamic model (although the variance around the estimates are large; Figure 7.2, Table 7.1). In this region the model suggests that the median carrying capacity (K) of

S. commerson was 1115 t, (95% CI: 757 – 2116 t), with a median population growth rate (*r*) of 0.31 (95% CI: 0.12 – 0.71) and a median catchability coefficient (*q*) of 0.09 (95% CI: 0.06 – 0.11). Since 1979 the estimated biomass has fluctuated from a low of 494 t in 1992 to 1111 t in 1979, and has been fairly stable since 1994 at around 850 t (Table 7.2). Catches in this region have therefore varied between 4 and 18 % of estimated biomass since 1979, with 9-11% of the biomass captured annually in recent years (Table 7.1).

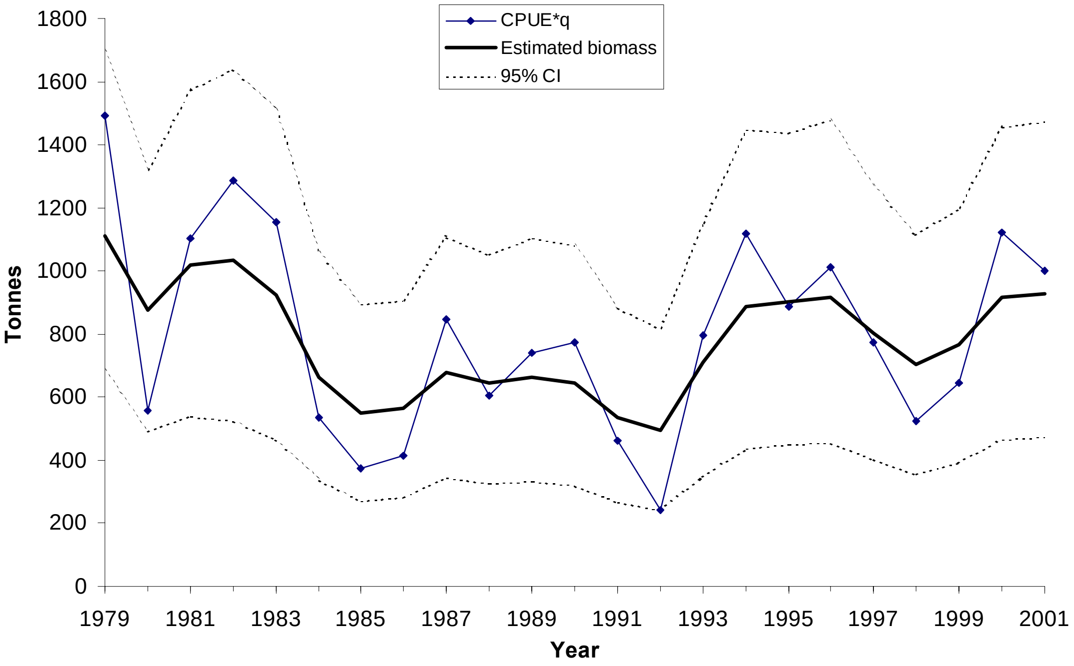


Figure 7.2 Relationship between biomass (and 95% CI, as estimated by the Schaefer model) and CPUE (weighted by q) of *S. commerson* in the west coast region. To improve reliability of the data, effort (# of successful mackerel fishing days) for those vessels known to target *S. commerson* have been used in conjunction with total catch in the region to provide a CPUE for the whole fleet (refer to text).

Table 7.1 Catch, estimated biomass and derived statistics for *S. commerson* in the commercial fishery of the west coast region. Estimates obtained from the biomass dynamic model.

		Estimated Biomass (t)				
Year	**Weighted catch (t)**	**Median**	**95 % CI**		**Catch/Biomass**	**Biomass/K**
1979	47.8	1111	686	1696	0.043	1.00
1980	39.1	877	490	1318	0.045	0.79
1981	90.2	1018	540	1572	0.089	0.91
1982	71.9	1035	524	1639	0.069	0.93
1983	76.3	922	467	1509	0.083	0.83
1984	84.6	663	338	1060	0.128	0.59
1985	74.0	548	272	895	0.135	0.49
1986	85.3	566	283	905	0.151	0.51
1987	121.0	680	345	1108	0.178	0.61
1988	86.5	646	328	1053	0.134	0.58
1989	55.5	664	332	1103	0.084	0.60
1990	50.4	644	318	1080	0.078	0.58
1991	19.1	534	266	882	0.036	0.48
1992	19.3	494	241	819	0.039	0.44
1993	34.5	710	350	1153	0.049	0.64
1994	31.8	888	435	1450	0.036	0.80
1995	42.4	900	452	1437	0.047	0.81
1996	79.5	916	454	1477	0.087	0.82
1997	92.5	803	402	1273	0.115	0.72
1998	66.4	704	357	1113	0.094	0.63
1999	71.5	765	393	1200	0.093	0.69
2000	83.0	917	464	1455	0.090	0.82
2001	103.5	926	471	1475	0.112	0.83

7.1.3 Yield per recruit model

Using an estimate of *M* derived from the Hoenig (1983) equation, the models indicate that YPR of *S. commerson* was less in the Kimberley region than in the Pilbara and west coast regions (Figures 7.3a-c). Nevertheless, in all regions the curves suggest that the species is resilient to fishing mortality, and at the current minimum legal length (≈ 1.5 yrs) growth overfishing would not occur until *F* was very high (> 1.2). This is well above standard target and limit levels of *F* ($F_{0.2}$ and $F_{0.1}$; Table 7.2). In contrast, growth overfishing may have occurred at $F \geq 0.6$ in the Pilbara and west coast regions with the previous minimum legal length (≈ 1 yr). At ages of first capture above 1 yr the YPR of *S. commerson* increase rapidly up to an *F* of around 0.4 and then change very little with further increases of *F*. Consequently, the level of *F* to achieve maximum YPR (F_{max}) is high.

The age at first capture to maximise YPR was 1.9 yrs in the Kimberley, compared to 2.9 and 2.7 yrs in the Pilbara and west coast regions. These equate to total lengths of ≈ 997, 1163 and 1147 mm, respectively (TL instead of FL provided for management purposes). However, the *F* required to achieve this maximum is extreme (Table 7.2). The ages at first capture that optimise YPR at $F_{0.2}$ and $F_{0.1}$ were again lower in the Kimberley region (1.4 yrs (884 mm TL) and 1.3 yrs (856 mm TL), respectively), compared to these levels in the Pilbara (1.9 yrs (1018 mm TL) and 1.7 yrs (975 mm TL), respectively, and west coast regions (1.9 (1010 mm TL) and 1.7 yrs (968 mm TL), respectively. The corresponding target and limit levels of *F* to optimise YPR at these ages did not differ substantially from those that would achieve these reference levels at the current minimum legal length (MLL; Table 7.2). These data indicate that the current MLL in the Kimberley region is appropriate for optimising YPR at $F_{0.2}$ and $F_{0.1}$, whereas in the Pilbara and west coast regions it would be desirable to increase the age at first capture by about 0.4 of a year, corresponding to an increase in the MLL to around 1010 mm TL.

The age at first capture to optimise YPR at $F_{0.2}$ and $F_{0.1}$ were also determined for alternative levels of *M* in light of the considerable uncertainty in estimation of this parameter (Table 7.3; refer to Chapter 5). These data suggest that the age at first capture to optimise YPR differed little with *M*, although because of the rapid growth rate of young *S. commerson* the lengths corresponding to these ages exhibit considerably greater variation. Using an *M* of 0.3 - 0.4 (similar to that used in the NT and QLD, and the Kimberley region using the Hoenig equation) the target age at first capture is ≈ 1.2 – 1.5 yrs or 830 – 920 mm TL, and the limit age at first capture is ≈ 1.3 – 1.7 yrs or 860 – 960 mm TL. The *F* to optimise YPR at this *M* is around 0.3 for target levels, and 0.45 for limit levels. Finally, with an *M* of 0.2 (similar to that estimated for the Pilbara and west coast regions using the Hoenig equation), the optimum age at first capture is ≈ 1.8 – 1.9 yrs (980 – 1000 mm TL), and the *F* around 0.2 – 0.3.

Table 7.2 Results of yield per recruit (YPR) analyses for *S. commerson* within each region. *F*; fishing mortality. t_c; age at first capture (yr). max/opt; maximise/optimise. Note that *M* used in analyses was estimated from maximum age using the equation of Hoenig (1983).

	Current*			**t_c to max/opt YPR at:**			**F to max/opt YPR at:**		
	F_{max}	$F_{0.1}$	$F_{0.2}$	F_{max}	$F_{0.1}$	$F_{0.2}$	F_{max}	$F_{0.1}$	$F_{0.2}$
Kimberley	2.943	0.492	0.310	1.9	1.4	1.3	10.779	0.487	0.301
Pilbara	0.882	0.250	0.160	2.9	1.9	1.7	10.260	0.270	0.166
West coast	0.987	0.297	0.191	2.7	1.9	1.7	9.336	0.325	0.200

*Based on current age at first capture.

Table 7.3 Age at first capture (t_c) and fishing mortality (*F*) to optimise the yield per recruit (YPR) of *S. commerson* at target ($F_{0.2}$) and limit levels ($F_{0.1}$), for different levels of natural mortality (*M*). An *M* of 0.2 is similar to that estimated for *S. commerson* in the Pilbara and west coast regions using the Hoenig (1983) equation (Table 5.13). *M* of 0.34 is the same as used in analyses of *S. commerson* in the Northern Territory and Queensland (R. Buckworth, Fisheries Division, Dept. of Business, Industry & Resource Development, *pers. comm.*). *M* of 0.4 is similar to that estimated for *S. commerson* in the Kimberley region using the Hoenig (1983) equation (Table 5.13), and is the same as recently estimated for *S. commerson* in Queensland (S. Hoyle, Southern Fishery Centre, QLD Dept. of Primary Industries, *pers. comm.*), and *M* of 0.9 is in the range of estimates for *S. commerson* in WA derived using the Pauly (1980) equation. Refer to Appendix 5, Table A5.7 for details. K, P, WC; Kimberley, Pilbara and west coast regions, respectively.

	t_c to optimise YPR at:						**F to optimise YPR at:**					
	$F_{0.1}$			**$F_{0.2}$**			**$F_{0.1}$**			**$F_{0.2}$**		
M	**K**	**P**	**WC**	**K**	**P**	**WC**	**K**	**P**	**WC**	**K**	**P**	**WC**
0.2	1.9	1.8	2.1	1.8	1.7	1.9	0.33	0.281	0.291	0.218	0.176	0.180
0.3	1.5	1.5	1.7	1.4	1.4	1.5	0.430	0.406	0.407	0.269	0.249	0.246
0.34	1.4	1.4	1.6	1.3	1.3	1.5	0.473	0.454	0.455	0.293	0.278	0.279
0.4	1.3	1.3	1.5	1.2	1.2	1.4	0.542	0.528	0.530	0.333	0.323	0.324
0.5	1.2	1.2	1.3	1.1	1.1	1.2	0.666	0.654	0.638	0.405	0.398	0.395
0.9	0.9	1.0	1.1	0.9	0.9	1.0	1.115	1.162	1.132	0.702	0.692	0.677

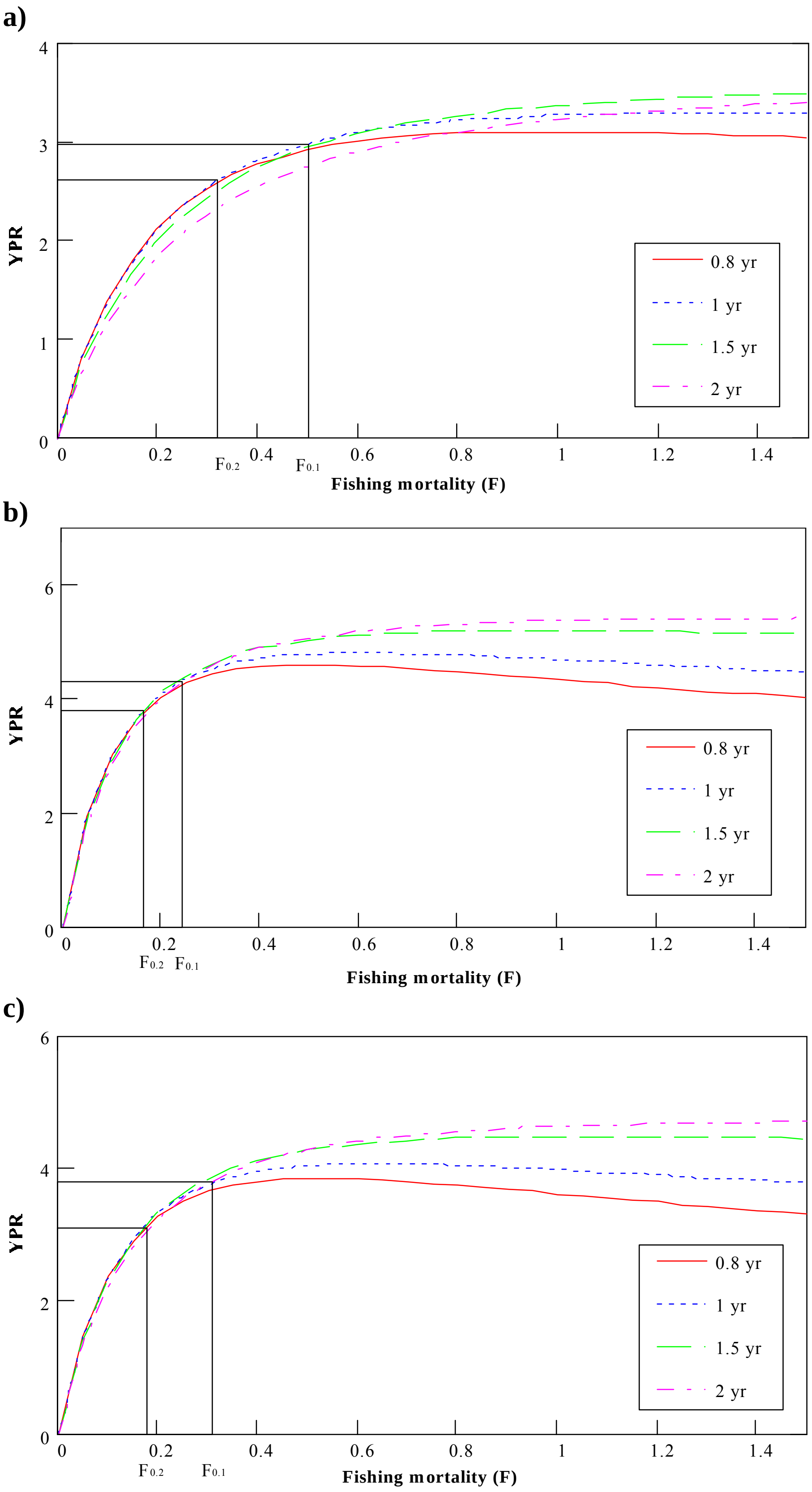


Figure 7.3 Yield per recruit with increasing mortality for *S. commerson* from a) the Kimberley region, b) the Pilbara region, and c) the west coast region, shown for differing ages at first capture. Age 1.0 approximates to 750mm TL (the previous minimum legal length; MLL) and age 1.5 to 900mm TL (current MLL). $F_{0.1}$ and $F_{0.2}$ estimates are for current age at first capture.

7.1.4 Egg per recruit model

As with YPR, the models indicate that the number of eggs per recruit (EPR) is much less for *S. commerson* in the Kimberley region than in the Pilbara and west coast regions (Figures 7.4a-c). The trends in the curves are similar between regions nonetheless; EPR decreases rapidly with increasing *F* if fish are captured at ≤ 1 yr, whereas little change occurs if the age of first capture is ≥ 2.5 yrs. The patterns for 1.5 – 2 year old fish are most relevant to the current MLL and YPR analyses, and indicate that the difference between these two ages at first capture are significant in terms of EPR. For instance, at *F* of 0.2 yr^{-1} the EPR is increased about 20 – 30% by changing the age at first capture from 1.5 to 2 yrs (Figures 7.4a-c). The models also show that the increase in size limit from 750 to 900 mm TL almost doubled the EPR (a 750 mm female is approx. 0.95 yrs, whereas a 900 mm fish is approx 1.4 yrs).

With the current MLL the models indicate that depletion of EPR to half its unexploited (virgin) level is rapid with increasing *F* (Figure 7.5). Because of differing growth characteristics in each region, *S. commerson* in the Pilbara region appear most vulnerable to exploitation. Hence *F* required to deplete the EPR to 50% of the unexploited EPR is just 0.18 yr^{-1} for this region, compared to 0.27 and 0.36 yr^{-1} in the west coast and Kimberley regions, respectively. Similarly, to maintain 40% of the unexploited EPR (a potential target reference point), the models indicate an *F* of 0.28 yr^{-1} in the Pilbara region, compared to 0.47 and 0.64 yr^{-1} in the west coast and Kimberley regions, respectively. Fishing mortality to reduce the EPR to 30% of unexploited levels (limit reference point) are very high in the Kimberley and west coast regions (1.68 and 1.11, respectively), compared to 0.47 in the Pilbara region.

7.1.5 Assessment of the daily egg production method

Literature review

The Daily Egg Production Method (DEPM) (Parker 1980, Lasker 1985) is a fishery-independent method of stock assessment developed specifically for the northern anchovy *Engraulis mordax* (Parker 1980), a batch spawning pelagic species with indeterminate fecundity. The DEPM has since been applied to many other species (Alheit 1993). This study investigates the feasibility of applying this method to predict the spawning biomass of *S. commerson* in waters of Western Australia.

Fishery independent methods of stock assessment have advantages over fishery based methods in that they provide real time, potentially unbiased estimates of stock abundance. The DEPM was developed as an improvement to the annual egg production method that had previously been used for pelagic species (Priede and Watson 1993). The DEPM gives an estimation of spawning biomass from a single survey, resulting in much lower operating costs than an annual egg production method survey, which requires a series of surveys. The DEPM also accounts for inter-annual variation in spawning of the species thereby resulting in improved precision of biomass estimates.

However, the DEPM has some recognised drawbacks. In particular, this method requires considerable resources and, for species whose peak spawning period can change, relies on a large number of regular adult fish samples (to track GSI) during the DEPM survey. It is also critical that the timing of a DEPM survey coincides with the period of peak spawning, that the plankton samples are collected quantitatively and with sufficient proximity to detect concentrations of eggs within the spawning area and that a large number of adult samples be obtained (suggested as a minimum of 35 independent samples of at least 12 to 15 mature females (Alheit 1993)).

S. commerson is a batch spawning, pelagic species with an indeterminate fecundity (McPherson 1993, Chapter 4). In such species the annual fecundity is not determined before the onset of the spawning season (Hunter and Macewicz 1985). Therefore, the DEPM may be appropriate for estimating spawning biomass of this species. The DEPM takes into account the variability of spawning fraction, batch fecundity and sex ratio within and between seasons, providing a snapshot of the fishery over the period of the survey which estimates all of these adult fish parameters and relates them to the distribution and abundance of their planktonic eggs. Once these parameters have been obtained the spawning biomass can be estimated using the formula;

$$Spawning\ \ Biomass = {(A \times P \times W \times k)}\Big/{(S \times F \times R)}$$

where

A = spawning area
P = egg production (number of eggs before losses to mortality)
W = weight of adult fish
k = conversion factor
S = spawning fraction; the proportion of females that spawn per day
F = fecundity; number of eggs per batch produced by a female
R = ratio of males to females by weight

Several studies have documented the spawning season of *S. commerson* (Munro 1942, Jones and Silas 1961, Williams 1961, McPherson 1993, Jenkins *et al.* 1985), which varies in timing and duration between regions. Near Townsville, on the east coast of Australia, the spawning season occurs from October to December and the diel timing of spawning occurs during the PM period (McPherson 1993). Few running ripe fish sampled were caught in the later afternoon indicating that actively spawning fish are not prone to capture (McPherson 1993, Munro 1942). These results are supported by those of the current study which indicate *S. commerson,* particularly in the north Kimberley, spawn in the afternoon to early evening throughout September and October (Chapter 4).

In the literature there are general references to the actual location of spawning, such as in the vicinity of coral reefs (Munro 1942) or at reefs on the inner edge of the Barrier Reef (McPherson 1993). Jenkins *et al.* (1985) found that the larvae of other mackerel species (*S. queenslandicus* and *S. semifasciatus*) occur predominantly inshore of *S.commerson* larvae, possibly because of different spawning areas for these species on the Great Barrier Reef. The current project recorded spawning activity of *S. commerson* at a number of separate reefs in the north Kimberley and it was observed that at these the majority of *S. commerson* congregate and are caught on the tidal pressure point of a reef. This suggests that *S. commerson* could be spawning in the tidal pressure wave and upwelling created by the reefs as this may assist in egg dispersal, which has been documented for other species (Boehlert 1996). However, the paucity of running ripe females in the commercial catches may also mean that spawning occurs away from the reef (or that females stop feeding when they are spawning).

The literature review found little information pertaining to the methods used in the collection of planktonic *Scomberomorus* eggs, particularly those of *S. commerson*. Eggs of this species were successfully collected in late October off Townsville (Munro 1942), and from May to July off the coast of India (Chacko 1949). However, apart from description by Chacko (1949) that 10 minute horizontal hauls with a tow-net were conducted both in the day and night, details on how, when and where sampling were made are lacking. Details on methods used to collect the eggs of other *Scomberomorus* species are also limited. Shoji *et al.*(1999b) collected both eggs and yolk staged larvae of *S. niphonius* by conducting 10 minute surface and mid water tows of a 1.3 m diameter net with 1 mm mesh. Kishida (1988) found that eggs and early larvae of this species were concentrated at the surface where there was distinct stratification of the water, but dispersed where there was no obvious stratification.

There have been several studies that incorporated collection of early *S. commerson* larvae. Thorrold (1993) collected early larvae using light traps and found higher abundances of *S. commerson* or *S. queenslandicus* (unable to distinguish) with distance from shore in the Great Barrier Reef Lagoon. Jenkins *et al*. (1985) collected *S. commerson* larvae during November-January in the outer region of the Great Barrier Reef Lagoon with double oblique tucker beam trawls of 30 minutes duration. This method sampled huge volumes of water but caught very few *S. commerson* larvae, a total of 62 larvae from 10 positive tows. Similarly, Beckley & Leis (2000) sampled 36 stations with 10 minute stepped-oblique tows of 500 micron Bongo nets on 3 separate cruises and collected a single *S. commerson* larva in water 100 metres deep off South Africa.

The majority of previous studies on the planktonic stages of other *Scomberomorus* species have also focussed on collecting the more easily identifiable larvae (Collins & Stender 1987, Grimes *et al*. 1990, Shoji *et al*. 1999a, De Vries *et al*. 1990, Peters & Schmidt 1997). Some of these studies have utilised large nets with 1-3 mm mesh that would miss eggs (Diameter 0.9 - 1.2 mm). The few studies that have used different mesh sizes noted that the finer mesh retained higher numbers of early larvae but no mention is made of eggs (Grimes *et al*. 1990), which have presumably been disregarded. In general, these studies have regularly sampled large volumes of water in both surface and oblique tows at stations along transects from the coast to the shelf.

Studies on the larvae of a northern American scombrid of similar size to *S. commerson*, *S. cavalla,* found active vertical migration and hence larvae were predominantly collected in daytime oblique tows and at night by surface tows, using 500 micron Bongo nets for 10 –15 minutes (Collins & Stender 1987). It was also found that there was an inshore-offshore separation of the mackerel species, with the larvae of the larger species, *S. cavalla* found offshore, in depths greater than 35 metres, whereas larvae from the smaller species *S. maculatus* were found inshore (McEachran *et al.* 1980, Collins & Stender 1987). This was thought to be due to separate spawning areas. Additionally, *S. cavalla* larvae were found in higher densities near a sea mount, where upwellings occurred, which may indicate the location of spawning activity (Collins & Stender 1987).

The developmental stages of *S. commerson* eggs and larvae have been described by Munro (1942) and Chacko (1949). Their eggs range from 1.0 to 1.2 mm in diameter with a large oil droplet (0.3 mm in diameter) and float with this uppermost. Histological analysis of *S. commerson* ovarian samples, during the present study, confirmed the presence of an oil droplet and hence positive buoyancy of spawned eggs. Munro (1942) was able to artificially fertilise *S. commerson* eggs to give detailed descriptions and illustrations of egg and larval stages. Additionally, Jenkins *et al.* (1985) gives detailed descriptions, illustrations and morphometric data for the larvae of *S. commerson*, *S. semifasciatus* and *S. queenslandicus*.

Field component

During the 9 day trip, 33 adult *S. commerson* were collected from 8 locations by research staff, as well as the frames of 50 from 4 locations that had been captured by commercial fishers. Spawning and recently spawned females were macroscopically identified at 3 of the locations (Albert Reef, Ingram Reef and White Island) (Figure 7.6). No spawning activity was detected in the ovaries of females collected enroute to the Cape Voltaire reefs and hence little time was spent at these other locations. Plankton sampling was comprehensively carried out at Ingram Reef on 2 days during the PM period. Additionally, the tender collected 9 plankton samples at 2 extra locations (Cassini and White Island) when adults close to spawning were captured by research staff.

- *Adult samples*

Only one of the 63 females sampled during the trip had a pre-spawning ovary (F5a) suitable for estimation of batch fecundity. This was partly because almost all (36 out of 38) of the females obtained from the spawning reefs (Ingram and Albert) were captured in the afternoon to early evening when the fish were spawning or had already spawned (Chapter 4). The fecundity of this female was assessed and is given in Chapter 4. The range in diameters of the pre-spawning hydrated oocytes and their oil globules were similar to those reported previously by Munro (1942) (Table 7.4).

Table 7.4 Range in diameters of hydrated oocytes and their oil globules, in eye piece units and millimetres at each magnification of the dissecting microscope, obtained from a pre-spawning ovary.

		Oocyte diameter	**Oil globule diameter**
X10 Magnification	Eye Piece Units	11	3
	Millimetres	1.1	0.3
X63 Magnification	Eye Piece Units	67-72	17-18
	Millimetres	1.06-1.14	0.27-0.29

Despite some bias towards sampling females with larger ovaries from the commercial catches, there were clear differences in spawning fraction between reefs with 58.8 % of the females sampled from Ingram (N=17) showing evidence of recent spawning activity (post ovulatory follicles) compared to 15.8 % from Albert Reef (N=19). Comparison of the head length based gonadosomatic index (HLI) data for females during September and October in the north Kimberley shows that the monthly average was lower in 2001 (HLI= 0.9) compared to 1999 (HLI= 1.1) and 2000 (HLI= 1.5) (Figure 4.21).

The histological results indicated that there was no spawning activity by *S. commerson* at the locations sampled in the Cape Leveque region. In contrast, there was widespread evidence of recent spawning activity in the Cape Voltaire region, with post ovulatory follicles (POFs) detected in ovaries of females at 6 of the 7 locations. Histological results also showed a relatively high percentage of atretic stage 6 ovaries in the Cape Voltaire region in 2001 (20%; Figure 7.6) compared with 6.5% and 12% in September/October 1999 and 2000, respectively.

- *Plankton samples*

At least 15 different types of fish eggs ranging in size from 0.5 mm to 2.6 mm in diameter were collected in the plankton samples. Of those with a diameter greater than 0.8 mm, 62% (N=116) were in the size range previously reported for *S. commerson* of 0.9 to 1.2 mm, and 22.4% (N=26) of these had an oil globule the same diameter as the oocytes from the fecundity ovary. These eggs, which were most similar to those of *S. commerson,* were all collected at the sampling station on Ingram Reef where high numbers of spawning and recently spawned adults were also collected. However, no fish eggs that could be those of *S. commerson* were found in the extra samples collected at different locations around Ingram Reef or in the samples collected at Cassini and White Island. Additionally, the Cassini and White Island plankton samples contained much lower densities of fish eggs greater than 0.8 mm diameter than similarly collected samples at Ingram Reef.

A total of 616 fish larvae were collected in the plankton samples. Preliminary examination found there to be at least 25 different types of larvae. However, no larvae similar in appearance to *S. commerson* larvae described by Munro (1942) were identified amongst these. The samples collected at Cassini and White Island contained similar densities and diversities of fish larvae as the samples from Ingram Reef.

- *Temporal and spatial occurrence of eggs and larvae at Ingram Reef*

The putative *S. commerson* eggs (those that were 0.9 to 1.2 mm in diameter with a 0.3 mm diameter oil globule) were collected at several times during the afternoon on the two sampling days at Ingram Reef, although the timing differed on each day (Figure 7.7). On the 6th of

October the densities of putative *S. commerson* eggs and other fish eggs (with a diameter greater than 0.8 mm) gradually increased through the afternoon while the following day the highest densities were collected early in the afternoon (Figure 7.7). These results could be influenced by the tidal currents as there was a noticeable change in the tide at around 16:30 on the first day and 17:30 on the second, which may have contributed to the lower densities of all fish eggs in the samples collected at and around these times.

Investigation into the location of spawning through the collection of additional oblique and surface samples by the tender at various locations on and around Ingram Reef did not locate any *S. commerson* like eggs, suggesting that spawning was restricted to the area adjacent to the main sampling station. The variation in the average density and diversity of fish larvae between sampling occasions showed the same pattern of change through the afternoon on both sampling days (Figure 7.8). The lowest densities and diversities were found at 16:30 and 17:30 on both days and increased markedly in the samples collected at 18:30 (around sunset) and later. The highest densities of fish larvae (all very early larvae of a similar type) were collected by surface tows of the CALVET net over the reef at 18:30.

- *Comparison of sampling methods*

All sampling techniques were successful at collecting a few planktonic *S. commerson* like eggs. On each occasion when these eggs were collected it was by more than one sampling method and by both net types, when both nets were used. However, because of low sample sizes (1 to 6 eggs) it is difficult to determine which net or tow type is best for sampling *S. commerson* like eggs. The Bongo net sampled much higher volumes of water and obtained lower densities of both mackerel like eggs and other fish eggs (Figure 7.9), although large variability in the data (particularly for the CalVET net) resulted in non-significant differences between the density of eggs collected (F=0.6606, P=0.625, df=4). This indicates that *S. commerson* like eggs were too widely dispersed in the water column at the time of sampling for the methods and net types to be effectively compared.

The number and types of fish eggs increased noticeably with the volume of water sampled (Figure 7.10). The Bongo nets sampled much larger volumes of water resulting in higher numbers and diversities of fish eggs. This also illustrates that the two net types collected similar numbers and diversities of fish eggs when the sample volume was similar. At the low densities of *S. commerson* eggs encountered in this study there is a clear risk of missing the eggs by sampling too small a volume of water with the CALVET net. Similar results were obtained for fish larvae (Figure 7.11).

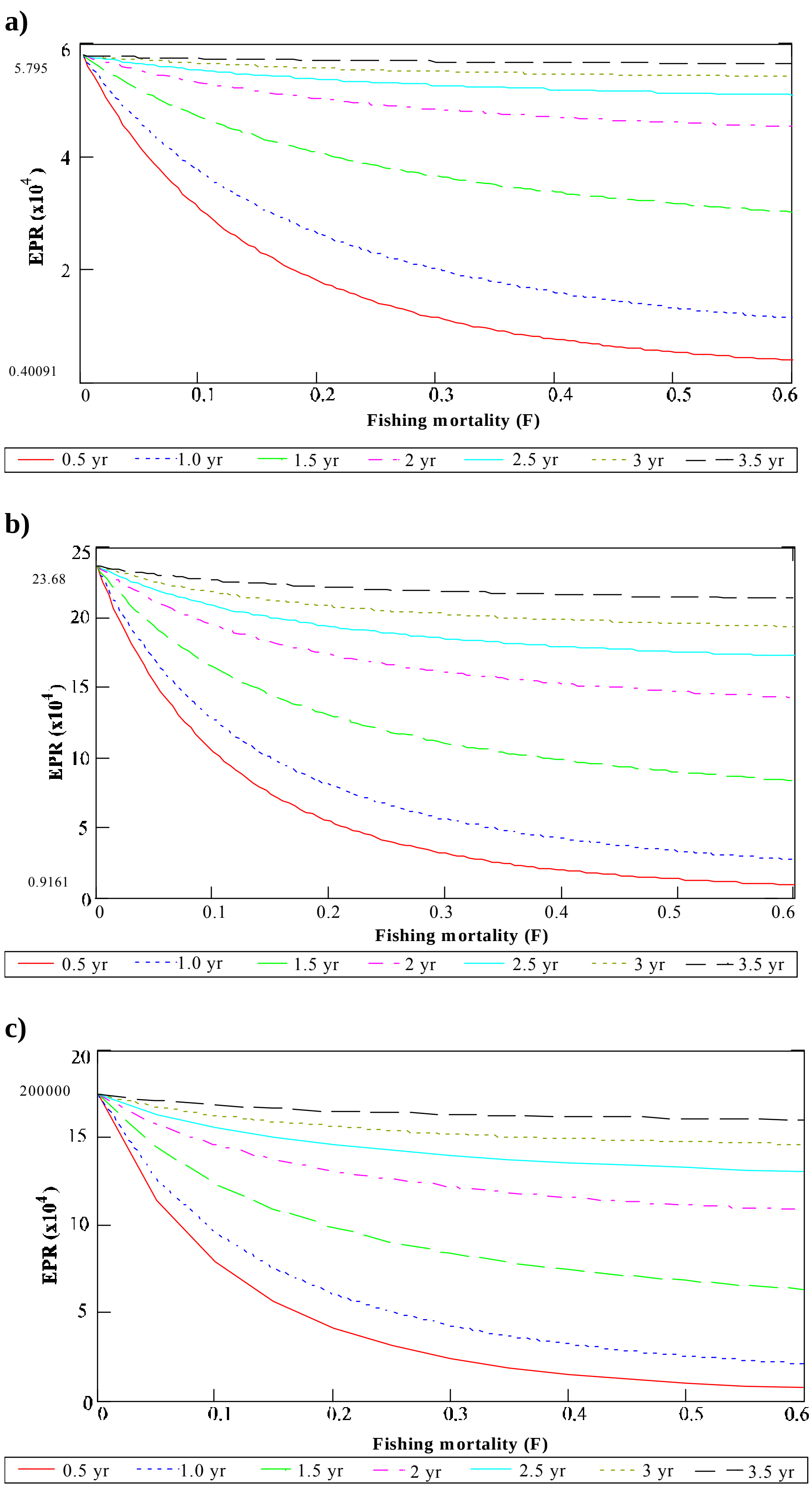


Figure 7.4 Relationship between the number of eggs per recruit (EPR) and fishing mortality for various ages at first capture of female *S. commerson* from a) the Kimberley region, b) the Pilbara region, and c) the west coast region.

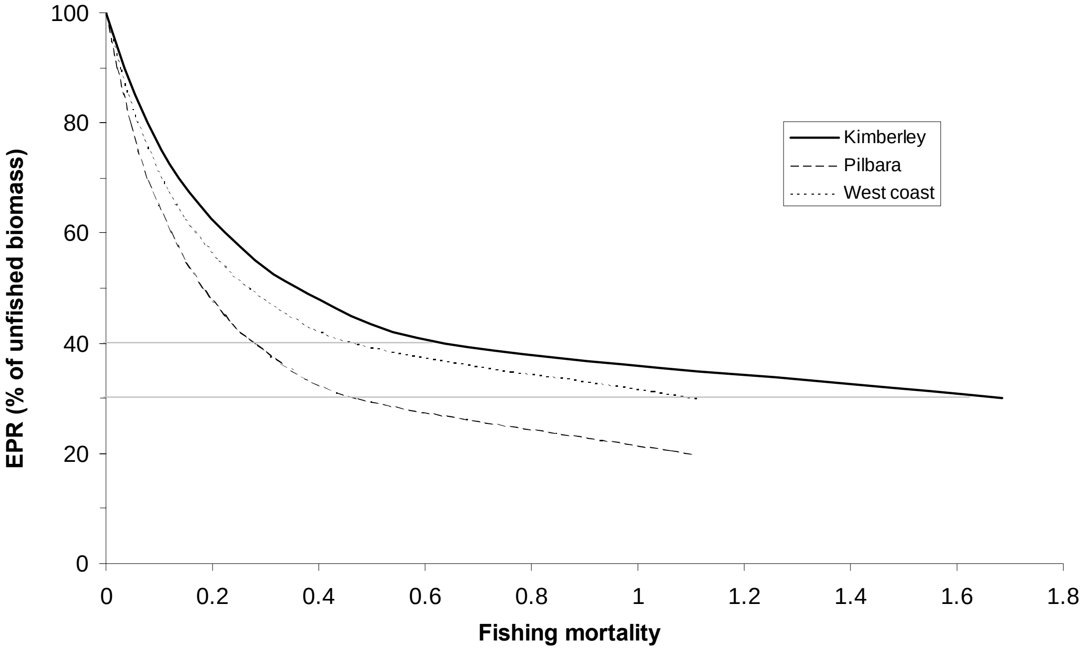


Figure 7.5 Relationship between EPR (% of unfished biomass) and fishing mortality for *S. commerson* in Western Australia.

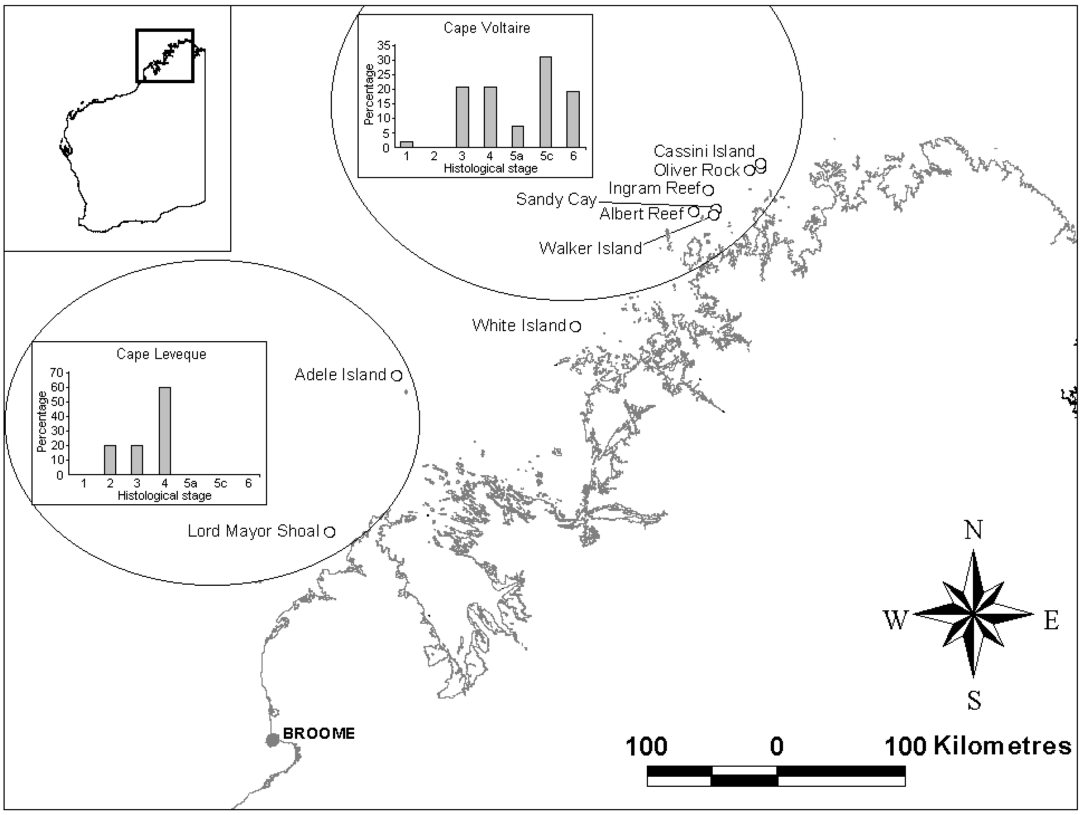


Figure 7.6 Adult *S. commerson* collection locations and reproductive status of females in the two general regions sampled during the October 2001 assessment of the daily egg production method (DEPM).

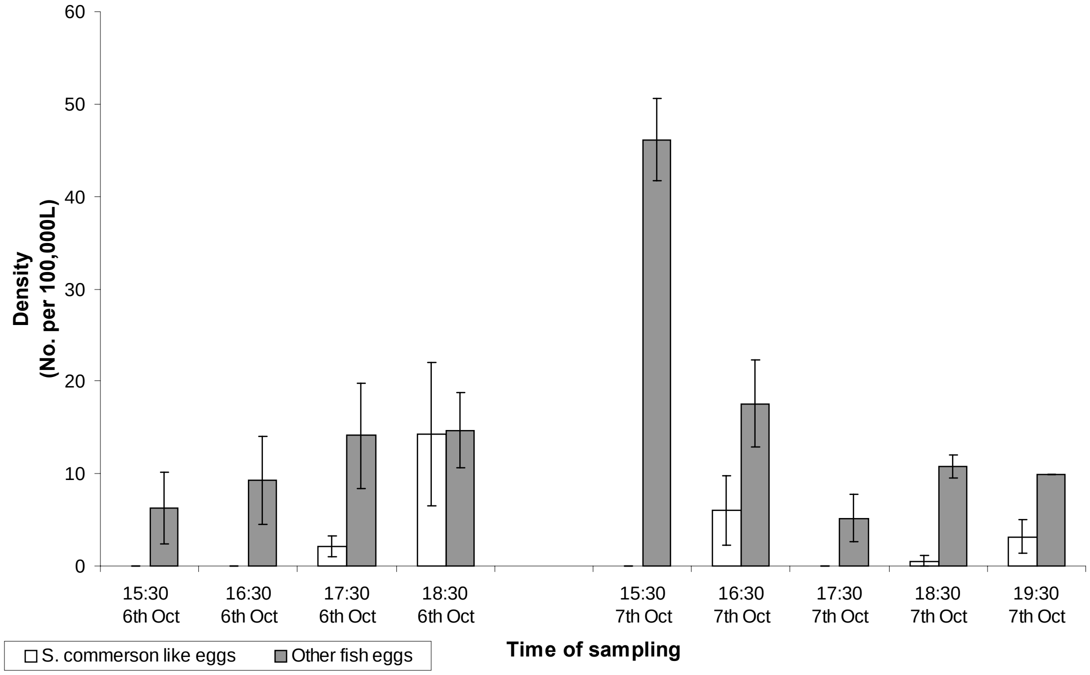


Figure 7.7 Average density (No. per 100,000 litres of water) of *S. commerson* like eggs and other fish eggs on each sampling occasion (± SE).

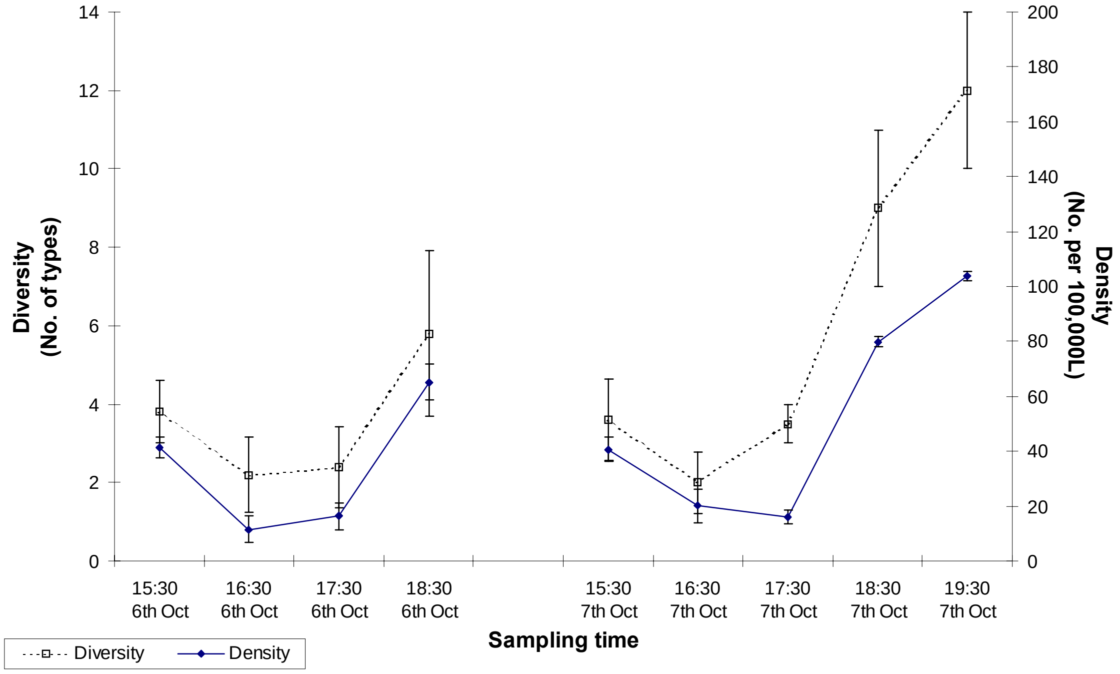


Figure 7.8 Average density (No. per 100,000 litres of water) and diversity of fish larvae on each sampling occasion at Ingram Reef (± SE).

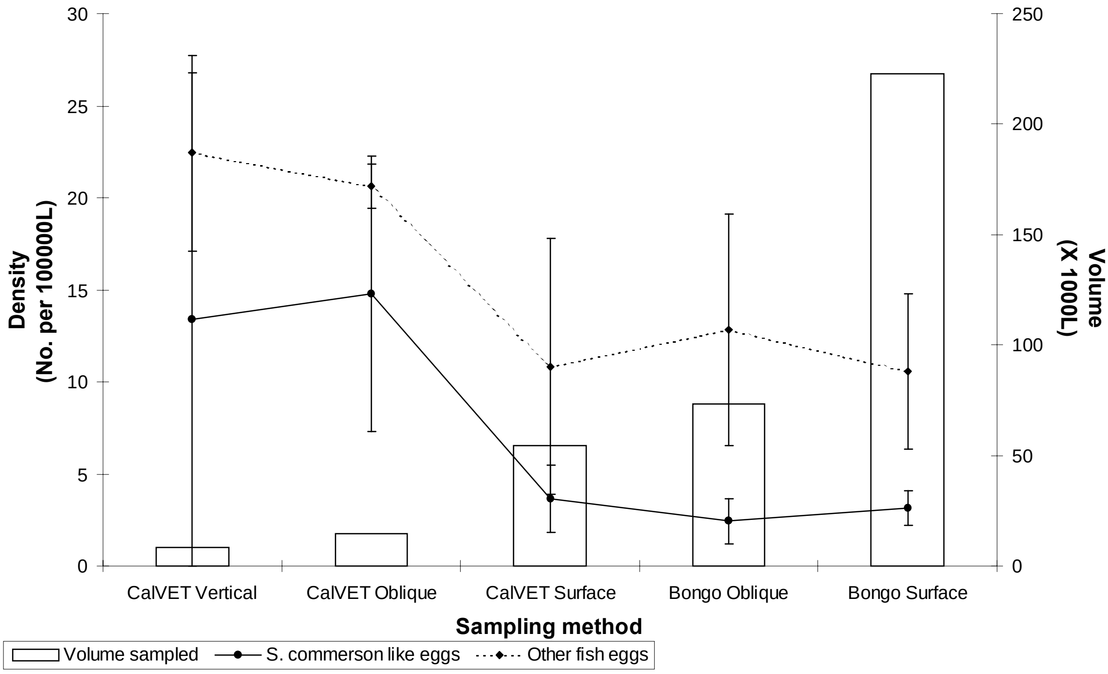


Figure 7.9 Average density of *S. commerson* like eggs and fish eggs (No. per 100,000 litres of water filtered) by each sampling method (± SE).

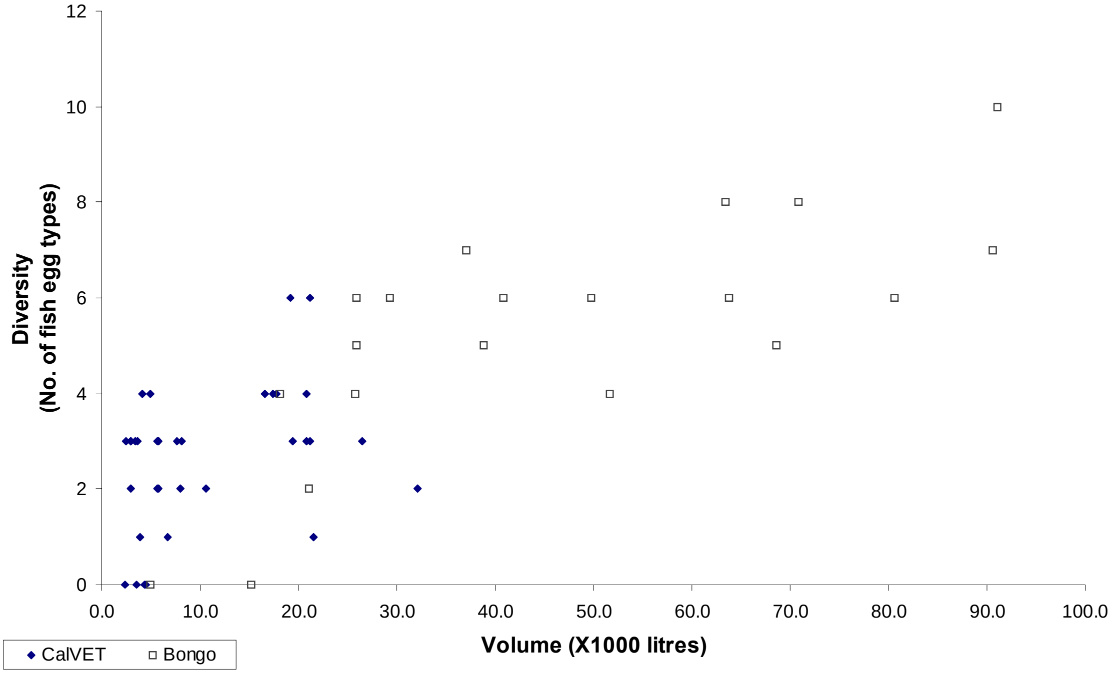


Figure 7.10 Diversity of fish eggs with volume of water sampled (X100,000 litres).

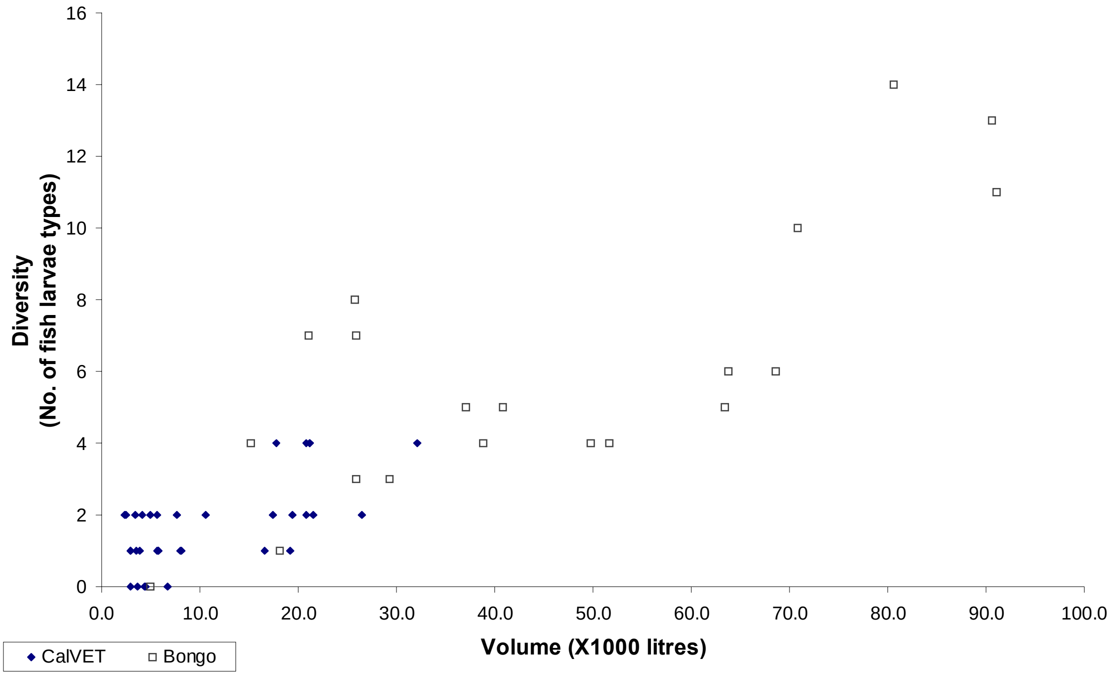


Figure 7.11 Number of fish larvae types by volume of water sampled (X100,000 litres).

7.2 Discussion

7.2.1 Biomass dynamics

All models require sufficient contrast in the range of observed independent variables in order to distinguish the modelled process from 'noise'. However, data sets available from developed fisheries usually lack contrast required for good estimates of parameters (Hall 1997). This was the case in the present study where biomass dynamic models were generally unsuccessful in estimating the biomass of *S. commerson* because of the lack of information provided by the catch and effort data.

Only in the west coast region was the modelling successful, and only using the model in which Bayesian methods were used to estimate error. These data suggests that stocks in the west coast were under most commercial fishing pressure during the mid-1980s when commercial fishers captured 13-18% of the standing biomass. With the addition of recreational catches (approximately 40% of the total catch; Mackie 2001), the total catch during the 1980s may have been between 18 and 25% of the standing biomass. In recent years the total fishing pressure (recreational estimates included) has been around 14% of the standing biomass. Even with several percent added to allow for loss of fish to sharks and other unreported fishing related mortality, these data suggest that stocks in the west coast are generally not under heavy fishing pressure relative to the standing biomass. However, significant declines in catches through the late 1980s to a low in 1992 (Chapter 3) may indicate that the relatively high percentages of standing biomass taken during the mid 1980s were not sustainable. Although it was not possible to model the data for the other regions, the estimated carrying capacity of 1115 t (≈ 110 000 fish at 10 kg average weight) for the west coast is likely to be low compared to that of the Pilbara and Kimberley regions which sustain higher catches of *S. commerson* (Chapter 3). While the biomass dynamics model was unable to provide an estimate of mackerel biomass for the Pilbara and Kimberley regions, the lack of contrast in the catch and effort data does, however, point towards a relatively stable fishery for both regions at current effort levels.

Aside from problems with the catch and effort database previously highlighted in the Results (Section 7.1.1), there is also the question of whether this data provides a reasonable index of trends in abundance. This is often not the case in schooling species such as *S. commerson* which may continue to be caught in numbers that belie the true size of the stock (Fréon and Misund 1999). Further, without standardisation of fishing effort to allow for improvements in technology, fishing equipment and skill (as done for *S. commerson*), the increased effectiveness of effort units results in an overestimate in relative abundance (Ehrhardt and Legault 1997). Implementation of a log book tailored to the mackerel fishery will help resolve problems associated with the catch and effort data over time, and is considered a priority for future management of the fishery. Development of more sophisticated models that incorporate information on age structure as well as catch and effort data may also extend the capabilities of the models and produce more reliable estimates of spawning biomass. In the least, more robust catch and effort data will provide an indication of the stability of the mackerel fishery in each region, which in turn will provide a basis for ongoing monitoring of the status of the regional stocks.

7.2.2 Yield and egg per recruit

As with growth and mortality, *S. commerson* in the Pilbara and west coast share similar YPR curves. They also have similar ages at first capture and levels of *F* to optimise yield. In contrast, YPR in the Kimberley region is relatively low due to the decreased maximum age and higher *M*. However, it is difficult to recommend an optimum age at first capture and *F* because of the uncertainty over *M* (see Chapter 5). Results of YPR analyses should also be used with caution because the optimum age/size at first capture and *F* can only be estimated with limited statistical precision, and assumptions of constant *M* and population structure, and equilibrium of the fishery with *F* are also likely to be unrealistic (Haddon 2001). Furthermore, given the substantially different growth rates between males and females (Chapter 5), the YPR analyses should be applied to each sex separately (Punt *et al*. 1993). Nevertheless, with an *M* similar to that used in QLD and NT of around 0.3 – 0.4, the optimum age at first capture is approximately equivalent to the current minimum legal length (MLL) of 900 mm TL. This length is based on the size at which 50% of the population is sexually mature (Chapter 4), and agrees with conclusions of many yield per recruit analyses that size at maturity and yield are correlated since somatic growth slows as energy requirements are directed towards reproductive activity (Newman *et al*. 2000). Further, the recent increase in MLL from 750 to 900 mm TL has been favourable in terms of predicted yield.

If *M* is around 0.2 (as suggested by the estimate of *Z*; Chapter 5), growth overfishing may occur at the current MLL as the fish will be caught below the size that optimises yield. However, a further increase in the MLL may have considerable impact on fishing operations since fish between 900 and 1000 mm TL may comprise a third of the commercial catch. Mortality of mackerel at this size is also likely to be high because of the difficulty in removing hooks without damage to either the fish or fisher. In contrast, relatively few *S. commerson* less than the current MLL are caught and fishers avoid locations where these fish are common.

Setting of *F* to attain optimum YPR is not possible at present due to difficulties in estimating this parameter. For instance, current estimates of *F* appear to be unreasonably low (maximum of 0.13 but generally < 0.06 using the Hoenig (1983) equation; Chapter 5, Table 5.15), and are significantly less than the estimates of optimum *F* provided here from YPR analyses. As the current MLL and recommended size at first capture from these analyses are similar, it is likely that *F* estimated from *Z* – *M* (Chapter 5) are erroneous. Difficulties in estimating this parameter for *S. commerson* in NT and QLD waters has thus recently led to a recent study to examine the feasibility of estimating *F* from a novel tag-release program that minimises the high post-release mortality of this species (R. Buckworth, Fisheries Division, NT Dept. of Business, Industry & Resource Development, *pers. comm.*).

Yield Per Recruit analyses also need to be treated with caution because the sustainability of outputs is not specifically considered. This is an advantage of EPR analyses. Despite uncertainty over *M,* a relative measure of the sustainability of YPR estimates is possible by comparing YPR and EPR values derived from analyses in which the same *M* is used (derived from the Hoenig equation). These comparisons indicate that the reproductive output in the Kimberley and west coast regions are robust to *F* and that the optimum levels of YPR are sustainable. For instance, target *F* for YPR ($F_{0.2}$) in the Kimberley and west coast (≈ 0.3 and 0.2, respectively) are low relative to the *F* predicted to reduce the EPR to 40% of the unexploited EPR (0.64 and 0.47, respectively). In fact at $F_{0.2}$ the EPR is predicted to be >50% of the unfished EPR, whereas at $F_{0.1}$ the EPR may still be >40% of the unfished EPR in both regions. In contrast, whilst $F_{0.2}$ in the Pilbara region (≈ 0.2) also appears to be sustainable, since the EPR at 40% of the unexploited EPR is 0.28, the margin for error is much reduced, and at $F_{0.1}$ (≈ 0.35) the EPR is predicted to fall below the 40% of unexploited EPR level. This is not desirable, since an *F* which reduces the EPR to no less that 40% of the unexploited biomass is recommended for species which have variable recruitment (as appears to be the case with *S. commerson*) or where the stock – recruitment relationship is unknown (Clark 1993, Mace 1994).

Thus, given the uncertainty over estimated mortality rates for *S. commerson*, care is needed in management of these stocks. For example, if values for *M* are lower than the Hoenig (1983) derived estimates used here in the EPR models, the EPR of unexploited stocks will be increased but the robustness of EPR to fishing pressure will be reduced and levels will decline rapidly as *F* increases. The reverse will be true with higher *M*. Furthermore, as fish in the west coast region may contribute little to reproductive output (Chapter 4), EPR analyses for the Pilbara region may be more relevant for the west coast stocks as well. Thus, as EPR of *S. commerson* in the Pilbara region appears to be less robust to fishing pressure, and because this area may be the main source of recruits to the west coast region, increased caution is required in the management of Pilbara fish to ensure recruitment overfishing does not occur.

7.2.3 Daily Egg Production Method

The field component of the study was not able to show that the DEPM could be used to assess the spawning biomass of *S. commerson* in waters of Western Australia. This was due in part to the timing of the sampling trip, which occurred when relatively few fish were present on the spawning reefs (T. Westerberg, *pers comm.*) and spawning activity was lower than the same time in previous years. This variability in the timing of spawning is a major impediment to future use of the DEPM as the timing of the survey should coincide with the peak in spawning. This would be very difficult or impossible to monitor closely with S. *commerson* due to the remoteness and range over which the species spawns (Chapter 4).

The adult sampling methods employed in the field study were successful in locating spawning *S. commerson* adults but only one of these samples could be utilised to gain daily population fecundity data, required for a DEPM survey. This was because most adult samples were caught during the afternoon when the majority of reproductively active females caught have already spawned or are spawning and are therefore not suitable for fecundity estimates (see Mackie and Lewis 2001). Thus, any future DEPM survey on this species would need to concentrate on collecting adult samples, for fecundities, in the morning prior to spawning.

Although the reproductive biology of *S. commerson* has recently been described (Chapter 4), there are still many aspects of spawning that remain unclear. In particular an understanding of where in their range spawning occurs is crucial for a DEPM survey but would take much time and money to resolve. However, if *S. commerson* only spawn at distinct locations the areas in which day 1 eggs would occur and hence the area for a future DEPM would be greatly reduced. It is also possible that not all fish spawn in synchrony. This is suggested by the differing spawning fractions at Albert and Ingram reefs, and by the large number of spawning fish that appeared on the north Kimberley reefs a month after the DEPM survey when fewer, often spent, fish were caught (T. Westerberg, commercial fisher, *pers. comm.*). As such spawning fraction may differ and not be indicative of the overall population which further complicates biomass estimates.

Further inhibiting the successful application of the DEPM to *S. commerson* is the number of adult samples required for this method. It has been suggested that a minimum of 35 independent samples of at least 12 to 15 mature females are required (Alheit 1993). Thus, a future DEPM would require considerable resources to not only collect adult samples from the commercial mackerel boats fishing the spawning reefs but also independently collect samples from other areas in the region being assessed, as the spawning fraction appears to vary and a range of samples representative of the population are required.

The plankton sampling methods collected very few planktonic fish eggs that fitted previous descriptions of *S. commerson* eggs (Munro 1942, Chacko 1949) and were similar in size to the hydrated oocytes in pre-spawning *S. commerson* ovaries. These eggs were only collected at Ingram Reef where a high proportion of recently spawned adults were also collected. Thus it seems quite likely that these planktonic eggs were those of *S. commerson.* However, due to the wide variety of other fish species that were also spawning in the region at the same time it is difficult to confidently identify these as *S. commerson* eggs without further genetic or grow out studies. The failure to collect any *S. commerson* larvae in the plankton samples suggests that 1) the eggs and hence larvae are rapidly dispersed away from the spawning grounds, as would be expected in the northern Kimberley where tides ranges by up to 8 metres or 2) that spawning may have only recently begun resulting in insufficient development time for the larvae or 3) that there is an inshore migration of *S. commerson* larvae as has been inferred by McPherson (1992).

Because of the low numbers of *S. commerson* like eggs and the lack of larvae collected during the field survey it is difficult to recommend any particular net or method. The bongo net samples much larger volumes of water and hence will probably be better if eggs are rare or are patchily distributed, as was the case and will probably be the case in areas where tidal currents are large. However, the CalVET net is easier to use from small boats and the resulting samples require a much shorter processing time and would be preferred if the eggs are found in high densities at the time of peak spawning. Further comprehensive sampling at the time of peak spawning activity is required to clarify the best plankton sampling strategy for *S. commerson* eggs.

Based on the literature review, field study and characteristics of the Western Australian mackerel fishery, we suggest that the logistics involved in comprehensively sampling the complete range of *S. commerson* and collecting sufficient adult samples from throughout this range, along with the variability in the spawning are impeding factors to successfully carrying out a DEPM survey on this species. In addition, the diversity of other species also spawning at the same time creates a problem in the identification of *S. commerson* eggs and slows the processing of plankton samples. The inconclusive results from the field component of this study are a direct result of the variability in spawning of *S. commerson* in the waters off Western Australia.

8.0 Project Summary

M. Mackie

8.1 Benefits

This project provides detailed information on the biology of *S. commerson* and the associated WA troll-based mackerel fishery which has, and will, be used to ensure the sustainability of this fishery. For instance, this information has been crucial in the development of the Mackerel Fishery (Interim) Management Plan which has recently been approved by the Minister for Agriculture, Forestry and Fisheries (Appendices 6 and 7). To facilitate development of the Interim Management Plan (IMP) an Independent Advisory Panel (IAP) was formed to consider various management options. Data obtained during this study was provided to the IAP as required and used as a basis by the Research Division for the recommending possible management approaches. For example, when it was thought by WA DoF staff that the IAP might accept a management plan based on total allowable effort (TAE), a substantial effort was made to provide concise data upon which to base a decision (Appendix 8). The project is complemented by FRDC project 98/159 on the stock structure of *S. commerson* in WA, NT and QLD waters. The main beneficiaries of these projects are the commercial and recreational fishers who target *S. commerson* along the WA coast and have an interest in the long-term health of the fishery. Fishers, researchers and managers of NT and QLD mackerel fisheries will also benefit from the comprehensive information provided here. Management of overseas fisheries in which this species is targeted will also benefit from this project as in many such fisheries there is little, if any, relevant information. Apart from the latter, these benefits and beneficiaries have not changed from those identified in the original proposal. Responses of two beneficiaries to the project are provided in Appendix 9.

8.2 Further Development

Future management and development of the WA mackerel fishery will be enhanced by:

- Implementation of a fishery specific logbook to improve the monitoring of *S. commerson* catch and effort information.
- Use of more sophisticated models that incorporate age structure information to enable more reliable examination of population dynamics and simulation of management options.

- Increased detail of *S. commerson* biology and ecology. Specific information that will provide more certainty in modelling and management decisions include: fecundity of larger females, habitat of *S. commerson* when not abundant on the coast, further understanding of the extent of spawning, site fidelity by individuals, and more rigorous validation of temporal periodicity of opaque zone formation in adult and juvenile otoliths.
- Further analysis of mortality. For example, with *M* this may be done by developing a more appropriate equation for tropical/subtropical species from a subset of the data used by Hoenig (1983) (N. Hall, Centre for Fish & Fisheries Research, Murdoch University, *pers. comm.*).
- Examination of the relationship between abundance of recruits and subsequent catches (i.e. stock-recruitment index). There is potential to do this with assistance from recreational fishers in the Dampier region.
- Provision of knowledge relevant to ecologically sustainable development requirements through collection of data on by-product and by-catch species in the troll fishery (noting that this fishery exports product to SE Asia). Data for grey mackerel (*S. semifasciatus*) is of particular importance since this species is valued on the export market and has become more vulnerable to fishing activities in recent years as fishing methods for this species are refined and become more widely known. Further information on the distribution and abundance of this species may also enhance the mackerel fishery.

8.3 Planned Outcomes

- Initiation of steps to formally manage the commercial mackerel fishery, and provision of data and advice required to complete the process. Although the implementation of formal management arrangements of the Spanish mackerel fishery is still underway, the current project has provided the baseline research data and industry liaison that is required to further the process.
- Provision of data and knowledge of the fishery that is required to fulfill Ecological Sustainable Development (ESD) reporting requirements for the Spanish mackerel fishery. Completion of an ESD report for the Spanish mackerel fishery was considered essential given the export market for mackerel.

8.4 Conclusion

As detailed below, this project has successfully achieved all of the Objectives outlined in Section 1.3.

Scomberomorus commerson is a fast growing species that reaches sexual maturity at a young age (< 1.5 years) and can live more than 20 years. Females grow faster and reach larger lengths, although males dominated the older age classes. The fishery is based on 1 – 4 year old fish, which comprise about 70% of the catch. Two year old fish are the dominant age class (between 24 – 48% of the catch, depending on region). The maximum age of *S. commerson* in WA (22 yrs) is considerably greater than has previously been reported elsewhere. The current minimum legal length (MLL) of 900 mm TL is appropriate since it approximates the size at which 50% of females reach sexual maturity. Males mature at a smaller size and at the MLL more than 90% are mature.

S. commerson is seasonally abundant along a large area of the tropical/sub-tropical coastline but is also caught in low numbers throughout the year in the Pilbara region. The seasonal appearance of *S. commerson* in shallower coastal waters is probably associated with feeding and gonad development prior to spawning at particular locations. The majority of spawning appears to occur in the Kimberley region, whereas little or no spawning was found south of Exmouth. Females are serial spawners and can spawn a batch of eggs every 1-3 days during the breeding season. Histological evidence shows they are capable of spawning on two but not three consecutive days. Final maturation of about 1300 eggs per gram of gonad occurs in the morning followed by spawning in the afternoon. The ovaries of large females can weigh more than 1.9 kg, with the largest ovary suitable for estimation of fecundity weighing 829 g. This ovary was about to spawn more than 1.2 million eggs. No distinct relationship between spawning and environmental cues were found, although water temperature is probably important for seasonal development of gonads.

Recruitment of *S. commerson* may vary considerably from year to year. Evidence for this comes from observations made by fishers as well as from the present study, which coincided with a large cohort of recruits that dominated catches in subsequent years in the Pilbara and parts of the west coast regions.

Most *S. commerson* appear to have fairly restricted long-shore movement patterns (FRDC project 98/159). This is reflected by regional differences in growth rates, growth parameters, otolith readability, maximum ages, relationships between body weight and length parameters and the timing of reproductive activity. The habitat of most of the population outside of the main fishing season is still unclear, although anecdotal evidence suggests that *S. commerson* move off the coast into deeper water at this time.

The commercial mackerel fishery extends from Geraldton to the NT border and is currently open to all WA licensed vessels, although in reality this is limited to approximately 91 vessels that operate north of Shark Bay. Only about twelve fishers target *S. commerson* full time during the six or so months when this species is abundant on the coast. Many other fishers catch *S. commerson* opportunistically whilst targeting other species. Following extensive liaison between the Department of Fisheries, the IAP and industry members, the fishery is expected to become formally managed in 2004 under the Mackerel Fishery (Interim) Management Plan (Chapter 11, Appendices 6.0 and 7.0). This Management Plan is likely to be based on a total allowable commercial catch estimated separately for the three regions used in the current report (Kimberley, Pilbara and Gascoyne/west coast). It is proposed that only those boats with sufficient historic catches prior to a benchmark date (3rd November 1997) will be permitted access. Each zone of the fishery will be unitised, the value of which will be proportional to the annual quota apportioned to each zone. The number of units apportioned to each boat will be determined from their historic catch as a proportion of total catch in each zone. However, a minimum of 5% of unit holdings will be required before a fisher can actually operate in the fishery.

The daily egg production method was shown to be logistically and economically unfeasible for estimating spawning biomass of *S. commerson*. Use of biomass dynamics models to estimate biomass of *S. commerson* were also generally unsuccessful because of the lack of contrast in the catch and effort data. Only in the west coast region could such estimates be determined. The model suggests that *S. commerson* in this region are not under heavy fishing pressure relative to the standing stock biomass.

Yield per recruit (YPR) analyses indicate a relatively low YPR in the Kimberley region. Nonetheless, in all regions *S. commerson* appears resilient to fishing mortality at the current MLL, although the models also suggest that this size at first capture is below that which optimises YPR (if low M is assumed). A further increase in the MLL is impractical though because of the difficulty in removing hooks from larger-sized mackerel. Economic impacts to fishing operations also need to be considered, since fish between 900 and 1000 TL may comprise about a third of the commercial catch. Uncertainty over mortality estimates prohibit specific recommendations of optimum age and size at first capture from YPR analyses, however. A new FRDC funded project (#2002/011) to examine the feasibility of estimating F

from a novel tag-release program in the NT may enable more reliable YPR analyses in the future.

Egg per recruit (EPR) analyses confirm that the reproductive output of females in the Kimberley region is robust to *F* and the optimum levels of YPR may be sustainable. However, EPR by female *S. commerson* in the Pilbara region appears less robust and may fall below the desirable 40% of unexploited EPR levels at limit levels of *F*. As this region may possibly also be the main source of recruits for the west coast region caution is required to ensure that recruitment overfishing does not occur.

Other management approaches, such as that used to manage *S. maculatus* in the US Gulf of Mexico may be considered in the future. This fishery is managed through the use of a total allowable catch (TAC) split amongst the different user groups (as is likely to be the case with the WA mackerel fishery). Setting of the TAC for the *S. maculatus* fishery requires estimation of a range of allowable biological catches through the use of a calibrated virtual population analysis. This is followed by forecasting of recruitment and determination of projected catch under a non-equilibrium *F* required to generate a given percentage spawning potential ratio relative to the virgin stock (Ehrhardt and Legault 1997).

However, the level of management for *S. maculatus* requires considerable resources. In contrast, ongoing management of the WA mackerel fishery will need to be economical given the broad range and value of the fishery ($2.5 million to fishers in 2001). Thus, the initial setting of a TAC in each of the WA regions is likely to be based on historical catch data. With implementation of a fishery-specific log book and computerised monitoring of vessel activity (Vessel Monitoring System, or VMS), trends in catch rates following implementation of the mackerel management plan will form the basis of management decisions such as setting of the TAC. Catch rate data will also complement and be used in more sophisticated models incorporating age-structure, so that more reliable examination of population dynamics and management options can be made. However, it is important to note that catch rates of schooling species such as *S. commerson* can be biased and will need considerable standardisation if they are to provide a reasonable reflection of the true abundance.

Further options for management include spatial and temporal closures. Temporal closures are already being considered under the Interim Management Plan as a means of reducing management costs for the fishery (by reducing compliance and operating costs). As a means of ensuring sustainability of the fishery, spatial and temporal closures provide alternatives to quota-cuts in the event of adverse trends in catch rates or model abundance scenarios. To be of greatest benefit the closures should be focussed on the main locations and times of spawning to protect spawning fish. The social and economic impact to fishers of closures should be considered since the fishery is already seasonal and much of the catch includes reproductively active fish. Nonetheless, with monitoring via the VMS it should be possible to selectively close reefs whilst permitting others to be fished.

In order to facilitate ongoing collection of data for *S. commerson*, various length-weight-age conversion equations have been developed during the current project. Methods used in the study of *S. commerson* reproduction and growth have also been published as Research Reports to assist future sampling.

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11.0 Appendices

Appendix 1. Intellectual Property

No saleable items were developed during this project.

Appendix 2. Staff

Staff that were employed on the project using FRDC funds were:

Mr P. Lewis and Dr M. Mackie.

Staff who assisted on the project using non-FRDC funds were:

Mr G. Baudains, Dr D. Gaughan, Mrs L. Higgins, Mr J. King, Mr T. Leary, Dr R. Lenanton, Mr R. Mitchell, Dr S. Newman, Mr J. Norris, Mr C. Skepper, Ms F. Webster, R.V. Flinders crew (Mr T. Berden, Mr K. Hillier, Mr T Shepherd,) P.V. Walcott crew (Mr K. Gosden, Mr M. Killick, Mr S. Van Houwelingen, Mr M. Verney).

Appendix 3. Methods used to tag, release and chemically mark the otoliths of *S. commerson*.

To determine the temporal periodicity of annuli formation in *S. commerson* sagittal otoliths a tag and recapture project in which fish were injected with calcein to chemically mark the otoliths was attempted.

The project was conducted over 27 days in the Dampier region and 9 days in the Shark Bay region from October 1999 until August 2000. All *S. commerson* to be tagged were caught using trolled or drifted baits and lures on 15-24 kg gamefishing outfits. Before fishing began all of the tagging apparatus was set up for easy access, these included:

- 2 tag inserters with individually numbered dart tags
- syringes filled with calcein solution (25mg/L)
- a pair of long nose pliers
- measuring board and rags on the deck of the boat
- fish cradle, made of vinyl (1 X 1m) with 2 wooded handles sewn along 2 edges and holes down the middle for drainage and injecting.

Hooked fish were retrieved as quickly as possible to minimise exhaustion and avoid predation by sharks. Once alongside one person would hold the 200lb leader in a way that allowed the second person to slip the cradle under the fish. Care had to be taken and welding gloves worn to avoid cuts to hands and arms by the sharp teeth. The cradle was used to keep the pressure off the jaw, gills and visceral areas of the fish when lifting into the boat, but was not considered necessary for fish smaller than 900mm total length. These were more quickly and easily handled by lifting straight aboard, thereby shortening the time spent out of the water. Once in the boat the cradle and fish were placed on the measuring board, using the cradle to keep the fish under control. If required a wet towel was also placed over the head and eyes to calm the fish. One person held the fish, measured, tagged and injected the calcein solution into the peritoneal cavity of fish whilst the other recorded the data, de-hooked the fish and assisted where necessary. In some instances it caused less damage to the fish if the hooks were cut with pliers instead of being removed (gangs of 7/0 hooks which were easier to cut were used for this reason). Prior to tagging the physical condition of each fish was assessed; any that were bleeding from the gills or had a badly damaged jaw were deemed unsuitable for tag and release. Fish to be tagged had their fork length measured and were injected with the calcein solution (25 mg/l) into the fish at an amount of 15 mg per kilogram of whole weight. The whole weight and hence calcein dose were estimated from the fork length (in mm) using Equation 1. The amount of calcein solution injected was recorded.

Equation 1. $$\mathit{Calcein\ Dose}\ (\mathit{ml}) = 15\ (6.1552818 \times 10^{-6}\ (\text{Fork Length})^{3.0476}) \big/ 25$$

Each fish was tagged with two dart tags while in the cradle by positioning the cradle and fish so the tags could be inserted through the holes in the cradle. The tags were inserted just below the dorsal fin rays of the fish. Each tag was inserted with the barb of the tag upright until the tag passed through the intermuscular bones of the fish and then given a 90° clockwise turn to lodge the barb securely behind the intermuscular bones. Once completed the tag numbers were checked and recorded.

The fish were released using the cradle to lower the fish back into the water. *S. commerson* do not recover well from capture and release, and would often sink or swim feebly if released immediately. Therefore, to improve survivorship fish were revived by towing them for some time (Figure A3.1). Fish were towed using a blunt gaff hooked through their lower jaw or a modified mango picker (the 'Mackerel Release Device' or MRD) (Figure A3.2). Before release, each fish was positioned so a good grip was obtained on the lower jaw with the MRD. This was positioned so the plate was in the mouth and the hook secured the jaw from underneath. In a team effort the boat is put into gear and driven slowly ahead, at idle speed, while the fish was lifted in the cradle and lowered into the water. Once in the water the cradle was removed and the fish held in an upright position with its head in the water by the MRD while being towed for at least 2 minutes. During this time most fish began a swimming motion and once the fish gave a few solid head shakes it was usually ready for release. The length of time the fish was revived and how it swam off were also recorded.

Figure A3.1 Reviving a tagged *S. commerson* by towing with the Mackerel Release Device (MRD). Note: 2 yellow dart tags on right side below dorsal fin.

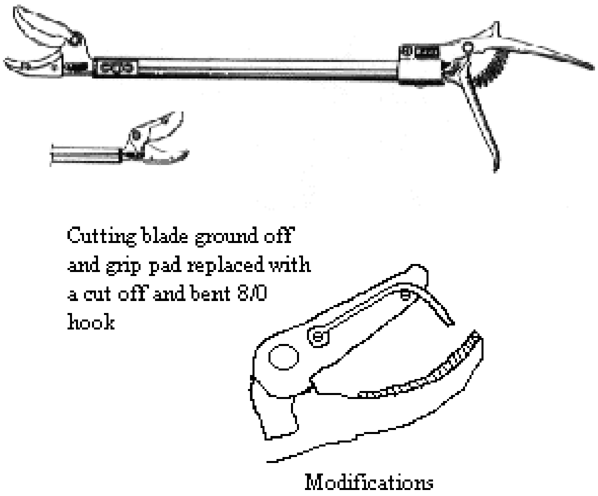

Figure A3.2 Modifications made to a mango picker to transform it into a Mackerel Release Device.

Appendix 4. Reproduction

Table A4.1 Results of Analysis of Variance testing the quadratic relationship between head and fork lengths by area and sex.

```
Response: fl.mm

Terms added sequentially (first to last)
                          Df Sum of Sq  Mean Sq  F Value     Pr(F)
                 hl.mm     1  43762349 43762349 53063.03 0.0000000
            I(hl.mm^2)     1    575752   575752   698.12 0.0000000
                  fsex     1         4        4     0.01 0.9431977
                 farea     3    123023    41008    49.72 0.0000000
            hl.mm:fsex     1      6985     6985     8.47 0.0036578
       I(hl.mm^2):fsex     1      2214     2214     2.68 0.1015239
           hl.mm:farea     3     28315     9438    11.44 0.0000002
      I(hl.mm^2):farea     3      3951     1317     1.60 0.1881870
            fsex:farea     3      3592     1197     1.45 0.2259352
      hl.mm:fsex:farea     3      1055      352     0.43 0.7339733
 I(hl.mm^2):fsex:farea     3       586      195     0.24 0.8705806
             Residuals  1723   1420999      825
```

Table A4.2. Predicted fork length (± SE) from head length measurements (mm). Pointwise standard errors were estimated using S-Plus statistical software.

Kimberley			Pilbara			Gascoyne			South		
HL	Pred FL	SE FL	HL	Pred FL	SE FL	HL	Pred FL	SE FL	HL	Pred FL	SE FL
70	286.7	6.6	70	279.1	6.6	70	261.1	9.1	70	279.1	10.7
71	293.2	6.5	71	285.6	6.5	71	267.7	9.0	71	285.7	10.6
72	299.6	6.4	72	292.1	6.4	72	274.3	9.0	72	292.3	10.6
73	306.0	6.4	73	298.6	6.3	73	280.8	8.9	73	298.9	10.5
74	312.4	6.3	74	305.0	6.2	74	287.4	8.8	74	305.5	10.4
75	318.8	6.2	75	311.5	6.1	75	293.9	8.8	75	312.0	10.4
76	325.2	6.1	76	317.9	6.1	76	300.4	8.7	76	318.6	10.3
77	331.6	6.1	77	324.3	6.0	77	306.9	8.6	77	325.1	10.2
78	337.9	6.0	78	330.7	5.9	78	313.4	8.6	78	331.7	10.2
79	344.3	5.9	79	337.1	5.8	79	319.9	8.5	79	338.2	10.1
80	350.6	5.8	80	343.4	5.7	80	326.3	8.4	80	344.7	10.0
81	356.9	5.8	81	349.8	5.7	81	332.7	8.4	81	351.1	10.0
82	363.2	5.7	82	356.1	5.6	82	339.2	8.3	82	357.6	9.9
83	369.4	5.6	83	362.4	5.5	83	345.6	8.2	83	364.1	9.8
84	375.7	5.5	84	368.7	5.4	84	352.0	8.2	84	370.5	9.8
85	381.9	5.5	85	375.0	5.4	85	358.4	8.1	85	376.9	9.7
86	388.1	5.4	86	381.3	5.3	86	364.7	8.0	86	383.3	9.6
87	394.3	5.3	87	387.6	5.2	87	371.1	8.0	87	389.7	9.6
88	400.5	5.2	88	393.8	5.1	88	377.4	7.9	88	396.1	9.5
89	406.7	5.2	89	400.0	5.1	89	383.7	7.9	89	402.5	9.4
90	412.9	5.1	90	406.2	5.0	90	390.0	7.8	90	408.8	9.4
91	419.0	5.0	91	412.4	4.9	91	396.3	7.7	91	415.2	9.3
92	425.1	5.0	92	418.6	4.9	92	402.6	7.7	92	421.5	9.2
93	431.2	4.9	93	424.8	4.8	93	408.9	7.6	93	427.8	9.2
94	437.3	4.8	94	430.9	4.7	94	415.1	7.5	94	434.1	9.1

95	443.4	4.8	95	437.0	4.6	95	421.4	7.5	95	440.4	9.1
96	449.5	4.7	96	443.1	4.6	96	427.6	7.4	96	446.7	9.0
97	455.5	4.6	97	449.2	4.5	97	433.8	7.4	97	453.0	8.9
98	461.5	4.6	98	455.3	4.4	98	440.0	7.3	98	459.2	8.9
99	467.5	4.5	99	461.4	4.4	99	446.2	7.2	99	465.4	8.8
100	473.5	4.5	100	467.5	4.3	100	452.4	7.2	100	471.7	8.7
101	479.5	4.4	101	473.5	4.2	101	458.5	7.1	101	477.9	8.7
102	485.5	4.3	102	479.5	4.2	102	464.6	7.1	102	484.1	8.6
103	491.4	4.3	103	485.5	4.1	103	470.8	7.0	103	490.2	8.6
104	497.4	4.2	104	491.5	4.1	104	476.9	6.9	104	496.4	8.5
105	503.3	4.1	105	497.5	4.0	105	483.0	6.9	105	502.6	8.4
106	509.2	4.1	106	503.5	3.9	106	489.1	6.8	106	508.7	8.4
107	515.1	4.0	107	509.4	3.9	107	495.1	6.8	107	514.8	8.3
108	520.9	4.0	108	515.3	3.8	108	501.2	6.7	108	520.9	8.3
109	526.8	3.9	109	521.2	3.8	109	507.2	6.7	109	527.0	8.2
110	532.6	3.9	110	527.1	3.7	110	513.2	6.6	110	533.1	8.1
111	538.4	3.8	111	533.0	3.6	111	519.3	6.5	111	539.2	8.1
112	544.2	3.7	112	538.9	3.6	112	525.2	6.5	112	545.2	8.0
113	550.0	3.7	113	544.8	3.5	113	531.2	6.4	113	551.3	7.9
114	555.8	3.6	114	550.6	3.5	114	537.2	6.4	114	557.3	7.9
115	561.6	3.6	115	556.4	3.4	115	543.1	6.3	115	563.3	7.8
116	567.3	3.5	116	562.2	3.4	116	549.1	6.3	116	569.3	7.8
117	573.0	3.5	117	568.0	3.3	117	555.0	6.2	117	575.3	7.7
118	578.7	3.4	118	573.8	3.2	118	560.9	6.1	118	581.3	7.6
119	584.4	3.4	119	579.5	3.2	119	566.8	6.1	119	587.2	7.6
120	590.1	3.3	120	585.3	3.1	120	572.7	6.0	120	593.2	7.5
121	595.8	3.3	121	591.0	3.1	121	578.6	6.0	121	599.1	7.5
122	601.4	3.2	122	596.7	3.0	122	584.4	5.9	122	605.0	7.4
123	607.0	3.2	123	602.4	3.0	123	590.3	5.9	123	610.9	7.3
124	612.6	3.1	124	608.1	2.9	124	596.1	5.8	124	616.8	7.3
125	618.2	3.1	125	613.8	2.9	125	601.9	5.8	125	622.7	7.2
126	623.8	3.0	126	619.4	2.8	126	607.7	5.7	126	628.5	7.2
127	629.4	3.0	127	625.1	2.8	127	613.5	5.7	127	634.4	7.1
128	634.9	2.9	128	630.7	2.7	128	619.2	5.6	128	640.2	7.1
129	640.5	2.9	129	636.3	2.7	129	625.0	5.6	129	646.0	7.0
130	646.0	2.8	130	641.9	2.7	130	630.7	5.5	130	651.9	6.9
131	651.5	2.8	131	647.5	2.6	131	636.4	5.4	131	657.6	6.9
132	657.0	2.7	132	653.0	2.6	132	642.2	5.4	132	663.4	6.8
133	662.4	2.7	133	658.6	2.5	133	647.8	5.3	133	669.2	6.8
134	667.9	2.7	134	664.1	2.5	134	653.5	5.3	134	674.9	6.7
135	673.3	2.6	135	669.6	2.4	135	659.2	5.2	135	680.7	6.6
136	678.7	2.6	136	675.1	2.4	136	664.8	5.2	136	686.4	6.6
137	684.1	2.5	137	680.6	2.4	137	670.5	5.1	137	692.1	6.5
138	689.5	2.5	138	686.1	2.3	138	676.1	5.1	138	697.8	6.5
139	694.9	2.4	139	691.5	2.3	139	681.7	5.0	139	703.5	6.4
140	700.3	2.4	140	697.0	2.2	140	687.3	5.0	140	709.2	6.3
141	705.6	2.4	141	702.4	2.2	141	692.9	4.9	141	714.8	6.3
142	710.9	2.3	142	707.8	2.2	142	698.5	4.9	142	720.5	6.2
143	716.2	2.3	143	713.2	2.1	143	704.0	4.8	143	726.1	6.2
144	721.5	2.2	144	718.5	2.1	144	709.6	4.8	144	731.7	6.1
145	726.8	2.2	145	723.9	2.1	145	715.1	4.7	145	737.3	6.1

146	732.1	2.2	146	729.2	2.0	146	720.6	4.7	146	742.9	6.0
147	737.3	2.1	147	734.6	2.0	147	726.1	4.6	147	748.5	5.9
148	742.5	2.1	148	739.9	2.0	148	731.6	4.6	148	754.0	5.9
149	747.7	2.1	149	745.2	1.9	149	737.0	4.5	149	759.6	5.8
150	752.9	2.0	150	750.5	1.9	150	742.5	4.5	150	765.1	5.8
151	758.1	2.0	151	755.7	1.9	151	747.9	4.4	151	770.6	5.7
152	763.3	2.0	152	761.0	1.8	152	753.3	4.4	152	776.1	5.6
153	768.4	1.9	153	766.2	1.8	153	758.8	4.3	153	781.6	5.6
154	773.6	1.9	154	771.4	1.8	154	764.1	4.3	154	787.1	5.5
155	778.7	1.9	155	776.7	1.8	155	769.5	4.2	155	792.6	5.5
156	783.8	1.8	156	781.8	1.7	156	774.9	4.2	156	798.0	5.4
157	788.9	1.8	157	787.0	1.7	157	780.2	4.2	157	803.4	5.4
158	793.9	1.8	158	792.2	1.7	158	785.6	4.1	158	808.9	5.3
159	799.0	1.7	159	797.3	1.7	159	790.9	4.1	159	814.3	5.2
160	804.0	1.7	160	802.4	1.6	160	796.2	4.0	160	819.7	5.2
161	809.0	1.7	161	807.6	1.6	161	801.5	4.0	161	825.0	5.1
162	814.0	1.6	162	812.7	1.6	162	806.8	3.9	162	830.4	5.1
163	819.0	1.6	163	817.7	1.6	163	812.1	3.9	163	835.8	5.0
164	824.0	1.6	164	822.8	1.5	164	817.3	3.8	164	841.1	5.0
165	828.9	1.6	165	827.9	1.5	165	822.5	3.8	165	846.4	4.9
166	833.9	1.5	166	832.9	1.5	166	827.8	3.8	166	851.7	4.8
167	838.8	1.5	167	837.9	1.5	167	833.0	3.7	167	857.0	4.8
168	843.7	1.5	168	842.9	1.5	168	838.2	3.7	168	862.3	4.7
169	848.6	1.4	169	847.9	1.5	169	843.4	3.6	169	867.6	4.7
170	853.5	1.4	170	852.9	1.4	170	848.5	3.6	170	872.8	4.6
171	858.3	1.4	171	857.8	1.4	171	853.7	3.5	171	878.1	4.6
172	863.2	1.4	172	862.8	1.4	172	858.8	3.5	172	883.3	4.5
173	868.0	1.4	173	867.7	1.4	173	863.9	3.5	173	888.5	4.5
174	872.8	1.3	174	872.6	1.4	174	869.0	3.4	174	893.7	4.4
175	877.6	1.3	175	877.5	1.4	175	874.1	3.4	175	898.9	4.3
176	882.4	1.3	176	882.4	1.4	176	879.2	3.4	176	904.1	4.3
177	887.2	1.3	177	887.3	1.3	177	884.3	3.3	177	909.3	4.2
178	891.9	1.2	178	892.1	1.3	178	889.3	3.3	178	914.4	4.2
179	896.6	1.2	179	896.9	1.3	179	894.4	3.3	179	919.5	4.1
180	901.4	1.2	180	901.8	1.3	180	899.4	3.2	180	924.6	4.1
181	906.0	1.2	181	906.6	1.3	181	904.4	3.2	181	929.8	4.0
182	910.7	1.2	182	911.4	1.3	182	909.4	3.2	182	934.8	4.0
183	915.4	1.2	183	916.1	1.3	183	914.4	3.1	183	939.9	3.9
184	920.1	1.1	184	920.9	1.3	184	919.4	3.1	184	945.0	3.9
185	924.7	1.1	185	925.6	1.3	185	924.3	3.1	185	950.0	3.8
186	929.3	1.1	186	930.4	1.3	186	929.2	3.1	186	955.1	3.8
187	933.9	1.1	187	935.1	1.3	187	934.2	3.0	187	960.1	3.7
188	938.5	1.1	188	939.8	1.2	188	939.1	3.0	188	965.1	3.7
189	943.1	1.1	189	944.4	1.2	189	944.0	3.0	189	970.1	3.6
190	947.6	1.1	190	949.1	1.2	190	948.8	3.0	190	975.1	3.6
191	952.2	1.1	191	953.8	1.2	191	953.7	3.0	191	980.0	3.5
192	956.7	1.1	192	958.4	1.2	192	958.6	3.0	192	985.0	3.5
193	961.2	1.1	193	963.0	1.2	193	963.4	2.9	193	989.9	3.5
194	965.7	1.1	194	967.6	1.2	194	968.2	2.9	194	994.9	3.4
195	970.2	1.1	195	972.2	1.2	195	973.0	2.9	195	999.8	3.4
196	974.6	1.0	196	976.8	1.2	196	977.8	2.9	196	1004.7	3.3

197	979.1	1.0	197	981.3	1.2	197	982.6	2.9	197	1009.6	3.3
198	983.5	1.0	198	985.9	1.2	198	987.4	2.9	198	1014.4	3.3
199	987.9	1.0	199	990.4	1.2	199	992.1	2.9	199	1019.3	3.2
200	992.3	1.0	200	994.9	1.2	200	996.9	2.9	200	1024.1	3.2
201	996.7	1.1	201	999.4	1.2	201	1001.6	2.9	201	1029.0	3.2
202	1001.0	1.1	202	1003.9	1.2	202	1006.3	2.9	202	1033.8	3.1
203	1005.4	1.1	203	1008.3	1.2	203	1011.0	2.9	203	1038.6	3.1
204	1009.7	1.1	204	1012.8	1.2	204	1015.7	2.9	204	1043.4	3.1
205	1014.0	1.1	205	1017.2	1.2	205	1020.3	2.9	205	1048.1	3.0
206	1018.3	1.1	206	1021.7	1.2	206	1025.0	3.0	206	1052.9	3.0
207	1022.6	1.1	207	1026.1	1.2	207	1029.6	3.0	207	1057.7	3.0
208	1026.9	1.1	208	1030.4	1.2	208	1034.3	3.0	208	1062.4	3.0
209	1031.1	1.1	209	1034.8	1.2	209	1038.9	3.0	209	1067.1	3.0
210	1035.4	1.1	210	1039.2	1.2	210	1043.5	3.0	210	1071.8	2.9
211	1039.6	1.1	211	1043.5	1.2	211	1048.0	3.1	211	1076.5	2.9
212	1043.8	1.2	212	1047.8	1.2	212	1052.6	3.1	212	1081.2	2.9
213	1048.0	1.2	213	1052.1	1.2	213	1057.2	3.1	213	1085.8	2.9
214	1052.1	1.2	214	1056.4	1.2	214	1061.7	3.1	214	1090.5	2.9
215	1056.3	1.2	215	1060.7	1.2	215	1066.2	3.2	215	1095.1	2.9
216	1060.4	1.2	216	1065.0	1.2	216	1070.7	3.2	216	1099.8	2.9
217	1064.6	1.3	217	1069.2	1.2	217	1075.2	3.2	217	1104.4	2.9
218	1068.7	1.3	218	1073.5	1.2	218	1079.7	3.3	218	1109.0	2.9
219	1072.8	1.3	219	1077.7	1.2	219	1084.2	3.3	219	1113.5	2.9
220	1076.8	1.3	220	1081.9	1.2	220	1088.6	3.4	220	1118.1	2.9
221	1080.9	1.3	221	1086.1	1.2	221	1093.1	3.4	221	1122.7	2.9
222	1084.9	1.4	222	1090.2	1.2	222	1097.5	3.4	222	1127.2	2.9
223	1089.0	1.4	223	1094.4	1.2	223	1101.9	3.5	223	1131.7	3.0
224	1093.0	1.4	224	1098.5	1.2	224	1106.3	3.5	224	1136.2	3.0
225	1097.0	1.4	225	1102.7	1.2	225	1110.7	3.6	225	1140.7	3.0
226	1100.9	1.5	226	1106.8	1.2	226	1115.0	3.6	226	1145.2	3.0
227	1104.9	1.5	227	1110.9	1.2	227	1119.4	3.7	227	1149.7	3.1
228	1108.8	1.5	228	1114.9	1.2	228	1123.7	3.8	228	1154.2	3.1
229	1112.8	1.6	229	1119.0	1.2	229	1128.0	3.8	229	1158.6	3.1
230	1116.7	1.6	230	1123.1	1.2	230	1132.3	3.9	230	1163.0	3.2
231	1120.6	1.6	231	1127.1	1.2	231	1136.6	3.9	231	1167.5	3.2
232	1124.5	1.6	232	1131.1	1.3	232	1140.9	4.0	232	1171.9	3.3
233	1128.3	1.7	233	1135.1	1.3	233	1145.2	4.1	233	1176.2	3.3
234	1132.2	1.7	234	1139.1	1.3	234	1149.4	4.1	234	1180.6	3.3
235	1136.0	1.7	235	1143.1	1.3	235	1153.7	4.2	235	1185.0	3.4
236	1139.8	1.8	236	1147.0	1.3	236	1157.9	4.2	236	1189.3	3.4
237	1143.6	1.8	237	1151.0	1.3	237	1162.1	4.3	237	1193.7	3.5
238	1147.4	1.9	238	1154.9	1.3	238	1166.3	4.4	238	1198.0	3.6
239	1151.2	1.9	239	1158.8	1.3	239	1170.5	4.5	239	1202.3	3.6
240	1155.0	1.9	240	1162.7	1.3	240	1174.7	4.5	240	1206.6	3.7
241	1158.7	2.0	241	1166.6	1.3	241	1178.8	4.6	241	1210.9	3.7
242	1162.4	2.0	242	1170.4	1.3	242	1182.9	4.7	242	1215.1	3.8
243	1166.1	2.0	243	1174.3	1.3	243	1187.1	4.8	243	1219.4	3.9
244	1169.8	2.1	244	1178.1	1.3	244	1191.2	4.8	244	1223.6	3.9
245	1173.5	2.1	245	1181.9	1.4	245	1195.3	4.9	245	1227.8	4.0
246	1177.1	2.2	246	1185.7	1.4	246	1199.3	5.0	246	1232.1	4.1
247	1180.8	2.2	247	1189.5	1.4	247	1203.4	5.1	247	1236.2	4.1

248	1184.4	2.2	248	1193.3	1.4	248	1207.5	5.2	248	1240.4	4.2
249	1188.0	2.3	249	1197.0	1.4	249	1211.5	5.2	249	1244.6	4.3
250	1191.6	2.3	250	1200.8	1.4	250	1215.5	5.3	250	1248.8	4.4
251	1195.2	2.4	251	1204.5	1.4	251	1219.5	5.4	251	1252.9	4.4
252	1198.8	2.4	252	1208.2	1.4	252	1223.5	5.5	252	1257.0	4.5
253	1202.3	2.5	253	1211.9	1.5	253	1227.5	5.6	253	1261.1	4.6
254	1205.8	2.5	254	1215.6	1.5	254	1231.5	5.7	254	1265.2	4.7
255	1209.4	2.6	255	1219.2	1.5	255	1235.4	5.7	255	1269.3	4.8
256	1212.9	2.6	256	1222.9	1.5	256	1239.4	5.8	256	1273.4	4.9
257	1216.3	2.6	257	1226.5	1.5	257	1243.3	5.9	257	1277.5	4.9
258	1219.8	2.7	258	1230.1	1.5	258	1247.2	6.0	258	1281.5	5.0
259	1223.3	2.7	259	1233.7	1.6	259	1251.1	6.1	259	1285.5	5.1
260	1226.7	2.8	260	1237.3	1.6	260	1255.0	6.2	260	1289.5	5.2
261	1230.1	2.8	261	1240.9	1.6	261	1258.8	6.3	261	1293.6	5.3
262	1233.5	2.9	262	1244.4	1.6	262	1262.7	6.4	262	1297.5	5.4
263	1236.9	2.9	263	1248.0	1.7	263	1266.5	6.5	263	1301.5	5.5
264	1240.3	3.0	264	1251.5	1.7	264	1270.3	6.6	264	1305.5	5.6
265	1243.6	3.0	265	1255.0	1.7	265	1274.2	6.7	265	1309.4	5.7
266	1247.0	3.1	266	1258.5	1.7	266	1277.9	6.8	266	1313.4	5.8
267	1250.3	3.1	267	1262.0	1.7	267	1281.7	6.9	267	1317.3	5.9
268	1253.6	3.2	268	1265.4	1.8	268	1285.5	7.0	268	1321.2	6.0
269	1256.9	3.3	269	1268.9	1.8	269	1289.2	7.1	269	1325.1	6.1
270	1260.1	3.3	270	1272.3	1.8	270	1293.0	7.2	270	1329.0	6.2
271	1263.4	3.4	271	1275.7	1.9	271	1296.7	7.3	271	1332.8	6.3
272	1266.6	3.4	272	1279.1	1.9	272	1300.4	7.4	272	1336.7	6.4
273	1269.9	3.5	273	1282.5	1.9	273	1304.1	7.5	273	1340.5	6.5
274	1273.1	3.5	274	1285.9	1.9	274	1307.8	7.6	274	1344.4	6.6
275	1276.3	3.6	275	1289.2	2.0	275	1311.5	7.7	275	1348.2	6.7
276	1279.5	3.6	276	1292.6	2.0	276	1315.1	7.8	276	1352.0	6.8
277	1282.6	3.7	277	1295.9	2.0	277	1318.7	7.9	277	1355.7	6.9
278	1285.8	3.8	278	1299.2	2.1	278	1322.4	8.0	278	1359.5	7.0
279	1288.9	3.8	279	1302.5	2.1	279	1326.0	8.1	279	1363.3	7.1
280	1292.0	3.9	280	1305.8	2.1	280	1329.6	8.2	280	1367.0	7.2
281	1295.1	3.9	281	1309.0	2.2	281	1333.1	8.3	281	1370.7	7.3
282	1298.2	4.0	282	1312.3	2.2	282	1336.7	8.5	282	1374.5	7.5
283	1301.3	4.1	283	1315.5	2.2	283	1340.3	8.6	283	1378.2	7.6
284	1304.3	4.1	284	1318.7	2.3	284	1343.8	8.7	284	1381.8	7.7
285	1307.3	4.2	285	1321.9	2.3	285	1347.3	8.8	285	1385.5	7.8
286	1310.4	4.3	286	1325.1	2.3	286	1350.8	8.9	286	1389.2	7.9
287	1313.4	4.3	287	1328.3	2.4	287	1354.3	9.0	287	1392.8	8.0
288	1316.3	4.4	288	1331.4	2.4	288	1357.8	9.1	288	1396.5	8.1
289	1319.3	4.5	289	1334.6	2.5	289	1361.3	9.3	289	1400.1	8.3
290	1322.3	4.5	290	1337.7	2.5	290	1364.7	9.4	290	1403.7	8.4
291	1325.2	4.6	291	1340.8	2.5	291	1368.2	9.5	291	1407.3	8.5
292	1328.1	4.7	292	1343.9	2.6	292	1371.6	9.6	292	1410.8	8.6
293	1331.0	4.7	293	1347.0	2.6	293	1375.0	9.7	293	1414.4	8.7
294	1333.9	4.8	294	1350.0	2.7	294	1378.4	9.9	294	1418.0	8.9
295	1336.8	4.9	295	1353.1	2.7	295	1381.8	10.0	295	1421.5	9.0
296	1339.7	4.9	296	1356.1	2.8	296	1385.1	10.1	296	1425.0	9.1
297	1342.5	5.0	297	1359.1	2.8	297	1388.5	10.2	297	1428.5	9.2
298	1345.3	5.1	298	1362.1	2.9	298	1391.8	10.3	298	1432.0	9.3

299	1348.1	5.1	299	1365.1	2.9	299	1395.1	10.5	299	1435.5	9.5
300	1350.9	5.2	300	1368.1	3.0	300	1398.4	10.6	300	1439.0	9.6
301	1353.7	5.3	301	1371.0	3.0	301	1401.7	10.7	301	1442.4	9.7
302	1356.5	5.4	302	1373.9	3.1	302	1405.0	10.8	302	1445.9	9.9
303	1359.2	5.4	303	1376.9	3.1	303	1408.3	11.0	303	1449.3	10.0
304	1361.9	5.5	304	1379.8	3.2	304	1411.5	11.1	304	1452.7	10.1
305	1364.7	5.6	305	1382.7	3.2	305	1414.8	11.2	305	1456.1	10.2
306	1367.4	5.7	306	1385.5	3.3	306	1418.0	11.3	306	1459.5	10.4
307	1370.0	5.7	307	1388.4	3.3	307	1421.2	11.5	307	1462.9	10.5
308	1372.7	5.8	308	1391.2	3.4	308	1424.4	11.6	308	1466.2	10.6
309	1375.4	5.9	309	1394.1	3.4	309	1427.6	11.7	309	1469.6	10.8
310	1378.0	6.0	310	1396.9	3.5	310	1430.7	11.9	310	1472.9	10.9
311	1380.6	6.1	311	1399.7	3.5	311	1433.9	12.0	311	1476.2	11.0
312	1383.2	6.1	312	1402.5	3.6	312	1437.0	12.1	312	1479.5	11.2
313	1385.8	6.2	313	1405.2	3.6	313	1440.2	12.3	313	1482.8	11.3
314	1388.4	6.3	314	1408.0	3.7	314	1443.3	12.4	314	1486.1	11.4
315	1390.9	6.4	315	1410.7	3.8	315	1446.4	12.5	315	1489.3	11.6
316	1393.4	6.5	316	1413.4	3.8	316	1449.4	12.7	316	1492.6	11.7
317	1396.0	6.5	317	1416.1	3.9	317	1452.5	12.8	317	1495.8	11.8
318	1398.5	6.6	318	1418.8	3.9	318	1455.6	12.9	318	1499.0	12.0
319	1401.0	6.7	319	1421.5	4.0	319	1458.6	13.1	319	1502.2	12.1
320	1403.4	6.8	320	1424.2	4.1	320	1461.6	13.2	320	1505.4	12.3
321	1405.9	6.9	321	1426.8	4.1	321	1464.6	13.4	321	1508.6	12.4
322	1408.3	7.0	322	1429.4	4.2	322	1467.6	13.5	322	1511.8	12.5
323	1410.8	7.0	323	1432.1	4.2	323	1470.6	13.6	323	1514.9	12.7
324	1413.2	7.1	324	1434.7	4.3	324	1473.6	13.8	324	1518.0	12.8
325	1415.6	7.2	325	1437.2	4.4	325	1476.5	13.9	325	1521.2	13.0
326	1417.9	7.3	326	1439.8	4.4	326	1479.4	14.1	326	1524.3	13.1
327	1420.3	7.4	327	1442.4	4.5	327	1482.4	14.2	327	1527.4	13.3
328	1422.7	7.5	328	1444.9	4.6	328	1485.3	14.4	328	1530.5	13.4
329	1425.0	7.6	329	1447.4	4.6	329	1488.2	14.5	329	1533.5	13.6
330	1427.3	7.7	330	1449.9	4.7	330	1491.0	14.6	330	1536.6	13.7
331	1429.6	7.8	331	1452.4	4.8	331	1493.9	14.8	331	1539.6	13.8
332	1431.9	7.8	332	1454.9	4.8	332	1496.8	14.9	332	1542.6	14.0
333	1434.1	7.9	333	1457.3	4.9	333	1499.6	15.1	333	1545.7	14.1
334	1436.4	8.0	334	1459.8	5.0	334	1502.4	15.2	334	1548.7	14.3
335	1438.6	8.1	335	1462.2	5.1	335	1505.2	15.4	335	1551.6	14.4
336	1440.8	8.2	336	1464.6	5.1	336	1508.0	15.5	336	1554.6	14.6
337	1443.0	8.3	337	1467.0	5.2	337	1510.8	15.7	337	1557.6	14.8
338	1445.2	8.4	338	1469.4	5.3	338	1513.6	15.8	338	1560.5	14.9
339	1447.4	8.5	339	1471.8	5.3	339	1516.3	16.0	339	1563.5	15.1
340	1449.5	8.6	340	1474.1	5.4	340	1519.1	16.1	340	1566.4	15.2
341	1451.7	8.7	341	1476.4	5.5	341	1521.8	16.3	341	1569.3	15.4
342	1453.8	8.8	342	1478.8	5.6	342	1524.5	16.4	342	1572.2	15.5
343	1455.9	8.9	343	1481.1	5.6	343	1527.2	16.6	343	1575.0	15.7
344	1458.0	9.0	344	1483.4	5.7	344	1529.9	16.8	344	1577.9	15.8
345	1460.1	9.1	345	1485.6	5.8	345	1532.5	16.9	345	1580.7	16.0
346	1462.1	9.2	346	1487.9	5.9	346	1535.2	17.1	346	1583.6	16.1
347	1464.2	9.3	347	1490.1	6.0	347	1537.8	17.2	347	1586.4	16.3
348	1466.2	9.4	348	1492.4	6.0	348	1540.4	17.4	348	1589.2	16.5
349	1468.2	9.5	349	1494.6	6.1	349	1543.0	17.5	349	1592.0	16.6

350	1470.2	9.6	350	1496.8	6.2	350	1545.6	17.7	350	1594.8	16.8
351	1472.2	9.7	351	1499.0	6.3	351	1548.2	17.9	351	1597.5	16.9
352	1474.1	9.8	352	1501.1	6.4	352	1550.8	18.0	352	1600.3	17.1
353	1476.1	9.9	353	1503.3	6.4	353	1553.3	18.2	353	1603.0	17.3
354	1478.0	10.0	354	1505.4	6.5	354	1555.9	18.3	354	1605.8	17.4
355	1479.9	10.1	355	1507.5	6.6	355	1558.4	18.5	355	1608.5	17.6
356	1481.8	10.2	356	1509.6	6.7	356	1560.9	18.7	356	1611.2	17.8
357	1483.7	10.3	357	1511.7	6.8	357	1563.4	18.8	357	1613.8	17.9
358	1485.6	10.5	358	1513.8	6.9	358	1565.9	19.0	358	1616.5	18.1
359	1487.4	10.6	359	1515.8	7.0	359	1568.3	19.2	359	1619.2	18.3
360	1489.3	10.7	360	1517.9	7.0	360	1570.8	19.3	360	1621.8	18.4
361	1491.1	10.8	361	1519.9	7.1	361	1573.2	19.5	361	1624.4	18.6
362	1492.9	10.9	362	1521.9	7.2	362	1575.6	19.7	362	1627.0	18.8
363	1494.7	11.0	363	1523.9	7.3	363	1578.1	19.8	363	1629.6	18.9
364	1496.4	11.1	364	1525.9	7.4	364	1580.4	20.0	364	1632.2	19.1
365	1498.2	11.2	365	1527.9	7.5	365	1582.8	20.2	365	1634.8	19.3
366	1499.9	11.3	366	1529.8	7.6	366	1585.2	20.3	366	1637.4	19.5
367	1501.6	11.5	367	1531.7	7.7	367	1587.5	20.5	367	1639.9	19.6
368	1503.3	11.6	368	1533.7	7.8	368	1589.9	20.7	368	1642.4	19.8
369	1505.0	11.7	369	1535.6	7.9	369	1592.2	20.9	369	1645.0	20.0
370	1506.7	11.8	370	1537.5	7.9	370	1594.5	21.0	370	1647.5	20.2
371	1508.4	11.9	371	1539.3	8.0	371	1596.8	21.2	371	1650.0	20.3
372	1510.0	12.0	372	1541.2	8.1	372	1599.1	21.4	372	1652.4	20.5
373	1511.6	12.1	373	1543.0	8.2	373	1601.3	21.6	373	1654.9	20.7
374	1513.2	12.3	374	1544.8	8.3	374	1603.6	21.7	374	1657.3	20.9
375	1514.8	12.4	375	1546.7	8.4	375	1605.8	21.9	375	1659.8	21.0
376	1516.4	12.5	376	1548.5	8.5	376	1608.1	22.1	376	1662.2	21.2
377	1518.0	12.6	377	1550.2	8.6	377	1610.3	22.3	377	1664.6	21.4
378	1519.5	12.7	378	1552.0	8.7	378	1612.5	22.5	378	1667.0	21.6
379	1521.0	12.9	379	1553.7	8.8	379	1614.6	22.6	379	1669.4	21.8
380	1522.6	13.0	380	1555.5	8.9	380	1616.8	22.8	380	1671.7	21.9
381	1524.1	13.1	381	1557.2	9.0	381	1618.9	23.0	381	1674.1	22.1
382	1525.5	13.2	382	1558.9	9.1	382	1621.1	23.2	382	1676.4	22.3
383	1527.0	13.4	383	1560.6	9.2	383	1623.2	23.4	383	1678.8	22.5
384	1528.4	13.5	384	1562.3	9.3	384	1625.3	23.5	384	1681.1	22.7
385	1529.9	13.6	385	1563.9	9.4	385	1627.4	23.7	385	1683.4	22.9
386	1531.3	13.7	386	1565.6	9.5	386	1629.5	23.9	386	1685.7	23.0
387	1532.7	13.9	387	1567.2	9.6	387	1631.6	24.1	387	1687.9	23.2
388	1534.1	14.0	388	1568.8	9.7	388	1633.6	24.3	388	1690.2	23.4
389	1535.5	14.1	389	1570.4	9.8	389	1635.6	24.5	389	1692.4	23.6
390	1536.8	14.2	390	1572.0	9.9	390	1637.7	24.7	390	1694.6	23.8
391	1538.1	14.4	391	1573.5	10.0	391	1639.7	24.8	391	1696.9	24.0
392	1539.5	14.5	392	1575.1	10.1	392	1641.7	25.0	392	1699.1	24.2
393	1540.8	14.6	393	1576.6	10.3	393	1643.6	25.2	393	1701.3	24.4

Table A4.3 Results of Analysis of Variance testing the quadratic relationship between jaw and fork lengths by area and sex.

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Response: fl.mm

Terms added sequentially (first to last)
                        Df Sum of Sq  Mean Sq  F Value     Pr(F)
              jl.mm      1  42728925 42728925 31770.40 0.0000000
         I(jl.mm^2)      1    678184   678184   504.25 0.0000000
               fsex      1      3251     3251     2.42 0.1201639
              farea      3    136366    45455    33.80 0.0000000
         jl.mm:fsex      1      2851     2851     2.12 0.1456098
    I(jl.mm^2):fsex      1      4549     4549     3.38 0.0660563
        jl.mm:farea      3     40360    13453    10.00 0.0000016
   I(jl.mm^2):farea      3      5401     1800     1.34 0.2601768
         fsex:farea      3      6174     2058     1.53 0.2047856
   jl.mm:fsex:farea      3      2038      679     0.51 0.6787533
I(jl.mm^2):fsex:farea    3      3415     1138     0.85 0.4683908
          Residuals   1723   2317312     1345
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Table A4.4 Predicted fork length (± SE) from jaw length measurements (mm). Pointwise standard errors were estimated using S-Plus statistical software.

Kimberley			Pilbara			Gascoyne			South		
JL	Pred FL	SE FL	JL	Pred FL	SE FL	JL	Pred FL	SE FL	JL	Pred FL	SE FL
41	291.1	8.4	41	279.4	8.3	41	253.5	11.7	41	280.6	13.5
42	302.1	8.2	42	290.5	8.1	42	264.9	11.5	42	291.9	13.4
43	313.1	8.1	43	301.6	7.9	43	276.2	11.4	43	303.2	13.3
44	324.1	7.9	44	312.7	7.7	44	287.4	11.2	44	314.5	13.1
45	335.0	7.7	45	323.7	7.6	45	298.6	11.1	45	325.7	13.0
46	345.8	7.6	46	334.7	7.4	46	309.8	11.0	46	336.9	12.8
47	356.6	7.4	47	345.6	7.2	47	320.9	10.8	47	348.0	12.7
48	367.4	7.2	48	356.4	7.1	48	332.0	10.7	48	359.1	12.5
49	378.1	7.1	49	367.3	6.9	49	343.0	10.5	49	370.2	12.4
50	388.7	6.9	50	378.0	6.7	50	354.0	10.4	50	381.2	12.3
51	399.3	6.8	51	388.8	6.6	51	364.9	10.3	51	392.2	12.1
52	409.9	6.6	52	399.4	6.4	52	375.9	10.1	52	403.1	12.0
53	420.4	6.5	53	410.1	6.3	53	386.7	10.0	53	414.0	11.8
54	430.8	6.3	54	420.6	6.1	54	397.5	9.9	54	424.8	11.7
55	441.2	6.2	55	431.2	6.0	55	408.3	9.7	55	435.6	11.6
56	451.6	6.1	56	441.7	5.8	56	419.0	9.6	56	446.4	11.4
57	461.9	5.9	57	452.1	5.7	57	429.7	9.5	57	457.1	11.3
58	472.2	5.8	58	462.5	5.5	58	440.4	9.3	58	467.8	11.2
59	482.4	5.6	59	472.9	5.4	59	451.0	9.2	59	478.4	11.0
60	492.5	5.5	60	483.2	5.3	60	461.6	9.1	60	489.0	10.9
61	502.6	5.4	61	493.4	5.1	61	472.1	9.0	61	499.5	10.8
62	512.7	5.2	62	503.6	5.0	62	482.6	8.8	62	510.1	10.6
63	522.7	5.1	63	513.8	4.9	63	493.0	8.7	63	520.5	10.5
64	532.6	5.0	64	523.9	4.7	64	503.4	8.6	64	530.9	10.4
65	542.5	4.9	65	533.9	4.6	65	513.7	8.5	65	541.3	10.2
66	552.4	4.7	66	544.0	4.5	66	524.0	8.3	66	551.6	10.1
67	562.2	4.6	67	553.9	4.4	67	534.3	8.2	67	561.9	10.0
68	571.9	4.5	68	563.9	4.3	68	544.5	8.1	68	572.2	9.8
69	581.7	4.4	69	573.7	4.1	69	554.7	8.0	69	582.4	9.7

70	591.3	4.3	70	583.6	4.0	70	564.8	7.8	70	592.5	9.6
71	600.9	4.2	71	593.3	3.9	71	574.9	7.7	71	602.7	9.5
72	610.5	4.1	72	603.1	3.8	72	585.0	7.6	72	612.7	9.3
73	620.0	4.0	73	612.8	3.7	73	595.0	7.5	73	622.8	9.2
74	629.4	3.8	74	622.4	3.6	74	604.9	7.4	74	632.8	9.1
75	638.8	3.7	75	632.0	3.5	75	614.8	7.3	75	642.7	8.9
76	648.2	3.6	76	641.5	3.4	76	624.7	7.1	76	652.6	8.8
77	657.5	3.5	77	651.0	3.3	77	634.6	7.0	77	662.5	8.7
78	666.8	3.4	78	660.5	3.2	78	644.3	6.9	78	672.3	8.6
79	676.0	3.3	79	669.9	3.1	79	654.1	6.8	79	682.1	8.4
80	685.1	3.3	80	679.2	3.0	80	663.8	6.7	80	691.8	8.3
81	694.2	3.2	81	688.5	2.9	81	673.5	6.6	81	701.5	8.2
82	703.3	3.1	82	697.8	2.9	82	683.1	6.5	82	711.2	8.1
83	712.3	3.0	83	707.0	2.8	83	692.7	6.3	83	720.8	7.9
84	721.3	2.9	84	716.2	2.7	84	702.2	6.2	84	730.4	7.8
85	730.2	2.8	85	725.3	2.6	85	711.7	6.1	85	739.9	7.7
86	739.0	2.7	86	734.3	2.6	86	721.1	6.0	86	749.4	7.6
87	747.8	2.7	87	743.4	2.5	87	730.5	5.9	87	758.8	7.4
88	756.6	2.6	88	752.3	2.4	88	739.9	5.8	88	768.2	7.3
89	765.3	2.5	89	761.3	2.4	89	749.2	5.7	89	777.6	7.2
90	774.0	2.4	90	770.2	2.3	90	758.5	5.6	90	786.9	7.1
91	782.6	2.4	91	779.0	2.2	91	767.7	5.5	91	796.2	6.9
92	791.1	2.3	92	787.8	2.2	92	776.9	5.4	92	805.4	6.8
93	799.7	2.2	93	796.5	2.1	93	786.0	5.3	93	814.6	6.7
94	808.1	2.1	94	805.2	2.1	94	795.2	5.2	94	823.7	6.6
95	816.5	2.1	95	813.8	2.0	95	804.2	5.1	95	832.8	6.4
96	824.9	2.0	96	822.4	2.0	96	813.2	5.0	96	841.9	6.3
97	833.2	2.0	97	831.0	1.9	97	822.2	4.9	97	850.9	6.2
98	841.5	1.9	98	839.5	1.9	98	831.1	4.8	98	859.9	6.1
99	849.7	1.8	99	847.9	1.9	99	840.0	4.7	99	868.8	6.0
100	857.8	1.8	100	856.4	1.8	100	848.9	4.6	100	877.7	5.8
101	866.0	1.7	101	864.7	1.8	101	857.7	4.5	101	886.5	5.7
102	874.0	1.7	102	873.0	1.8	102	866.4	4.4	102	895.3	5.6
103	882.0	1.6	103	881.3	1.7	103	875.2	4.3	103	904.1	5.5
104	890.0	1.6	104	889.5	1.7	104	883.8	4.3	104	912.8	5.4
105	897.9	1.6	105	897.7	1.7	105	892.5	4.2	105	921.5	5.3
106	905.8	1.5	106	905.8	1.7	106	901.1	4.1	106	930.1	5.1
107	913.6	1.5	107	913.9	1.6	107	909.6	4.1	107	938.7	5.0
108	921.4	1.5	108	921.9	1.6	108	918.1	4.0	108	947.3	4.9
109	929.1	1.4	109	929.9	1.6	109	926.6	3.9	109	955.8	4.8
110	936.7	1.4	110	937.8	1.6	110	935.0	3.9	110	964.2	4.7
111	944.4	1.4	111	945.7	1.6	111	943.4	3.8	111	972.7	4.6
112	951.9	1.4	112	953.6	1.6	112	951.7	3.8	112	981.0	4.5
113	959.4	1.4	113	961.3	1.6	113	960.0	3.8	113	989.4	4.4
114	966.9	1.3	114	969.1	1.6	114	968.2	3.7	114	997.7	4.3
115	974.3	1.3	115	976.8	1.5	115	976.4	3.7	115	1005.9	4.2
116	981.7	1.3	116	984.4	1.5	116	984.6	3.7	116	1014.1	4.2
117	989.0	1.3	117	992.0	1.5	117	992.7	3.7	117	1022.3	4.1
118	996.3	1.3	118	999.6	1.5	118	1000.8	3.7	118	1030.4	4.0
119	1003.5	1.4	119	1007.1	1.5	119	1008.8	3.7	119	1038.5	4.0
120	1010.6	1.4	120	1014.6	1.5	120	1016.8	3.7	120	1046.5	3.9

121	1017.8	1.4	121	1022.0	1.5	121	1024.7	3.8	121	1054.5	3.8
122	1024.8	1.4	122	1029.3	1.5	122	1032.6	3.8	122	1062.5	3.8
123	1031.9	1.4	123	1036.7	1.5	123	1040.5	3.8	123	1070.4	3.8
124	1038.8	1.5	124	1043.9	1.5	124	1048.3	3.9	124	1078.3	3.7
125	1045.7	1.5	125	1051.2	1.5	125	1056.1	4.0	125	1086.1	3.7
126	1052.6	1.5	126	1058.3	1.5	126	1063.8	4.0	126	1093.9	3.7
127	1059.4	1.6	127	1065.5	1.5	127	1071.5	4.1	127	1101.6	3.7
128	1066.2	1.6	128	1072.6	1.5	128	1079.2	4.2	128	1109.3	3.7
129	1072.9	1.7	129	1079.6	1.5	129	1086.8	4.3	129	1117.0	3.7
130	1079.6	1.7	130	1086.6	1.5	130	1094.3	4.4	130	1124.6	3.7
131	1086.2	1.8	131	1093.5	1.5	131	1101.8	4.5	131	1132.2	3.8
132	1092.8	1.8	132	1100.4	1.6	132	1109.3	4.6	132	1139.7	3.8
133	1099.3	1.9	133	1107.3	1.6	133	1116.7	4.7	133	1147.2	3.9
134	1105.8	1.9	134	1114.1	1.6	134	1124.1	4.8	134	1154.6	4.0
135	1112.2	2.0	135	1120.8	1.6	135	1131.5	5.0	135	1162.0	4.0
136	1118.6	2.1	136	1127.5	1.6	136	1138.8	5.1	136	1169.4	4.1
137	1124.9	2.1	137	1134.2	1.6	137	1146.0	5.2	137	1176.7	4.2
138	1131.2	2.2	138	1140.8	1.6	138	1153.2	5.4	138	1184.0	4.3
139	1137.4	2.3	139	1147.3	1.6	139	1160.4	5.5	139	1191.2	4.4
140	1143.5	2.3	140	1153.9	1.6	140	1167.6	5.7	140	1198.4	4.5
141	1149.7	2.4	141	1160.3	1.7	141	1174.6	5.9	141	1205.6	4.7
142	1155.7	2.5	142	1166.7	1.7	142	1181.7	6.0	142	1212.7	4.8
143	1161.8	2.6	143	1173.1	1.7	143	1188.7	6.2	143	1219.7	4.9
144	1167.7	2.7	144	1179.4	1.7	144	1195.6	6.4	144	1226.7	5.1
145	1173.7	2.7	145	1185.7	1.7	145	1202.6	6.5	145	1233.7	5.3
146	1179.5	2.8	146	1191.9	1.8	146	1209.4	6.7	146	1240.7	5.4
147	1185.4	2.9	147	1198.1	1.8	147	1216.3	6.9	147	1247.6	5.6
148	1191.1	3.0	148	1204.3	1.8	148	1223.1	7.1	148	1254.4	5.7
149	1196.9	3.1	149	1210.4	1.9	149	1229.8	7.3	149	1261.2	5.9
150	1202.5	3.2	150	1216.4	1.9	150	1236.5	7.5	150	1268.0	6.1
151	1208.2	3.3	151	1222.4	1.9	151	1243.2	7.7	151	1274.7	6.3
152	1213.7	3.4	152	1228.3	2.0	152	1249.8	7.9	152	1281.4	6.5
153	1219.3	3.5	153	1234.2	2.0	153	1256.3	8.1	153	1288.0	6.7
154	1224.7	3.6	154	1240.1	2.1	154	1262.9	8.3	154	1294.6	6.9
155	1230.2	3.7	155	1245.9	2.1	155	1269.4	8.5	155	1301.2	7.1
156	1235.5	3.8	156	1251.7	2.1	156	1275.8	8.7	156	1307.7	7.3
157	1240.9	3.9	157	1257.4	2.2	157	1282.2	9.0	157	1314.1	7.5
158	1246.1	4.0	158	1263.0	2.3	158	1288.6	9.2	158	1320.6	7.7
159	1251.4	4.1	159	1268.6	2.3	159	1294.9	9.4	159	1327.0	7.9
160	1256.5	4.3	160	1274.2	2.4	160	1301.2	9.6	160	1333.3	8.1
161	1261.7	4.4	161	1279.7	2.4	161	1307.4	9.9	161	1339.6	8.4
162	1266.7	4.5	162	1285.2	2.5	162	1313.6	10.1	162	1345.8	8.6
163	1271.8	4.6	163	1290.6	2.6	163	1319.7	10.3	163	1352.1	8.8
164	1276.7	4.7	164	1296.0	2.6	164	1325.8	10.6	164	1358.2	9.0
165	1281.7	4.9	165	1301.3	2.7	165	1331.9	10.8	165	1364.4	9.3
166	1286.6	5.0	166	1306.6	2.8	166	1337.9	11.1	166	1370.4	9.5
167	1291.4	5.1	167	1311.9	2.8	167	1343.9	11.3	167	1376.5	9.8
168	1296.2	5.2	168	1317.1	2.9	168	1349.8	11.6	168	1382.5	10.0
169	1300.9	5.4	169	1322.2	3.0	169	1355.7	11.8	169	1388.4	10.3
170	1305.6	5.5	170	1327.3	3.1	170	1361.5	12.1	170	1394.4	10.5
171	1310.2	5.7	171	1332.3	3.2	171	1367.3	12.3	171	1400.2	10.8

172	1314.8	5.8	172	1337.3	3.3	172	1373.1	12.6	172	1406.1	11.0
173	1319.3	5.9	173	1342.3	3.4	173	1378.8	12.9	173	1411.9	11.3
174	1323.8	6.1	174	1347.2	3.4	174	1384.5	13.1	174	1417.6	11.5
175	1328.2	6.2	175	1352.1	3.5	175	1390.1	13.4	175	1423.3	11.8
176	1332.6	6.4	176	1356.9	3.6	176	1395.7	13.7	176	1429.0	12.1
177	1336.9	6.5	177	1361.6	3.7	177	1401.2	14.0	177	1434.6	12.4
178	1341.2	6.7	178	1366.4	3.9	178	1406.7	14.2	178	1440.2	12.6
179	1345.4	6.8	179	1371.0	4.0	179	1412.2	14.5	179	1445.7	12.9
180	1349.6	7.0	180	1375.6	4.1	180	1417.6	14.8	180	1451.2	13.2
181	1353.7	7.2	181	1380.2	4.2	181	1423.0	15.1	181	1456.6	13.5
182	1357.8	7.3	182	1384.7	4.3	182	1428.3	15.4	182	1462.0	13.8
183	1361.9	7.5	183	1389.2	4.4	183	1433.6	15.7	183	1467.4	14.0
184	1365.8	7.6	184	1393.7	4.5	184	1438.8	16.0	184	1472.7	14.3
185	1369.8	7.8	185	1398.0	4.7	185	1444.0	16.3	185	1478.0	14.6
186	1373.7	8.0	186	1402.4	4.8	186	1449.2	16.6	186	1483.2	14.9
187	1377.5	8.2	187	1406.7	4.9	187	1454.3	16.9	187	1488.4	15.2
188	1381.3	8.3	188	1410.9	5.0	188	1459.4	17.2	188	1493.6	15.5
189	1385.0	8.5	189	1415.1	5.2	189	1464.4	17.5	189	1498.7	15.8
190	1388.7	8.7	190	1419.3	5.3	190	1469.4	17.8	190	1503.8	16.1
191	1392.3	8.9	191	1423.4	5.4	191	1474.3	18.1	191	1508.8	16.4
192	1395.9	9.1	192	1427.4	5.6	192	1479.2	18.4	192	1513.8	16.7
193	1399.4	9.2	193	1431.4	5.7	193	1484.1	18.7	193	1518.7	17.1
194	1402.9	9.4	194	1435.4	5.9	194	1488.9	19.0	194	1523.6	17.4
195	1406.4	9.6	195	1439.3	6.0	195	1493.7	19.4	195	1528.5	17.7
196	1409.7	9.8	196	1443.2	6.1	196	1498.4	19.7	196	1533.3	18.0
197	1413.1	10.0	197	1447.0	6.3	197	1503.1	20.0	197	1538.0	18.3
198	1416.4	10.2	198	1450.8	6.4	198	1507.7	20.3	198	1542.8	18.7
199	1419.6	10.4	199	1454.5	6.6	199	1512.3	20.7	199	1547.4	19.0
200	1422.8	10.6	200	1458.2	6.8	200	1516.9	21.0	200	1552.1	19.3
201	1425.9	10.8	201	1461.8	6.9	201	1521.4	21.4	201	1556.7	19.6
202	1429.0	11.0	202	1465.4	7.1	202	1525.9	21.7	202	1561.2	20.0
203	1432.0	11.2	203	1468.9	7.2	203	1530.3	22.0	203	1565.8	20.3
204	1435.0	11.4	204	1472.4	7.4	204	1534.7	22.4	204	1570.2	20.7
205	1438.0	11.6	205	1475.8	7.6	205	1539.0	22.7	205	1574.7	21.0
206	1440.9	11.9	206	1479.2	7.7	206	1543.3	23.1	206	1579.0	21.3
207	1443.7	12.1	207	1482.6	7.9	207	1547.6	23.4	207	1583.4	21.7
208	1446.5	12.3	208	1485.9	8.1	208	1551.8	23.8	208	1587.7	22.0
209	1449.2	12.5	209	1489.1	8.3	209	1555.9	24.2	209	1591.9	22.4
210	1451.9	12.7	210	1492.3	8.5	210	1560.1	24.5	210	1596.2	22.8
211	1454.6	13.0	211	1495.5	8.6	211	1564.2	24.9	211	1600.3	23.1
212	1457.1	13.2	212	1498.6	8.8	212	1568.2	25.2	212	1604.5	23.5
213	1459.7	13.4	213	1501.6	9.0	213	1572.2	25.6	213	1608.6	23.8
214	1462.2	13.7	214	1504.7	9.2	214	1576.2	26.0	214	1612.6	24.2
215	1464.6	13.9	215	1507.6	9.4	215	1580.1	26.4	215	1616.6	24.6
216	1467.0	14.1	216	1510.5	9.6	216	1583.9	26.7	216	1620.6	24.9
217	1469.3	14.4	217	1513.4	9.8	217	1587.8	27.1	217	1624.5	25.3
218	1471.6	14.6	218	1516.2	10.0	218	1591.6	27.5	218	1628.4	25.7
219	1473.9	14.9	219	1519.0	10.2	219	1595.3	27.9	219	1632.2	26.1
220	1476.1	15.1	220	1521.7	10.4	220	1599.0	28.3	220	1636.0	26.4
221	1478.2	15.3	221	1524.4	10.6	221	1602.6	28.7	221	1639.7	26.8
222	1480.3	15.6	222	1527.1	10.8	222	1606.3	29.1	222	1643.5	27.2

223	1482.3	15.9	223	1529.6	11.0	223	1609.8	29.4	223	1647.1	27.6
224	1484.3	16.1	224	1532.2	11.2	224	1613.4	29.8	224	1650.7	28.0
225	1486.3	16.4	225	1534.7	11.4	225	1616.8	30.2	225	1654.3	28.4
226	1488.2	16.6	226	1537.1	11.6	226	1620.3	30.6	226	1657.9	28.8
227	1490.0	16.9	227	1539.5	11.9	227	1623.7	31.1	227	1661.3	29.2

Appendix 5. Age and Growth

Table A5.1 Results of analysis using the Best Subsets Regression procedure in Minitab to determine the variables that most accurately describe the relationship with *S. commerson* age, based on all body and otolith parameters. Headlt; head length. Otolt; otolith length. Otoarl; otolith antirostrum length. Curtot; otolith weight$^{1/3}$. Note that the age was transformed prior to analyses (= $\frac{age}{(1+1.3age)}$). Variables were selected to provide the most parsimonious regressions that maximised the adjust r^2 and minimised the model error (highlighted in grey).

i) Kimberley females

```
                                      F H   O C C
                                      O E O T U U
                                      R A T O R R
                                      K D O A T T
              Adj.                    L L L R W O
Vars   R-sq   R-sq    C-p      error   T T T L H T

   1    76.8   76.6   10.7  0.033165             X
   1    75.0   74.8   23.8  0.034425   X
   1    74.1   73.9   30.2  0.035023           X
   2    78.3   78.1    1.1  0.032117           X X
   2    78.2   77.9    2.2  0.032229   X         X
   2    77.6   77.3    6.7  0.032682     X       X
   3    78.4   78.0    2.5  0.032153         X X X
   3    78.4   78.0    3.0  0.032201       X   X X
   3    78.4   78.0    3.0  0.032202   X       X X
   4    78.6   78.0    3.5  0.032157       X X X X
   4    78.5   77.9    4.3  0.032240   X     X X X
   4    78.5   77.9    4.4  0.032242     X   X X X
```

ii) Kimberley males

```
                                      F H   O C C
                                      O E O T U U
                                      R A T O R R
                                      K D O A W O
              Adj.                    L L L R H T
Vars   R-sq   R-sq    C-p      error   T T T l O O

   1    75.9   75.7   13.0  0.037654     X
   1    75.9   75.7   13.2  0.037669             X
   1    73.0   72.8   33.9  0.039875   X
   2    77.9   77.6    0.5  0.036145     X       X
   2    77.3   77.0    5.1  0.036665   X         X
   2    77.1   76.8    6.5  0.036820           X X
   3    78.1   77.6    1.5  0.036145     X X     X
   3    78.0   77.6    2.0  0.036198     X   X   X
   3    78.0   77.6    2.2  0.036225   X X       X
```

```
   4   78.1   77.6    3.1  0.036208   X X X     X
   4   78.1   77.6    3.2  0.036217     X X   X X
   4   78.1   77.5    3.5  0.036250   X X   X   X
```

iii) Pilbara females

```
                                      F H   O C C
                                      O E O T U U
                                      R A T O R R
                                      K D O A T T
              Adj.                    L L L R W O
Vars   R-sq   R-sq    C-p     error   T T T L H T

   1   83.4   83.3   34.7  0.038697           X
   1   82.5   82.4   49.1  0.039721   X
   1   80.7   80.6   77.4  0.041668             X
   2   84.8   84.7   12.9  0.037018           X X
   2   83.9   83.8   27.2  0.038087       X   X
   2   83.9   83.7   28.4  0.038177   X         X
   3   85.5   85.4    3.4  0.036209   X       X X
   3   85.3   85.1    7.5  0.036528     X     X X
   3   84.9   84.7   14.0  0.037030         X X X
   4   85.7   85.4    3.7  0.036156   X     X X X
   4   85.6   85.3    4.8  0.036245   X X     X X
   4   85.6   85.3    5.3  0.036282   X   X   X X
```

iv) Pilbara males

```
                                      F H   O C C
                                      O E O T U U
                                      R A T O R R
                                      K D O A T T
              Adj.                    L L L R W O
Vars   R-sq   R-sq    C-p     error   T T T L H T

   1   90.4   90.4   15.6  0.037972     X
   1   89.0   88.9   41.6  0.040743   X
   1   87.7   87.6   64.6  0.043052             X
   2   91.2   91.1    3.5  0.036493     X       X
   2   90.7   90.6   12.6  0.037536     X X
   2   90.7   90.6   13.2  0.037606   X X
   3   91.3   91.1    3.8  0.036407   X X       X
   3   91.2   91.1    4.9  0.036539     X     X X
   3   91.2   91.1    5.2  0.036580     X   X   X
   4   91.4   91.1    5.0  0.036435   X X     X X
   4   91.3   91.1    5.1  0.036450   X X   X   X
   4   91.3   91.1    5.7  0.036522   X X X     X
```

Table A5.2 Results of analysis using the Best Subsets Regression procedure in Minitab to determine the variables that most accurately describe the relationship with *S. commerson* age, based only on head length and otolith parameters. Headlt; head length. Otolt; otolith length. Otoarl; otolith antirostrum length. Curtot; otolith weight$^{1/3}$. Note that the age was transformed prior to analyses (= $\frac{age}{(1+1.3age)}$). Variables were selected to provide the most parsimonious regressions that maximised the adjust r^2 and minimised the model error (highlighted in grey).

i) Kimberley females.

```
                                      H   O C
                                      E O T U
                                      A T O R
                                      D O A T
              Adj.                    L L R O
Vars   R-sq   R-sq    C-p     error   T T L T

   1   76.8   76.6     6.6  0.033165        X
   1   73.6   73.5    29.0  0.035337  X
   1   70.2   70.1    53.1  0.037532      X
   2   77.6   77.3     2.9  0.032682  X     X
   2   77.2   76.9     5.9  0.032992    X   X
   2   76.8   76.5     8.4  0.033242      X X
   3   77.7   77.3     4.1  0.032707  X X   X
   3   77.6   77.2     4.7  0.032766  X   X X
   3   77.2   76.8     7.6  0.033061    X X X
   4   77.8   77.3     5.0  0.032697  X X X X
```

ii) Kimberley males.

```
                                      H   O C
                                      E O T U
                                      A T O R
                                      D O A O
              Adj.                    L L R T
Vars   R-sq   R-sq    C-p   error     T T l O

   1   75.9   75.7    14.6  0.037654  X
   1   75.9   75.7    14.8  0.037669        X
   1   61.0   60.7   122.2  0.047917      X
   2   77.9   77.6     2.0  0.036145  X     X
   2   76.3   76.0    14.1  0.037489  X   X
   2   76.1   75.8    15.4  0.037640  X X
   3   78.1   77.6     3.0  0.036145  X X   X
   3   78.0   77.6     3.5  0.036198  X   X X
   3   76.3   75.8    16.0  0.037605  X X X
   4   78.1   77.5     5.0  0.036257  X X X X
```

iii) Pilbara females

```
                                      H   O C
                                      E O T U
                                      A T O R
                                      D O A T
              Adj.                    L L R O
Vars   R-sq   R-sq    C-p     error   T T L T

   1   80.7   80.6     9.4  0.041668        X
   1   78.3   78.3    39.0  0.044134  X
   1   75.6   75.5    73.8  0.046873      X
   2   81.4   81.2     2.8  0.041005  X     X
   2   80.9   80.8     8.6  0.041516    X   X
   2   80.8   80.7     9.8  0.041615      X X
   3   81.5   81.3     3.0  0.040937  X X   X
```

```
   3   81.4   81.2    4.2  0.041043   X   X X
   3   80.9   80.7   10.5  0.041594     X X X
   4   81.5   81.2    5.0  0.041025   X X X X
```

iv) Pilbara males

```
                                      H   O C
                                      E O T U
                                      A T O R
                                      D O A T
              Adj.                    L L R O
Vars   R-sq   R-sq    C-p    error    T T L T

   1   90.4   90.4   14.7  0.037972   X
   1   87.7   87.6   63.5  0.043052         X
   1   81.3   81.2  177.2  0.053045       X
   2   91.2   91.1    2.7  0.036493   X     X
   2   90.7   90.6   11.8  0.037536   X X
   2   90.6   90.5   13.6  0.037743   X   X
   3   91.2   91.1    4.5  0.036580   X   X X
   3   91.2   91.1    4.5  0.036588   X X   X
   3   90.7   90.5   13.8  0.037656   X X X
   4   91.3   91.1    5.0  0.036527   X X X X
```

Table A5.3 Age – head length keys for *S. commerson*.

a) Kimberley Females

Head Length Groups (mm)

Age (yrs)	121 to 130	131 to 140	141 to 150	151 to 160	161 to 170	171 to 180	181 to 190	191 to 200	201 to 210	211 to 220	221 to 230	231 to 240	241 to 250	251 to 260	261 to 270	271 to 280	281 to 290	291 to 300	301 to 310	311 to 320	321 to 330	331 to 340
1	100.0		100.0	100.0	100.0	60.0		10.3	12.0	5.7												
2						40.0	100.0	82.8	64.0	28.6	25.0	5.0										
3								6.9	24.0	62.9	58.3	40.0	46.2	11.1								
4										2.9	16.7	30.0	30.8	22.2	11.1	20.0		20.0				
5												20.0	15.4	33.3	33.3		66.7	20.0				
6												5.0		11.1	11.1	40.0		20.0				
7													7.7	11.1	44.4	40.0		40.0				100.0
8														11.1			33.3				100.0	
9																						
10																			100.0	100.0		
11																						
N	**1**	**2**	**4**	**4**	**5**	**11**	**29**	**25**	**35**	**36**	**20**	**13**	**9**	**9**	**5**	**3**	**5**	**1**	**1**	**1**	**1**	**1**

b) Kimberley Males

Age (yrs)	121 to 130	131 to 140	141 to 150	151 to 160	161 to 170	171 to 180	181 to 190	191 to 200	201 to 210	211 to 220	221 to 230	231 to 240	241 to 250	251 to 260
1	100.0	100.0	100.0	60.0	16.0	17.3	3.6							
2				40.0	84.0	76.9	67.9	48.6	6.3					
3						5.8	26.8	45.9	68.8					
4							1.8	5.4	12.5	10.0	23.1			
5										30.0	7.7	12.5		
6									12.5	10.0	15.4			
7										30.0	38.5	37.5		
8										20.0	7.7	25.0	50.0	
9											7.7	12.5	50.0	
10														
11												12.5		
N	**0**	**1**	**0**	**2**	**3**	**5**	**25**	**52**	**56**	**37**	**16**	**10**	**13**	**0**

c) Pilbara/west coast females

Head Length Groups (mm)

Age (yrs)	131 to 140	141 to 150	151 to 160	161 to 170	171 to 180	181 to 190	191 to 200	201 to 210	211 to 220	221 to 230	231 to 240	241 to 250	251 to 260	261 to 270	271 to 280	281 to 290	291 to 300	301 to 310	311 to 320	321 to 330	331 to 340	341 to 350	351 to 360	361 to 370	371 to 380	381 to 390	391 to 400
1	100.0	100.0	100.0	93.8	75.0	45.7	32.6	7.1																			
2				6.3	25.0	54.3	60.5	51.8	32.2	12.1	8.9	1.8	2.0														
3							2.3	35.7	54.2	48.5	32.1	12.5	8.2	3.4													
4							2.3	3.6	11.9	27.3	37.5	33.9	26.5	3.4	8.3	11.8											
5									1.7	7.6	12.5	25.0	22.4	34.5	8.3	11.8		16.7									
6										1.5	3.6	8.9	14.3	10.3	20.8	23.5	7.7			14.3							
7								1.8		3.0	3.6	7.1	12.2	10.3	20.8	17.6	23.1	8.3	11.1		33.3						
8												1.8	6.1	17.2	20.8	17.6	7.7	25.0	33.3	14.3	33.3						
9											1.8	3.6	6.1	10.3		5.9	7.7	8.3	11.1	14.3							
10							2.3					1.8		3.4	16.7	11.8	15.4	25.0	22.2	14.3							
11												1.8					7.7	8.3			33.3	33.3					
12												1.8	2.0		4.2		23.1			14.3							100.0
13														6.9					11.1			66.7	100.0				
14																	7.7			14.3							
15																		8.3						100.0	100.0		
16																											
17																				14.3							
18																			11.1								
N	**1**	**5**	**6**	**16**	**32**	**46**	**43**	**56**	**59**	**66**	**56**	**56**	**49**	**29**	**24**	**17**	**13**	**12**	**9**	**7**	**3**	**3**	**1**	**1**	**1**	**0**	**1**

d) Pilbara/west coast males

Head Length Groups (mm)

Age (yrs)	111 to 120	121 to 130	131 to 140	141 to 150	151 to 160	161 to 170	171 to 180	181 to 190	191 to 200	201 to 210	211 to 220	221 to 230	231 to 240	241 to 250	251 to 260	261 to 270	271 to 280	281 to 290	291 to 300	301 to 310	311 to 320	321 to 330
1	100.0	100.0	100.0	100.0	86.7	70.0	48.4	33.3	3.8													
2					13.3	30.0	48.4	52.4	54.7	23.4	10.7	3.2	3.6									
3							3.2	9.5	34.0	48.9	28.6	16.1	3.6	4.8			16.7					
4								4.8	5.7	17.0	32.1	38.7		4.8								
5									1.9	6.4	17.9		14.3									
6										2.1	7.1	12.9	17.9	4.8		9.1						
7												12.9	17.9	9.5	10.0							
8										2.1	3.6	6.5	10.7	33.3	5.0	9.1						
9												6.5	10.7	4.8		9.1						
10													7.1	4.8	30.0	18.2	16.7					
11												3.2	3.6	4.8	5.0		16.7					
12													7.1	9.5	10.0							
13													3.6	4.8	5.0	9.1						100.0
14														4.8	5.0	18.2						
15														4.8	10.0							
16															10.0		16.7					
17														4.8	5.0	18.2						
18																	33.3		50.0			
19																						
20																9.1						
21															5.0							
22																			50.0			
N	**1**	**1**	**4**	**1**	**15**	**20**	**31**	**21**	**53**	**47**	**28**	**31**	**28**	**21**	**20**	**11**	**6**	**0**	**2**	**0**	**0**	**1**

Table A5.4 Age – fork length keys for *S. commerson*. The length class including the minimum size limit (900 mm TL) is highlighted in grey.

a) Kimberley Females

Fork Length Groups (mm)

Age (yrs)	551 to 600	601 to 650	651 to 700	701 to 750	751 to 800	801 to 850	851 to 900	901 to 950	951 to 1000	1001 to 1050	1051 to 1100	1101 to 1150	1151 to 1200	1201 to 1250	1251 to 1300	1301 to 1350	1351 to 1400	1401 to 1450	1451 to 1500
1	100.0		100.0	100.0	100.0	40.0		9.4	9.1	4.3									
2						60.0	90.9	90.6	57.6	36.2	12.5	2.9							
3							9.1		33.3	51.1	65.0	29.4	25.0						
4										6.4	22.5	32.4	16.7	16.7	10.0	20.0			
5										2.1		23.5	16.7	25.0	30.0	20.0			
6												2.9	16.7	41.7		20.0			
7												8.8	16.7	8.3	40.0	20.0	50.0		
8													8.3		10.0		50.0		
9															10.0				
10																20.0		100.0	100.0
11																			
12														8.3					
N	**1**	**0**	**2**	**5**	**3**	**5**	**11**	**32**	**33**	**47**	**40**	**34**	**12**	**12**	**10**	**5**	**2**	**1**	**1**

b) Kimberley Males

Age (yrs)	551 to 600	601 to 650	651 to 700	701 to 750	751 to 800	801 to 850	851 to 900	901 to 950	951 to 1000	1001 to 1050	1051 to 1100	1101 to 1150	1151 to 1200	1201 to 1250	1251 to 1300	1301 to 1350	1351 to 1400	1401 to 1450	1451 to 1500
1		100.0		100.0	80.0	12.0	13.7	8.2											
2					20.0	88.0	80.4	64.4	46.3	4.2									
3							5.9	26.0	41.5	37.5	11.5								
4								1.4	9.8	29.2	15.4	10.0							
5										12.5	15.4	10.0	14.3						
6									2.4	4.2	15.4	10.0							
7										12.5	19.2	40.0	14.3						
8											19.2		42.9						
9												30.0	28.6						
10																			
11											3.8								
N	**0**	**3**	**0**	**2**	**5**	**25**	**51**	**73**	**41**	**24**	**26**	**10**	**7**	**0**	**0**	**0**	**0**	**0**	**0**

c) Pilbara/west coast Females

Fork Length Groups (mm)

Age (yrs)	551 to 600	601 to 650	651 to 700	701 to 750	751 to 800	801 to 850	851 to 900	901 to 950	951 to 1000	1001 to 1050	1051 to 1100	1101 to 1150	1151 to 1200	1201 to 1250	1251 to 1300	1301 to 1350	1351 to 1400	1401 to 1450	1451 to 1500	1501 to 1550	1551 to 1600	1601 to 1650
1			100.0	100.0	100.0	75.0	70.8	48.4	28.6													
2						25.0	29.2	51.6	53.6	56.3	19.4	10.6	4.4									
3									17.9	37.5	63.9	38.3	13.3	6.7								
4										3.1	13.9	34.0	37.8	16.7	7.1	7.7						
5											2.8	8.5	20.0	30.0	14.3	15.4						
6												4.3	8.9	10.0	7.1	15.4	14.3					
7										3.1		4.3	6.7	13.3	14.3	7.7						
8													6.7	10.0	14.3	7.7	28.6	75.0				
9													2.2	6.7	14.3		14.3					
10															21.4	38.5	14.3		33.3			
11																			33.3			
12														3.3	7.1	7.7		25.0				100.0
13														3.3			14.3					
14																	14.3					
15																						
16																					100.0	
17																			33.3			
18																						
19																						
20																						
21																						
22																						
N	**0**	**0**	**3**	**4**	**8**	**12**	**24**	**31**	**28**	**32**	**36**	**47**	**45**	**30**	**14**	**13**	**7**	**4**	**3**	**0**	**1**	**1**

d) Pilbara/west coast Males

Fork Length Groups (mm)

Age (yrs)	551 to 600	601 to 650	651 to 700	701 to 750	751 to 800	801 to 850	851 to 900	901 to 950	951 to 1000	1001 to 1050	1051 to 1100	1101 to 1150	1151 to 1200	1201 to 1250	1251 to 1300	1301 to 1350	1351 to 1400	1401 to 1450	1451 to 1500
1		100.0	100.0	100.0	100.0	66.7	44.4	17.2											
2						33.3	55.6	58.6	53.3	22.0	6.1								
3								24.1	46.7	53.7	18.2	4.0	4.3						
4										19.5	45.5	16.0							
5											12.1	20.0							
6										2.4	9.1	4.0	13.0	5.6					
7											9.1	20.0	4.3	16.7					
8										2.4		20.0	8.7						
9												4.0	8.7	5.6					
10												4.0	21.7	27.8	22.2				
11													4.3	16.7	11.1				
12												4.0	17.4						
13														11.1					
14												4.0		5.6	11.1				
15													4.3	5.6	11.1				
16													8.7		11.1				
17														5.6	11.1				
18															22.2				
19																100.0			
20																			
21													4.3						
22																	100.0		
N	**0**	**2**	**2**	**4**	**7**	**24**	**18**	**29**	**30**	**41**	**33**	**25**	**23**	**18**	**9**	**1**	**1**	**0**	**0**

Table A5.5 Age- otolith weight keys for *S. commerson*.

a) Kimberley Females Otolith Weight Groups (mg)

Age (yrs)	21 to 30	31 to 40	41 to 50	51 to 60	61 to 70	71 to 80	81 to 90	91 to 100	101 to 110	111 to 120	121 to 130	131 to 140	141 to 150	151 to 160	161 to 170
1	100	43.8	12.2	2.0	2.6										
2		56.3	75.6	43.1	17.9	3.0									
3			12.2	52.9	66.7	33.3	7.1								
4				2.0	5.1	48.5	28.6	7.7	25.0						
5					7.7	15.2	21.4	23.1	25.0	25.0					
6							35.7	23.1		25.0					
7							7.1	38.5	50.0	25.0		50.0			
8								7.7				50.0			
9											50.0				
10											50.0		100.0	100.0	
11															
12										25.0					
N	**5**	**16**	**41**	**51**	**39**	**33**	**14**	**13**	**4**	**4**	**2**	**2**	**1**	**1**	**0**

b) Kimberley Males Otolith Weight Groups (mg)

Age (yrs)	21 to 30	31 to 40	41 to 50	51 to 60	61 to 70	71 to 80	81 to 90	91 to 100	101 to 110	111 to 120	121 to 130	131 to 140	141 to 150	151 to 160	161 to 170
1	75.0	25.9	12.7	1.8											
2	25.0	70.4	70.9	66.1	11.1										
3		3.7	16.5	25.0	48.1										
4				7.1	18.5	18.2	10.0								
5					7.4	36.4	15.0								
6					11.1	27.3	5.0								
7					3.7	18.2	35.0	40.0	25.0						
8							25.0	20.0	25.0						
9							10.0	40.0	25.0						
10															
11									25.0						
N	**4**	**27**	**79**	**56**	**27**	**11**	**20**	**5**	**4**	**0**	**0**	**0**	**0**	**0**	**0**

c) Pilbara/west coast Females

Otolith Weight Groups (mg)

Age (yrs)	21 to 30	31 to 40	41 to 50	51 to 60	61 to 70	71 to 80	81 to 90	91 to 100	101 to 110	111 to 120	121 to 130	131 to 140	141 to 150	151 to 160	161 to 170	171 to 180	181 to 190	191 to 200	201 to 210	211 to 220
1	100	85.0	54.9	5.1																
2		15.0	39.4	60.8	18.6	1.7														
3			4.2	26.6	61.4	32.2	12.1													
4			1.4	5.1	18.6	42.4	34.5	20.0												
5					1.4	15.3	24.1	28.6	16.7				25.0							
6						6.8	10.3	11.4	16.7	14.3	12.5									
7				1.3		1.7	13.8	11.4	33.3	14.3	18.8	7.7								
8							1.7	11.4	16.7	28.6	43.8	7.7				33.3				
9								5.7	12.5		6.3	30.8								
10				1.3				8.6	4.2	35.7	12.5	15.4	25.0							
11							1.7				6.3	7.7			50.0					
12							1.7			7.1		15.4	25.0	100.0				100.0		
13								2.9					25.0		50.0					
14												7.7								
15												7.7				33.3				50.0
16																				
17																33.3				
18																				50.0
19																				
20																				
21																				
22																				
N	**7**	**40**	**71**	**79**	**70**	**59**	**58**	**35**	**24**	**14**	**16**	**13**	**4**	**1**	**2**	**3**	**0**	**1**	**0**	**2**

d) Pilbara/west coast Males

Otolith Weight Groups (mg)

Age (yrs)	21 to 30	31 to 40	41 to 50	51 to 60	61 to 70	71 to 80	81 to 90	91 to 100	101 to 110	111 to 120	121 to 130	131 to 140	141 to 150	151 to 160	161 to 170	171 to 180	181 to 190	191 to 200
1	100	66.7	23.4	2.0														
2		33.3	53.2	44.9	6.0													
3			21.3	32.7	38.0	10.7			7.7									
4			2.1	14.3	34.0	21.4	5.0											
5				2.0	16.0	10.7												
6				4.1	4.0	21.4	5.0	8.3	7.7									
7						21.4	20.0		7.7									
8					2.0	3.6	20.0	16.7	23.1									
9							15.0	8.3										
10						7.1	25.0	33.3	7.7									
11							5.0			25.0		50.0						
12							5.0	25.0	7.7									
13						3.6		8.3		12.5								
14									23.1									
15									7.7	12.5	33.3							
16									7.7	25.0								
17										12.5				50.0				
18										12.5	33.3	50.0						
19											33.3							
20														50.0				
21																		
22																		
N	**8**	**45**	**47**	**49**	**50**	**28**	**20**	**12**	**13**	**8**	**3**	**2**	**0**	**2**	**0**	**0**	**0**	**0**

Table A5.6 Head length- fork length keys for *S. commerson*. The length class including the minimum size limit (900 mm TL) is highlighted (grey).

	Head Length Groups (mm)																																						
FL (mm)	11 to 20	21 to 30	31 to 40	41 to 50	51 to 60	61 to 70	71 to 80	81 to 90	91 to 100	101 to 110	111 to 120	121 to 130	131 to 140	141 to 150	151 to 160	161 to 170	171 to 180	181 to 190	191 to 200	201 to 210	211 to 220	221 to 230	231 to 240	241 to 250	251 to 260	261 to 270	271 to 280	281 to 290	291 to 300	301 to 310	311 to 320	321 to 330	331 to 340	341 to 350	351 to 360	361 to 370	371 to 380	381 to 390	391 to 400
51 to 100	100																																						
101 to 150		100																																					
151 to 200			100																																				
201 to 250					100																																		
251 to 300						62.5																																	
301 to 350						37.5	84.4	13.5																															
351 to 400							15.6	86.5	71.4																														
451 to 500									28.6	100																													
501 to 550											33.3																												
551 to 600											66.7	34.6																											
601 to 650												65.4	28.3																										
651 to 700													65.2	32.4	1.6																								
701 to 750													6.5	62.2	17.5	0.5																							
751 to 800														5.4	61.9	9.1	0.6																						
801 to 850															17.5	63.0	15.2	0.6																					
851 to 900															1.6	27.4	63.9	15.1	2.4	0.4																			
901 to 950																	19.4	67.0	24.6	2.2																			
951 to 1000																	0.9	17.3	56.9	29.6	3.2																		
1001 to 1050																			15.8	55.6	42.7	7.8	1.4	2.0															
1051 to 1100																			0.3	11.5	51.4	46.1	14.3	3.0															
1101 to 1150																				0.7	2.8	41.7	55.7	22.2	5.3														
1151 to 1200																						4.4	24.3	54.5	40.8	12.0													
1201 to 1250																							4.3	18.2	46.1	52.0	17.4	6.3											
1251 to 1300																									7.9	30.0	52.2	37.5	12.5	20.0									
1301 to 1350																										6.0	26.1	50.0	56.3	20.0									
1351 to 1400																											4.3		31.3	40.0	100	16.7							
1401 to 1450																												6.3		20.0		50.0	50.0						
1451 to 1500																																33.3	50.0						
1501 to 1550																																							
1551 to 1600																																					100		
1601 to 1650																																							100
N	**1**	**3**	**1**	**0**	**2**	**8**	**32**	**37**	**21**	**5**	**9**	**26**	**46**	**37**	**63**	**208**	**330**	**352**	**297**	**270**	**218**	**180**	**140**	**99**	**76**	**50**	**23**	**16**	**16**	**5**	**4**	**6**	**4**	**0**	**0**	**0**	**1**		**1**

Table A5.7 Comparison of the various natural mortality estimates (from the equations 1-4 below) derived from the von Bertalanffy and empirically derived estimates (equations 5-6) of the growth parameters L_∞ and K (year^{-1}) of *S. commerson* for a) the current study, b) estimates given by Buckworth (1999) with T assumed equal to the Kimberley and c) estimates given by McPherson (1992) with T assumed to equal the Pilbara. Note; T represents mean annual water temperature in ºC, VB indicates that Von Bertalanffy estimates of growth parameters and Phi-prime (calculated by equation 7) is given for each estimate of the growth parameters.

a) Present Study

											Natural Mortality Estimates									
		Water Temp	Input values		Von Bertalanffy values (derived from length weight data)			Empirical values (derived from input values)			using T and VB K and L_∞ values		using VB L_∞ and T or t_{max} values		using T and VB K and empirical L_∞		using T and empirical K and L_∞ values		using empirical L_∞ and T or t_{max} values	
Region	Sex	T (ºC)	L_{max} (cm)	t_{max} (yr)	L_∞ (cm)	K (year^{-1})	Phi prime	L_∞ (cm)	K (year^{-1})	Phi prime	M (Pauly)	M (Brey)	M (F&B)	M (Hesp)	M (Pauly)	M (Brey)	M (Pauly)	M (Brey)	M (F&B)	M (Hesp)
Kimberley	M	28.2	120.1	11.0	106.72	0.85	3.98	123.1	0.27	3.62	1.13	1.19	0.47	0.24	1.09	1.15	0.55	0.57	0.43	0.22
Kimberley	F	28.2	148.0	12.5	121.88	0.65	3.98	151.3	0.24	3.74	0.92	0.97	0.43	0.21	0.86	0.92	0.48	0.50	0.37	0.19
	Both	28.2	148.1	12.5	115.08	0.71	3.97	151.3	0.24	3.74	1.00	1.05	0.45	0.21	0.92	0.98	0.48	0.50	0.37	0.18
Pilbara	M	26.8	138.0	22.0	115.53	0.69	3.97	141.2	0.14	3.43	0.95	0.99	0.42	0.15	0.90	0.94	0.34	0.34	0.36	0.13
Pilbara	F	26.8	165.0	18.0	125.90	0.63	4.00	168.4	0.17	3.67	0.88	0.92	0.39	0.16	0.81	0.85	0.36	0.37	0.32	0.12
	Both	26.8	165.0	22.0	120.85	0.67	3.99	168.4	0.14	3.59	0.92	0.96	0.40	0.15	0.84	0.89	0.32	0.33	0.32	0.12
West Coast	M	22.7	134.0	18.5	113.97	0.76	3.99	137.2	0.16	3.48	0.93	0.93	0.35	0.17	0.89	0.89	0.35	0.34	0.31	0.15
West Coast	F	22.7	172.0	18.5	120.49	0.66	3.98	175.4	0.16	3.70	0.84	0.84	0.34	0.17	0.76	0.77	0.32	0.32	0.26	0.13
	Both	22.7	172.0	18.5	116.74	0.72	3.99	175.4	0.16	3.70	0.90	0.89	0.34	0.17	0.81	0.81	0.32	0.32	0.26	0.13
Overall		26.8	172.0	22.0				175.4	0.14	3.62							0.32		0.31	

b) using results from Buckworth (1999)

NT	M	28.2	125	11.0	128.58	0.10	3.22	128.1	0.27	3.65	0.29		0.41	0.21	0.27		0.54		0.41	0.21
NT	F	28.2	150	11.0	151.56	0.12	3.43	153.3	0.27	3.81	0.31		0.37	0.19	0.28		0.51		0.36	0.19
Overall		28.2	150	11.0	121.79	0.24	3.56	153.3	0.27	3.81	0.51		0.43	0.22	0.45		0.51		0.36	0.19
NT *	M	28.2			102.68	0.64	3.83	128.1			0.96		0.49		0.90					
NT *	F	28.2			121.61	0.52	3.89	153.3			0.81		0.43		0.75					
Overall *		28.2			113.05	0.57	3.86	153.3			0.88		0.45		0.79					

* second set of values obtained with t_{zero} constrained to 0

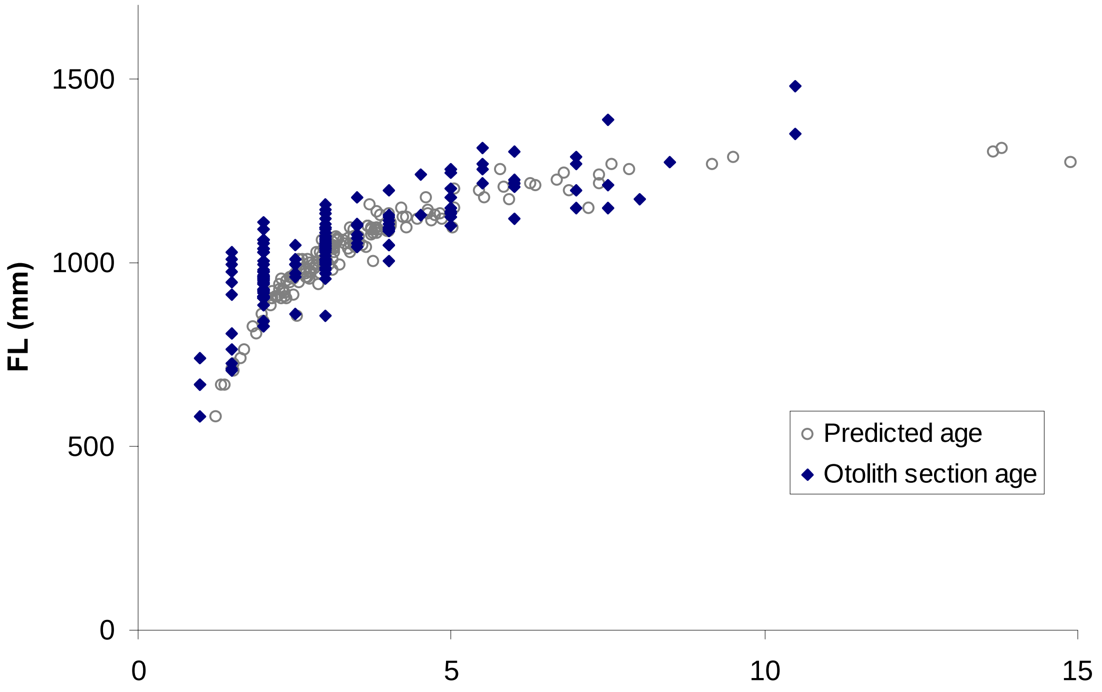
c) using results from McPherson (1992)

QLD	M	26.8	133	10.0	127.5	0.25	3.61	136.2	0.30	3.75	0.50		0.39	0.23	0.47		0.55		0.55	0.22
QLD	F	26.8	178	14.0	155	0.17	3.61	181.4	0.21	3.85	0.38		0.34	0.16	0.34		0.41		0.41	0.15

Equations

1. Pauly; $M = 10^\wedge(-0.065 - 0.287 \log_{10}(L_\infty) + 0.604 \log_{10}(K) + 0.513 \log_{10}(T))$ (Pauly 1980)
2. Brey; $M = 10^\wedge(4.355 - 0.083 * \log_{10}(W_\infty) + 6.39 * W_\infty / (L_\infty^3) + 0.627 * \log_{10}(K) - 1190.43 * (1 / (T + 273)))$ (Brey 1999)
3. F & B; $M = 10^\wedge(0.566 - 0.718 * \log_{10}(L_\infty) + 0.02 * T)$ (Froese and Binohlan 1999)
4. Hesp; $M = \mathrm{EXP}(3.017 - 0.656 * \mathrm{Ln}(L_\infty) - 0.574 * \mathrm{Ln}(t_{max}))$ (Hesp *et al* 2002)
5. $\mathrm{Linf} = 10^\wedge(0.044 + 0.9841 * \log_{10}(L_{max}))$ (Froese and Binohlan 1999)
6. $K = 3 / t_{max}$ (Froese and Binohlan 1999)
7. $\mathrm{Phi\ Prime} = \log_{10}(K) + 2 * \log_{10}(L_\infty)$ Growth performance index value (Pauly and Munro 1984)

a) Kimberley female



b) Kimberley male

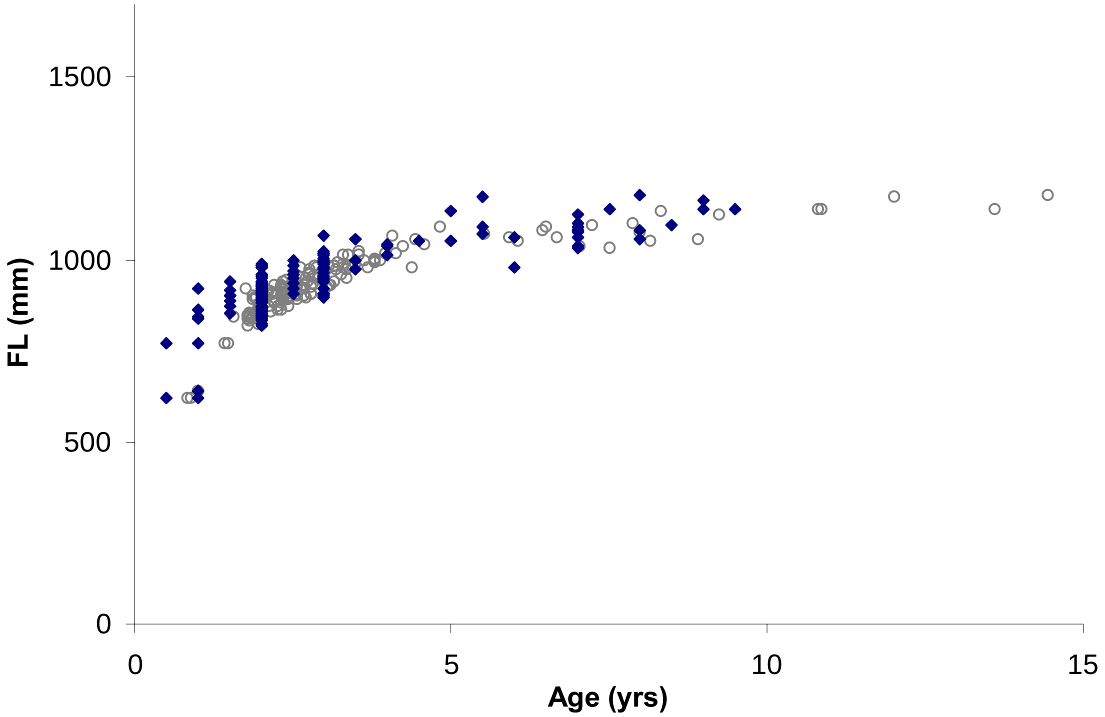
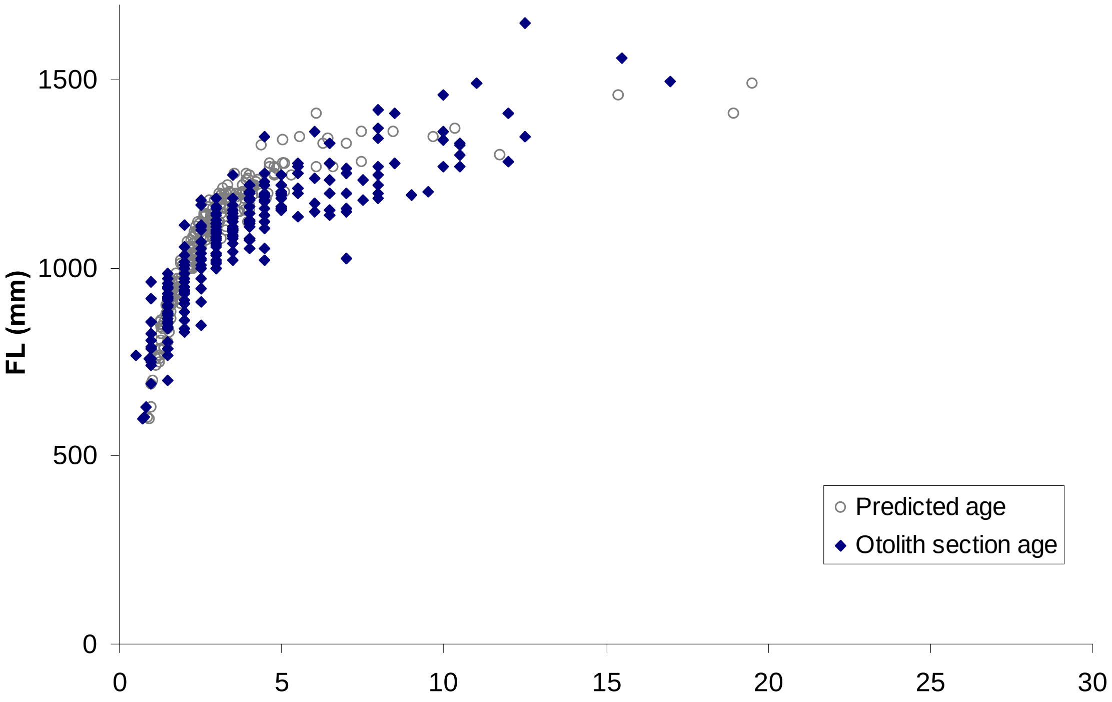


Figure A5.1 a and b Length at age data for a) female and b) male *S. commerson* within the Kimberley region, using ages obtained from counts of annuli in otolith sections and predicted from regression equations developed from otolith weight and head length.

c) Pilbara female



d) Pilbara male

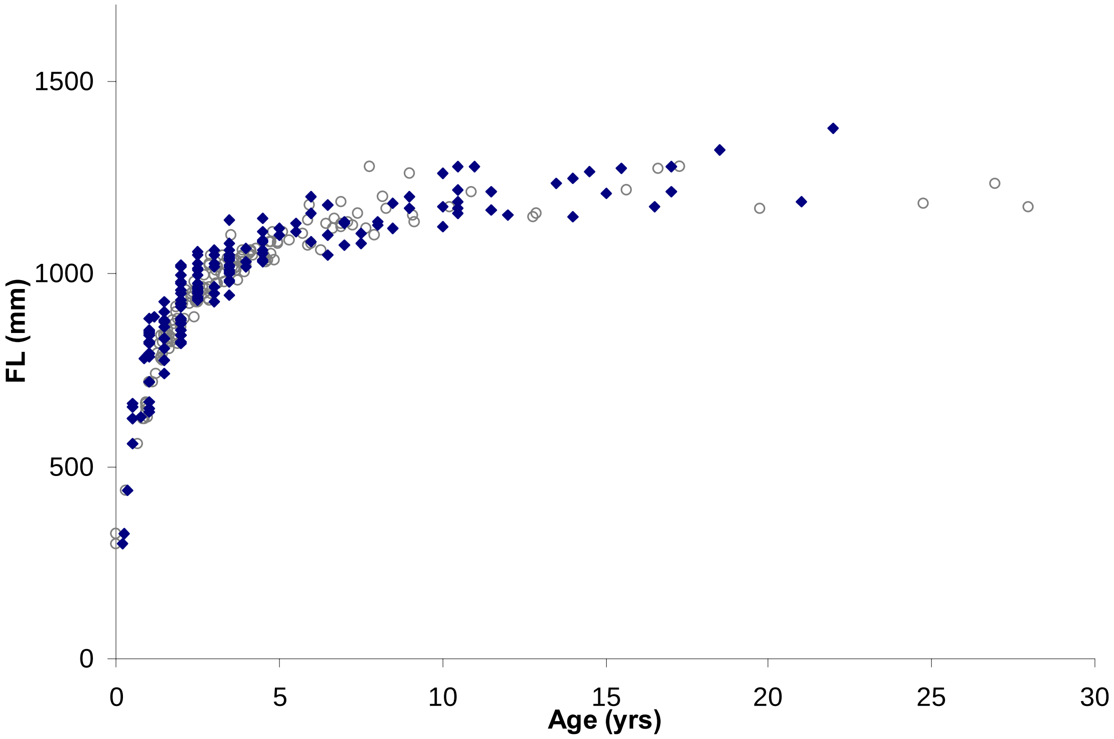


Figure A5.1c and d Length at age data for c) female and d) male *S. commerson* within the Pilbara region, using ages obtained from counts of annuli in otolith sections and predicted from regression equations developed from otolith weight and head length.

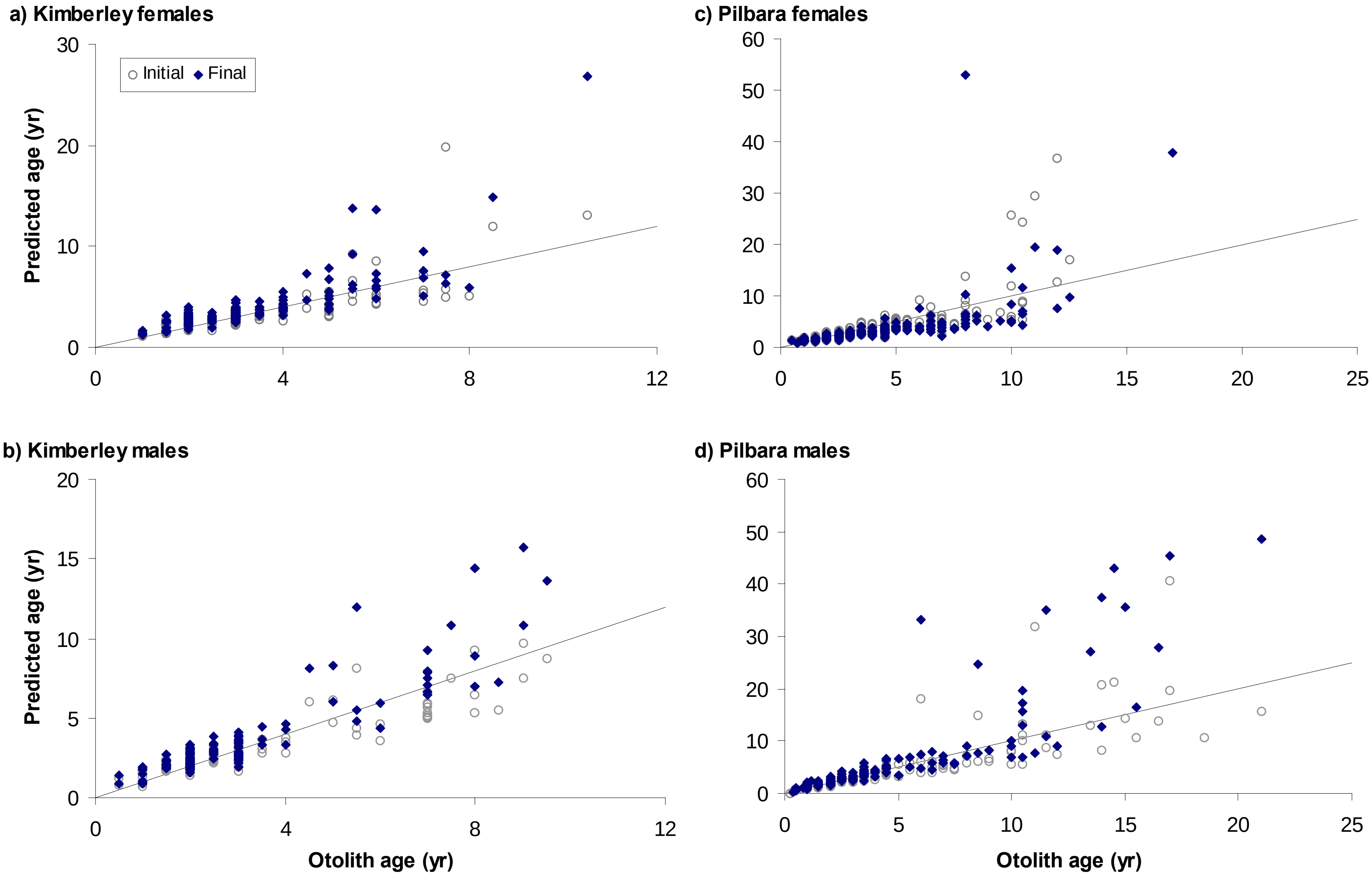


Figure A5.2 Comparison between ages obtained from counts of annuli and predicted from regression equations developed from otolith weight and head length for a) Kimberley females, b) Kimberley males, c) Pilbara females, and d) Pilbara males. Initial; initial regression used to identify the head and otolith parameters that best described age. Final; final regression used in prediction of ages from otolith weight and head length.

Appendix 6. Letter to be sent to industry members outlining the Interim Management Plan for the mackerel fishery (as approved by the Minister for Fisheries).

2242/00 08

Dear Fishing Boat Licence holder

MACKEREL FISHERY (INTERIM) MANAGEMENT PLAN

Following extensive consultation, recommendations of the Mackerel Independent Advisory Panel (MIAP), and advice from the Department of Fisheries, the Minister for Fisheries has approved the drafting of an Interim Management Plan for the Mackerel Fishery.

The Minister has approved the following recommendations and management arrangements for drafting into an Interim Management Plan for his final consideration:

- The plan will be called *Mackerel Fishery (Interim) Management Plan* and will commence operation on 1 January 2004 or as near to that date as is administratively possible.
- The plan will cease to have effect five years from the date of commencement, or earlier, if appropriate.
- The mackerel fishery will be zoned:
    - The Gascoyne-West Coast Zone from Cape Leeuwin northwards to 114° East longitude,
    - The Pilbara Zone from 114° East longitude to 121° east longitude; and
    - The Kimberley Zone from 121° East longitude to Northern Territory border.
- All zones will be managed under a quota management system, with the use of a vessel monitoring system, prior reporting and an option for the Executive Director to vary the mackerel fishing season.
- The Total Allowable Commercial Catch (TACC) for each zone of the fishery will be set by the Executive Director, after taking the best scientific and

operational advice available to him to ensure the sustainability of the mackerel fishery.

- The TACC will not be subject to annual review and will be set for three to five years. However, biological reference points will be put in place and if they are reached in two consecutive years, the TACC will be reviewed.
- The legal minimum length of 90 cm for Spanish mackerel will remain.
- There will be a six month season in each zone of the fishery. The Kimberley Zone from 1 June to 30 November and the Pilbara and Gascoyne-West Coast Zones from 1 April to 30 September.
- The ports/anchorages of Denham, the Blow Holes, Carnarvon, Kalbarri, Geraldton, Dongara, Jurien and Fremantle must be used to unload mackerel taken in the Gascoyne-West Coast Zone and the Fisheries Regional Offices will manage the Catch and Disposal Records.
- The ports/anchorages of Exmouth, Point Sampson, Onslow, Dampier, Port Hedland and Broome must be used to unload mackerel taken in the Pilbara Zone and the Fisheries Regional Offices will manage the Catch and Disposal Records.
- The ports/anchorages of Broome and Darwin must be used to unload mackerel taken in the Kimberley Zone and that the Catch and Disposal Records will be managed by the Broome Regional Office and through a memorandum of understanding with the Northern Territory.
- Only permit holders in a particular Zone will be permitted to unload mackerel in that Zone.
- The benchmark date for criteria to enter the fishery is 3 November 1997. A criteria period of seven years will be taken into account, from 1 November 1990 to 31 October 1997.
- Access to the Kimberley Zone mackerel fishery will be based on the following criteria:
    - Must have caught a minimum of one tonne each year for four out of seven years from 1 November 1990 to 31 October 1997; or
    - Must have caught an average of a minimum of 1 tonne a year over seven years from 1 November 1990 to 31 October 1997,

as shown on the returns submitted to the Department.

- Access to the Pilbara Zone mackerel fishery will be based on the following criteria:
    - Must have caught a minimum of 750 kg each year for four out of seven years from 1 November 1990 to 31 October 1997; or
    - Must have caught an average of a minimum of 750 kg a year over seven years from 1 November 1990 to 31 October 1997,

  as shown on the returns submitted to the Department.
- Access to the Gascoyne-West Coast Zone mackerel fishery will be based on the following criteria:
    - Must have caught a minimum of 500 kg each year for four out of seven years from 1 November 1990 to 31 October 1997; or
    - Must have caught an average of a minimum of 500 kg a year over seven years from 1 November 1990 to 31 October 1997,

  as shown on the returns submitted to the Department.
- The proportion of each boat's catch to the sum of the catches of all boats that meet the criteria will determine that boat's proportional access to the fishery.
- Each zone of the fishery will be unitised, with the unit value being derived from the TACC for the Zone.
- The following conversion rates will be used when assessing the landed weight of product for criteria for access to the mackerel fishery:
    - Whole weight = head/gutted weight (kg) x 1.176
    - Whole weight = gutted/gilled weight (kg) x 1.048
    - Whole weight = fillet weight (kg) x 1.608
- At the commencement date of the Interim Management Plan a minimum proportion of five per cent of the units in the zone of the fishery must be held before an operator can fish in the fishery. Any new operators in the fishery must hold a minimum unit holding of ten per cent of the units to operate in the fishery.

- A person must not sell, deal in or purchase any mackerel taken from the fishery unless the fish were taken by a person who holds a permit in the fishery.
- The number and value of units will be specified on the permits.
- No auxiliary boats/dories are to be used in the Gascoyne-West Coast or Pilbara Zones of the fishery.
- Dories will be allowed in the Kimberley Zone of the fishery.
- A person fishing from an authorised boat in the fishery must not use a reel other than a manually powered reel to set, haul or pull gear.
- Carrier boats are not to be used in the Mackerel Fishery.
- The Department is to negotiate with the Commonwealth to exclude bycatch of mackerel in other adjacent Commonwealth Managed Fisheries and to provide separate advice to the Minister on this issue.
- Completion of research logbooks will be a compulsory requirement for all permit holders.

The following process needs to occur before the Interim Management Plan can be finalised:

1. Drafting of legislation will take place;
2. Ministerial signature will be sought on the legislation and the Minister may require some further public consultation;
3. Depending on whether more consultation is required, final Ministerial signature will be sought after further consideration;
4. The Interim Plan will be gazetted in the Government Gazette;
5. The Interim Plan will be tabled in Parliament;
6. Ratification of existing catch records will be undertaken;
7. Applicants will be invited to apply for a permit in the fishery;
8. Access will be granted to those who meet the criteria for access to the fishery;
9. Appeals for access will be heard;

10. Access to the fishery finalised and permits showing the units of entitlement issued; and
11. Total Allowable Commercial Catch determined for each zone and extent of entitlement determined from unit value.

If you have any further questions or wish to receive a copy of the MIAP Final Report (Fisheries Management Paper No.164) please phone Kristy Saville on 9482 7223.

P P Rogers

EXECUTIVE DIRECTOR

5 December 2002

Appendix 7. Press release distributed to media on the 5th December 2002 regarding implementation of the mackerel Interim Management Plan.

MINISTER FOR AGRICULTURE, FORESTRY
AND FISHERIES

MEDIA STATEMENT

Attention: News Editor/Chief of Staff

5/12/02

Spanish mackerel to be protected under new management plan

Western Australia’s Spanish mackerel fishery will receive future protection under a new Interim Management Plan.

Under the new plan, to take effect on January 1, 2004, professional fishers will have to be licensed to fish for mackerel and will be allocated a quota.

The introduction of the interim management plan follows recommendations from a Ministerial Independent Advisory Panel and the Department of Fisheries.

Fisheries Minister Kim Chance said the decision to change the fishery from ‘open access’ was supported by the majority of commercial and recreational fishers consulted over the past three years by the expert panel.

“Spanish mackerel are vulnerable to overfishing because they school in large numbers at well known locations,” Mr Chance said.

“Research has also shown that commercial catches of mackerel have been at historically high levels and are starting to diminish.

“The introduction of this plan means the fishery will be closely managed to ensure its future sustainability.

“The plan is also consistent with the Government’s strategy to progressively convert open access fisheries to managed fisheries.”

Quota access to the fishery will be determined by a licence holders' previous mackerel fishing history between 1990 and 1997. Catches since then will not be considered by the Department during allocation of quotas.

Mr Chance said the plan involved a fundamental shift in the approach to allocation of entitlement for minor fisheries towards a proportional basis.

Key management details include:

- The fishery will be divided into three zones – Kimberley, Pilbara and Gascoyne-West Coast;
- The legal minimum length of 90cm will remain;
- The season will run for six months;
- The total allowable commercial catch for each zone will be set by the Department of Fisheries following scientific research advice.

The interim plan will run for five years while a management strategy for wetfish is developed under the Integrated Fisheries Management Strategy.

Media Contact: Mike Marren on 9213 6700 or 0428 911 240

Appendix 8. Report to the Mackerel Independent Advisory Panel. Calculation of total allowable effort within each sector of the proposed Western Australian mackerel fishery.

DRAFT ONLY

Calculation of total allowable effort within each sector of the proposed Western Australian mackerel fishery

Michael Mackie
Fisheries Research Division
WA Marine Research Laboratories
PO Box 20,
North Beach 6020.

14th May 2001

Note that this document contains **CONFIDENTIAL** information. Note also that the conclusions provided in this document are not based on a formal stock assessment and may be altered as new information becomes available. In particular, the conclusions should be re-examined once the number of vessels within each sector and their respective proportion of the Total Allowable Effort have been finalised, in order to determine if the fishing effort allotted each vessel is feasible.

Introduction

Two main options have been proposed by Fisheries WA for managing fishing effort within the Western Australian mackerel fishery. Under the second of these options (Option 2) fisher who meets certain criteria to show past reliance on mackerel will be allotted a number of days during which they can fish for mackerel. The number of days will depend on each fishers' catch relative to other fishers and will be a proportion of the total number of days that all boats combined can fish for mackerel. The aim of the report presented here was to determine the total number of days (total allowable effort) that can be fished for mackerel within each sector of the proposed management plan. Note that some of the data used in this report is confidential and should not be released outside the Agency.

Methods

Because Spanish mackerel (*Scomberomorus commerson*) is the main target species and comprise the bulk of mackerel catches, all estimates of total allowable effort (TAE) were based on catches and effort reported for this species. This data was obtained from catch and effort records (CAES) provided by industry to Fisheries WA. Data for *S. commerson* captured by all methods except purse-seine and charter were used in analyses because they and other mackerel are recorded under a number of capture methods. However, purse-seine may erroneously include small mackerel species such as blue mackerel and charter catches are not considered within the proposed management plan.

The TAE within each sector of the mackerel fishery was estimated by two methods. The first was derived from estimates of Average Catch and Catch Per Unit Effort (CPUE), whilst the second was estimated from the average days fished by the main mackerel fishing vessels within each sector.

Data was divided into the three regions of the WA coast as per the proposed management plan. These are: the Kimberley sector (East of 121 degrees Longitude to the NT border), Pilbara sector (114-121 degrees Longitude), and Gascoyne sector (112 – 113 degrees Longitude north of 27 degrees Latitude). These are also referred to as Zones 1 –3 (respectively) in the proposed management plan.

Method 1. TAE derived from Average Catch and CPUE

The relationship between these parameters is:

TAE = Average Catch / CPUE

A number of methods were used to estimate Average Catch and CPUE because little information is available to assess the status of *S. commerson* stocks in WA, and the catch and effort database lacks detail and is considered unreliable. The alternate methods were therefore designed to provide contrasting estimates for these parameters and in turn a range of values for TAE. These values reflect several 'risk' scenarios in terms of sustainability of mackerel stocks from which the most appropriate TAE in each sector was determined.

1) Estimation of Average Catch

Estimates of Average Catch required for determining TAE were obtained from analysis of historic catches of this species. Firstly, periods of high and low catches were used to determine periods of relatively high and low exploitation levels within each sector. Depending on the data these periods covered from 3 to 9 years, being made as long as possible in order to dampen the affect of abnormal years or cycles (Table 1, Figure 1). Whilst indicative of high and low catch levels these periods do not necessarily reflect periods of high and low fishing effort. The mean of catches within these periods was subsequently used in assessment of high and low risk scenarios.

Secondly, the Average Catch for the long-term period covering cycles of both high and low catches was used to estimate a medium level of exploitation within each sector (Table 1, Figure 1). This was used in assessment of a medium risk scenario. Finally, the projected catch for 2001 based on catch trends from 1996 to 2000 was also included in assessments as an indicator of recent trends. Linear regression was used in the latter analyses as this provided a good fit to the data for the Gascoyne and Pilbara Regions, and may provide a more realistic projected catch for the Kimberley (assuming that the recent trend of decreasing catches will bottom out).

Table 1. Time periods used to determine Average Catches of *S. commerson* within each zone. The relative level of catch and risk associated with each time period are also shown.

Zone	Time Period (inclusive)	Relative Catch Level	Relative Risk Level
Kimberley	1991-1999	High	High
Pilbara	1983-1985	High	High
Gascoyne	1981-1987	High	High
Kimberley	1983-1990	Low	Low
Pilbara	1986-1990	Low	Low
Gascoyne	1991-1995	Low	Low
All	1980-2000	Average	Medium
All	1995-2000	2001 (projected)	Recent trend

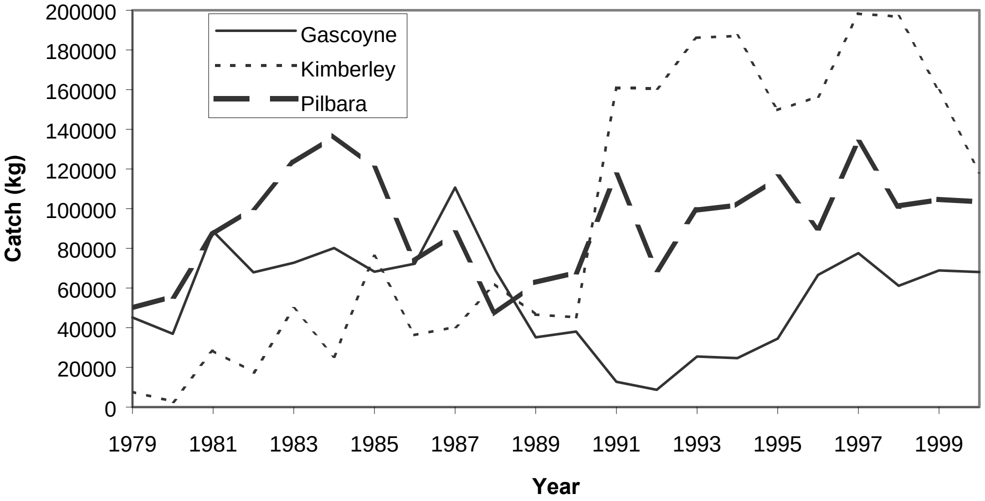


Figure 1. Annual catches of Spanish mackerel within each region.

2) Estimation of CPUE

The average number of days fished by each vessel was estimated from the CAES database, with a 'day' comprising from 1-24 hours fishing time on a particular date when Spanish mackerel (*S. commerson*) were landed. Catches of this species by individual boats were determined as detailed above.

Catch per unit effort (whole weight (kg) per day) was subsequently estimated using two separate data sets. The first of these included data for all vessels that recorded annual catches of *S. commerson* of more than 500 kg in the Gascoyne and 1000 kg in the Pilbara and Kimberley sectors. This eliminated vessels with incidental catches of mackerel but still included vessels for which mackerel were not the main target species. As a consequence, there is uncertainty in the effort data for mackerel as it is often mixed with effort used to catch other species of fish. Despite this, the CPUE of these vessels may be more representative of the overall mackerel fishing fleet. Calculation of CPUE was determined after pooling the individual catch and effort of all vessels meeting the catch criteria each year from 1980 to 2000 (mean number of vessels each year was 15, 14 and 7 in the Gascoyne, Pilbara and Kimberley sectors, respectively).

The second data set was based on those vessels known to target and land high catches of mackerel during the mackerel season. Most of these vessels are currently operating in the fishery and their fishing methods have been validated by FWA research staff. In some cases the vessels were no longer involved in the mackerel fishery or their effort data had not been validated. The effort data for these vessels was only utilised if the CAES database indicated that other fish species comprised a minor proportion of the catch during the mackerel season and/or the other fish species had been taken by methods that limit the likelihood of catching mackerel. This minimised uncertainty in the estimates of mackerel fishing effort. Further, data was only used for those vessels that had recorded mackerel catches over several consecutive years. With these considerations, this second data set included CPUE information for 17 vessels within the three zones, for varying time periods from 1978 to 2000. As this information was as reliable as possible it was used in assessment of a low risk strategy.

Method 2. TAE determined from the average effort of the main mackerel fishing vessels currently operating within the fishery.

Total allowable effort in each sector of the fishery is estimated as:

TAE = $\sum$ (average # of fishing days of each of the main mackerel fishing vessels during the time criteria period of Option 1)

Estimation of TAE using this method is relatively straightforward compared to the calculations in Method 1, and in theory results in the same limits to fishing pressure that would occur under Option 1 of the proposed management plan (whereby the main mackerel fishing boats have exclusive and unlimited access to the mackerel fishery).

As with Method 1, estimates of fishing effort were based on the number of days in which *S. commerson* were captured. The identity of the main mackerel fishing vessels was based on those meeting the time and catch criteria or Option 1 (catches of at least 10 t, 3.5 t and 1 t in Zone 1-3, respectively, for four of the seven years from 1/11/90 to 31/10/97). The annual number of days fished by these vessels for *S. commerson* varied substantially (Figures A1-A3), with the average number of days for each vessel estimated for the period of the time criteria (1990-1997). This was relevant to the comparison with Option 1 and provides a reasonable estimate of catch per day over the history of the fishery (Figures A4-A6).

Results and Discussion

Average Catch

Average Catches of *S. commerson* in the Kimberley sector have historically ranged from about 48 to 173 t, with a long-term average of 100 t and a projected catch of about 130 t in 2001 (Table 2). The latter prediction should be viewed with caution because the linear trend in catches since 1998 suggest that catches could fall below 90 t (Figure 1). Nevertheless, the relatively stable catches prior to 1998 and the trend in CPUE in recent years (Figure A6) indicate that catches should not fall to such levels. Average Catches in the Pilbara sector have ranged from 68 to 127 t, with a long-term average of 95 t and a predicted 2001 catch of 106 t. Average Catches in the Gascoyne are noticeably lower, ranging from 21 to 80 t, averaging about 57 t and likely to be around 67 t in 2001.

CPUE

Catch per unit effort of the main mackerel fishing vessels was substantially higher than that estimated for the wider mackerel fishing fleet (Tables 3 and 4). These differences of 16, 44 and 26% for the Kimberley, Pilbara and Gascoyne sectors (respectively) are probably due in part to the more refined expertise of the dedicated mackerel fishers. Changes in efficiency of the fleet (and hence CPUE; Figure A7) may also have contributed to the differences since estimates of CPUE for the wider mackerel fleet are more influenced by data from earlier years.

TAE

i) Kimberley Sector

In the Kimberley sector the two methods of deriving CPUE have comparatively minor impact on TAE estimates (Table 5, Figure 2). This is due to the low number of operators other than the main fishers that catch more than 1000 kg of mackerel in this region each year. Risk scenarios are thus determined from the average of the two methods, providing high and low estimates of TAE for this sector of about 630 and 175 days, with a medium of about 365 days and a prediction for 2001 of about 480 days. This compares favourably with the estimate of 437 days based on the combined effort of the main vessels as per Option 1 of the management plan (Table 6).

ii) Pilbara Sector

In contrast to the Kimberley data, estimates of TAE for the Pilbara sector differ considerably depending on which CPUE data set is used (Table 5, Figure 2). This is mainly because the main mackerel vessels have a much higher CPUE than the wider mackerel fleet, probably due to the influence of low annual CPUE during the 1980's. It is only in the past few years that CPUE of the wider mackerel fleet has approached that of the main vessels. As a consequence of their relatively high CPUE, the estimated TAE's of the main vessels are substantially lower than that of the wider fleet. These are therefore the preferred estimates given the lack of information on mackerel stocks. They are also more relevant because the proportion of the mackerel catch by the main vessels has increased in the past decade to a point where relatively few mackerel are now captured by other vessels. The high and low risk estimates of the Pilbara TAE are therefore about 610 and 330 days, with a medium of about 460 days, a 2001 prediction of 510 days, and a combined total for the main vessels (as per Option 1) of about 520 days (Table 6).

iii) Gascoyne Sector

Estimates of TAE for the Gascoyne sector also vary with the CPUE data in a similar fashion to the Pilbara (Table 5, Figure 2). However this is less due to decreased CPUE of the wider mackerel fleet during the 1980's (Figure A7), and more likely because of the greater proportion of fishers in the Gascoyne who do not specifically target mackerel. The effort data for these vessels is therefore likely to be over-inflated if capture of the odd mackerel whilst targeting other fish equates to a mackerel fishing day. Thus, for the same reasons given in the Pilbara, the TAE estimated using the CPUE of the main vessels is considered more prudent and relevant. The high and low risk estimates of the Gascoyne TAE are therefore about 870 and 230 days, with a medium of about 620 days, a 2001 prediction of 730 days, and a combined total for the main vessels of 270 days (Table 6). Of note is the relatively low combined total of the main vessels, which is similar to the lower bound and may be indicative of the low fishing pressure that would occur in this sector under Option 1 (although CPUE of the main vessels could increase due to decreased fishing competition).

Also of note are the relatively high upper and medium bounds and predicted 2001 TAE compared to the other sectors. Again, this is probably due to the higher number of vessels with over-inflated effort (and hence lower CPUE) that contribute to the annual catches of mackerel in this sector. This is particularly so during periods of higher catches such as during the 1980s and since 1996 when more vessels were involved in the fishery.

Conclusion

Because there is little information on the status of mackerel stocks in WA a cautious approach needs to be taken in determining TAE required for Option 2 of the proposed mackerel management plan. This is particularly so for the Kimberley sector where catches have dropped significantly over the past few years. This may not be mirrored in the CPUE for this area, although CPUE is based on unreliable effort data and hence may be misleading. Nevertheless, decreased catches of other mackerel species further indicate that fishing effort was down in 2000, and the pattern of mackerel abundance also appeared to be unusual during this year. Therefore, a TAE that reflects a downward trend in catches, but not as severely as indicated since 1998 is recommended:

- **Recommended TAE for the Kimberley sector: 440 days** (approximately the predicted 2001 estimate based on CPUE of the main vessels, as well as the combined effort of the main vessels that will be included in Option 1 of the management plan).

In contrast to the Kimberley, catches and CPUE in the Pilbara sector have remained fairly steady in recent years. However, the effort required to match the large catches of the early 1980s is considered too high given the drop in catches during subsequent years (this is probably due in part to movement of vessels out of the fishery but also because of decreasing catch rates – Figure A5). Given that the current trend in catches is approaching this high level, some caution is therefore justified:

- **Recommended TAE for the Pilbara sector: 500 days** (slightly lower than the predicted 2001 estimate and the combined effort of the main vessels in order to arrest the upward trend).

Estimated TAE for the Gascoyne is likely to be over-inflated by low and unreliable CPUE, particularly during periods of high catches. High, medium and predicted estimates of TAE are therefore considered excessive for this sector. Current catch trends, which are increasing towards the high levels of the 1980s confirm the need for caution because catches and catch rates dropped significantly during the early 1990s (Figure A4):

- **Recommended TAE for the Gascoyne sector: 450 days** (a value between the excessive medium and upper bounds and the lower bound. Note that the wide variation in TAE estimates make it difficult to determine a fair and sustainable figure.

This highlights the need for ongoing adjustment of the recommended TAEs as fresh and/or updated information becomes available).

Table 2. Average Catches of *S. commerson* within each sector during high, low and long-term catch periods and also predicted catches based on linear regression analyses of recent catches (1996-2000).

Sector	**Time Period (inclusive)**	**Relative Catch Level**	**Mean Annual Catch (kg)**
Kimberley	1991-1999	High	172 800
Kimberley	1983-1990	Low	47 700
Kimberley	1980-2000	Long-term	100 200
Kimberley	2001	Predicted	131 300
Pilbara	1983-1985	High	126 800
Pilbara	1986-1990	Low	67 900
Pilbara	1980-2000	Long-term	95 200
Pilbara	2001	Predicted	105 900
Gascoyne	1981-1987	High	80 100
Gascoyne	1991-1995	Low	21 200
Gascoyne	1980-2000	Long-term	56 600
Gascoyne	2001	Predicted	66 700

Table 3. Mean CPUE (kg of whole weight per day) of *S. commerson* by the main mackerel fishing vessels within each sector. The individual catch and effort data for all vessels was pooled prior to estimation of the overall CPUE. Data obtained from 1978 to 2000 with data for individual vessels extending from 7 to 22 years.

Sector	**# of vessels**	**Mean CPUE**
Kimberley	5	300.2
Pilbara	7	208.5
Gascoyne	5	91.9

Table 4. Mean CPUE (kg of whole weight per day) of *S. commerson* by mackerel fishing vessels within each sector. Data is based on those vessels catching more than 1000 kg in the Kimberley and Pilbara, and more than 500 kg in the Gascoyne. The individual catch and effort data for all vessels was pooled prior to estimation of the overall CPUE. Mean # of vessels is the average per year.

Sector	Mean # of vessels	Mean CPUE
Kimberley	7	251.8
Pilbara	14	120.7
Gascoyne	15	67.8

Table 5. Total allowable effort (TAE) for mackerel fishing vessels within each sector. Data were estimated by dividing average catch by the catch per day of *S. commerson* within each sector (as per Method 1in the Methods section). High, medium and low refer to risk scenarios for data estimated from periods of high, average and low catches, respectively. '2001' refers to TAE for 2001 based on catch trends over the previous 5 years. TAE-main vessels refers to data estimated using the CPUE of the main mackerel fishing vessels within each area. TAE-all vessels refers to data estimated using the CPUE of all vessels catching more than 1000 kg of *S. commerson* in the Kimberley and Pilbara sectors, and more than 500 kg in the Gascoyne sector.

	TAE-main vessels				TAE-all vessels			
Sector	**High**	*Med*	**Low**	**2001**	**High**	**Med**	**Low**	**2001**
Kimberley	576	334	159	437	686	398	189	521
Pilbara	608	457	326	508	1051	789	563	877
Gascoyne	872	616	231	726	1181	835	313	984

Table 6. Total annual days fished for *S. commerson* by the main mackerel fishing vessels within each sector. Data were obtained by pooling the mean number of days fished by each vessel from 1990 to 1997 (as per Method 2 in the Methods section).

Sector	# vessels	Total days fished
Kimberley	5	437
Pilbara	8	516
Gascoyne	7	271

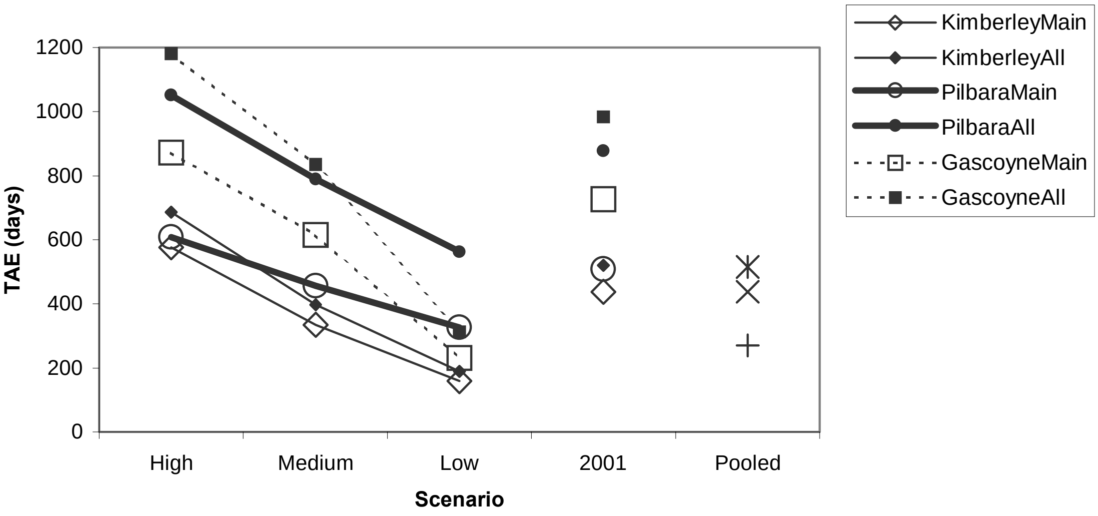


Figure 2. Total allowable effort for mackerel fishing vessels within each sector of the fishery. (1) Data calculated by dividing catch by CPUE: (i) using CPUE derived from the main mackerel fishing vessels (Kimberley Main, etc) and CPUE derived from all vessels meeting the minimum tonnage criteria (Kimberley All, etc), and (ii) using catch data calculated from high, medium and low catch scenarios, and from predicted 2001 catches. (2) Data estimated as the combined total number of fishing days of all vessels that meet the time and tonnage criteria in Option 1 of the proposed management plan (x; Kimberley sector. *; Pilbara sector. +; Gascoyne sector).

Appendices

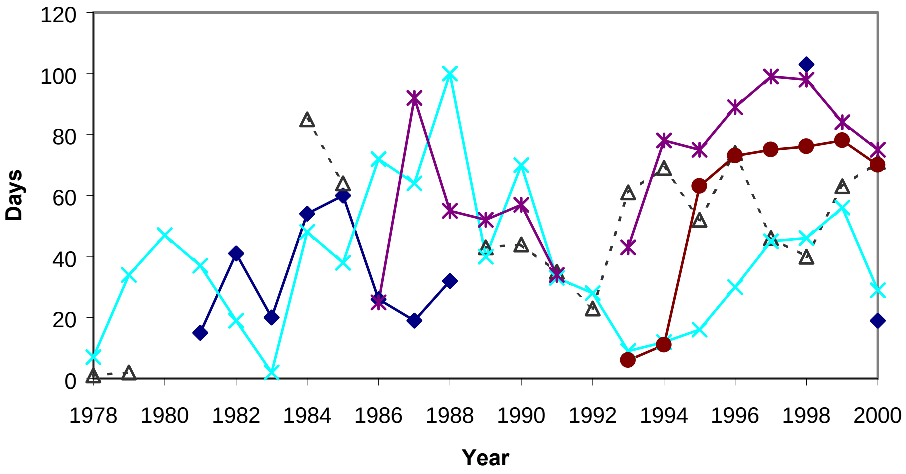


Figure A1. Number of days fished for *S. commerson* by the main mackerel fishing vessels in the Gascoyne sector. Number of vessels = 6.

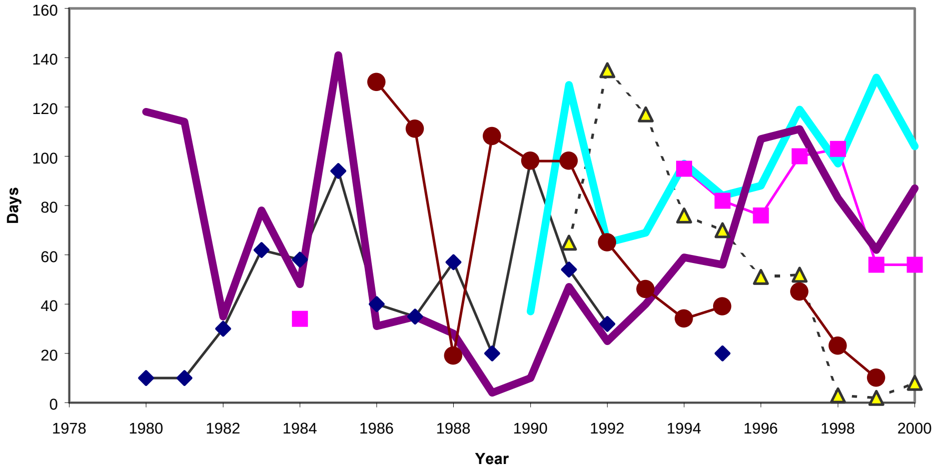


Figure A2. Number of days fished for *S. commerson* by the main mackerel fishing vessels in the Pilbara sector. Number of vessels = 8.

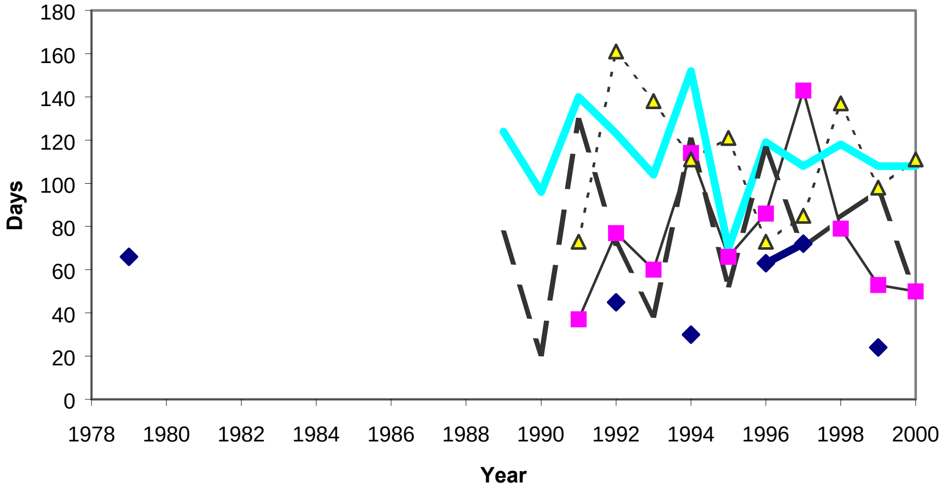


Figure A3. Number of days fished for *S. commerson* by the main mackerel fishing vessels in the Kimberley sector. Number of vessels = 5.

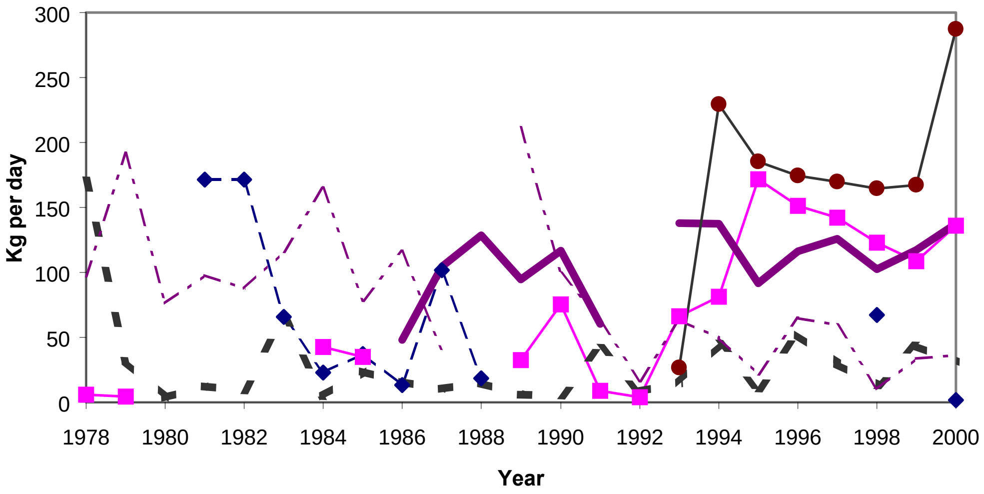


Figure A4. Catch per day of *S. commerson* by main mackerel fishing vessels in the Gascoyne sector. Number of vessels = 6.

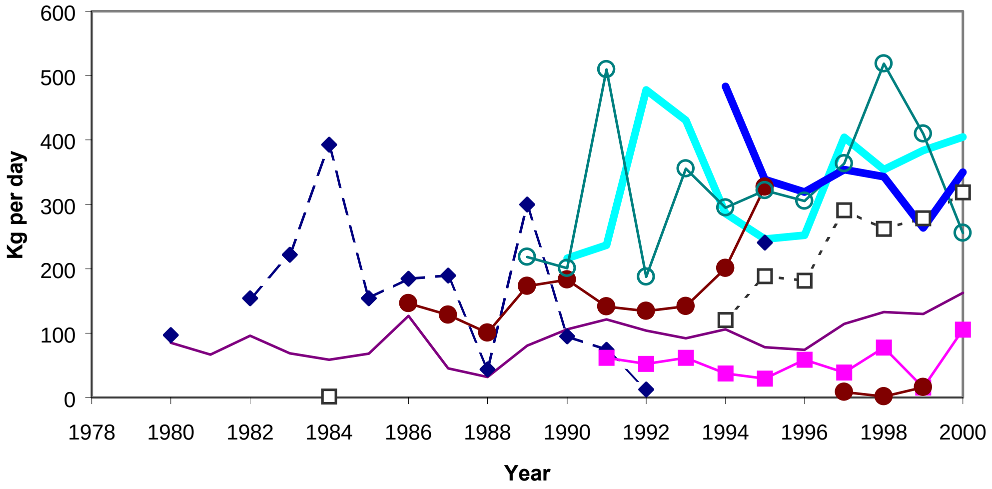


Figure A5. Catch per day of *S. commerson* by main mackerel fishing vessels in the Pilbara sector. Number of vessels = 8.

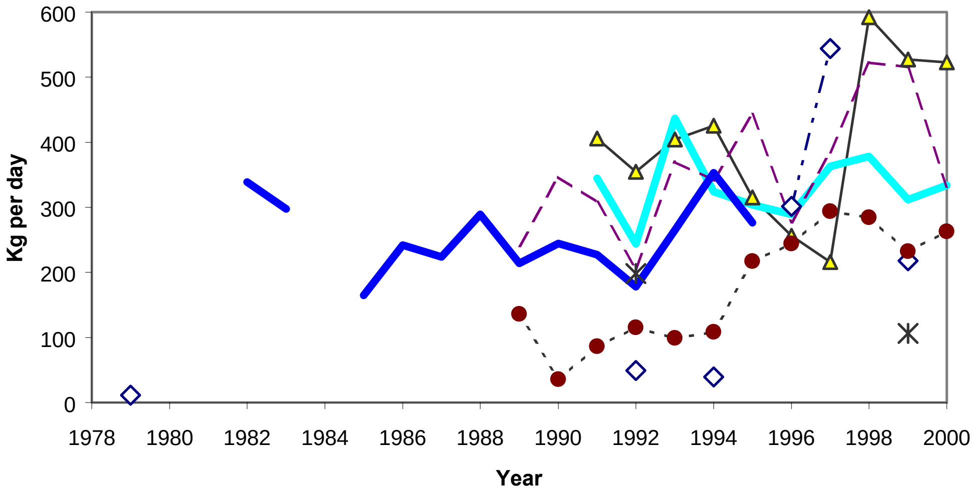


Figure A6. Catch per day of *S. commerson* by main mackerel fishing vessels in the Kimberley sector. Number of vessels = 7.

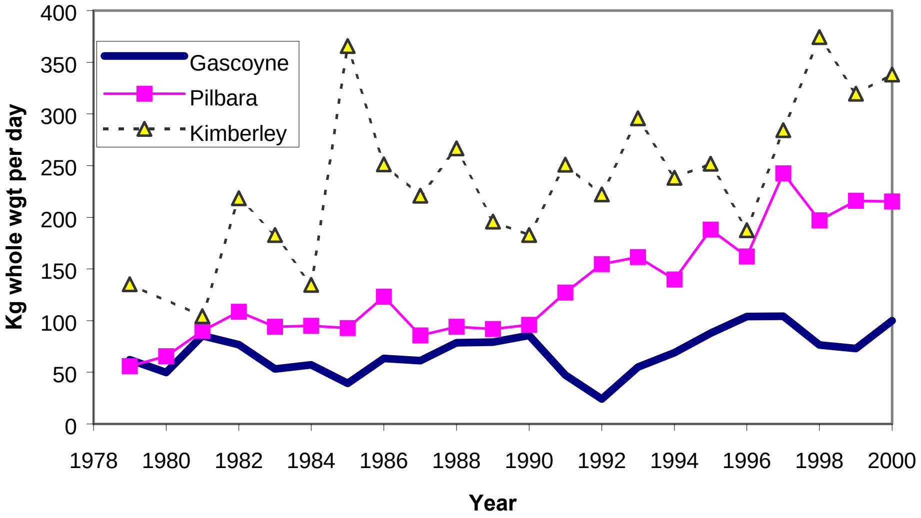
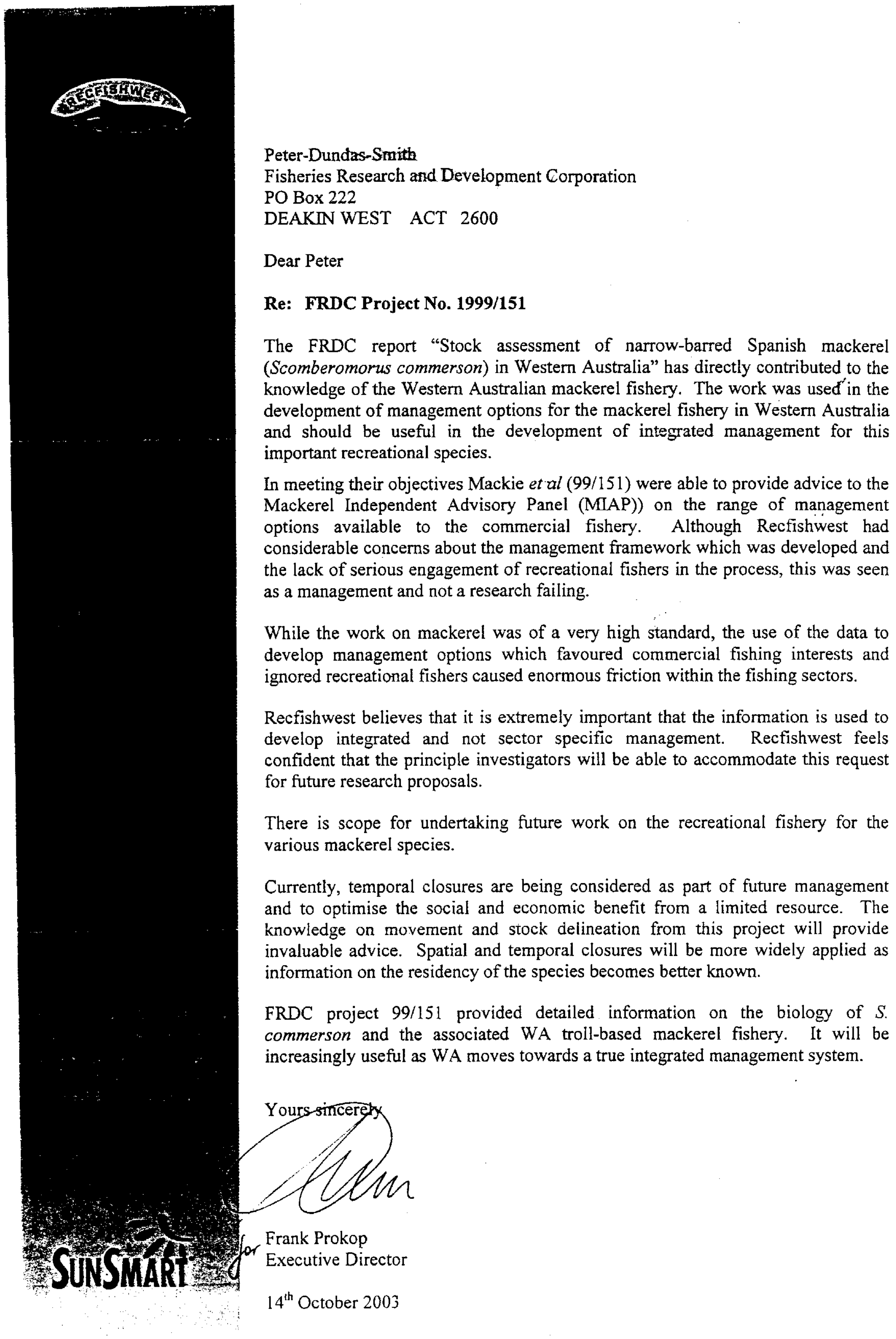


Figure A7. Catch per day of *S. commerson* by mackerel fishing vessels that caught at least 1000 kg whole weight of *S. commerson* in the Kimberley and Pilbara sectors and at least 500 kg whole weight of *S. commerson* in the Gascoyne sector.

Appendix 9. Responses of two beneficiaries to the final report.



RECFISHWEST

Peter-Dundas-Smith
Fisheries Research and Development Corporation
PO Box 222
DEAKIN WEST ACT 2600

Dear Peter

Re: FRDC Project No. 1999/151

The FRDC report "Stock assessment of narrow-barred Spanish mackerel (*Scomberomorus commerson*) in Western Australia" has directly contributed to the knowledge of the Western Australian mackerel fishery. The work was used in the development of management options for the mackerel fishery in Western Australia and should be useful in the development of integrated management for this important recreational species.

In meeting their objectives Mackie *et al* (99/151) were able to provide advice to the Mackerel Independent Advisory Panel (MIAP)) on the range of management options available to the commercial fishery. Although Recfishwest had considerable concerns about the management framework which was developed and the lack of serious engagement of recreational fishers in the process, this was seen as a management and not a research failing.

While the work on mackerel was of a very high standard, the use of the data to develop management options which favoured commercial fishing interests and ignored recreational fishers caused enormous friction within the fishing sectors.

Recfishwest believes that it is extremely important that the information is used to develop integrated and not sector specific management. Recfishwest feels confident that the principle investigators will be able to accommodate this request for future research proposals.

There is scope for undertaking future work on the recreational fishery for the various mackerel species.

Currently, temporal closures are being considered as part of future management and to optimise the social and economic benefit from a limited resource. The knowledge on movement and stock delineation from this project will provide invaluable advice. Spatial and temporal closures will be more widely applied as information on the residency of the species becomes better known.

FRDC project 99/151 provided detailed information on the biology of *S. commerson* and the associated WA troll-based mackerel fishery. It will be increasingly useful as WA moves towards a true integrated management system.

Yours sincerely

for Frank Prokop
Executive Director

14th October 2003

SUNSMART

Department of Fisheries
Government of Western Australia

Fish for the future

Fisheries Research and Development Corporation

Re: FRDC Project No. 1999/151

To whom it may concern

The above FRDC report "Stock assessment of narrow-barred Spanish mackerel (*Scomberomorus commerson*) in Western Australia" has directly contributed to the management of the Western Australian mackerel fishery.

In meeting their objectives Mackie *et al* (99/151) were able to provide advice to the Minister for Fisheries (through the Commercial Fisheries Management Program, industry members and the Mackerel Independent Advisory Panel (MIAP)) on the range of effective management options available to the commercial fishery. As a result, the *Mackerel Fishery (Interim) Management Plan 2004* (the Plan) for the Western Australian commercial mackerel fishery is due to commence in 2004.

The principle reason for the Minister's decision to implement the Plan for the commercial mackerel fishery was based on recommendations from the Department of Fisheries Research Division (based on FRDC projects 99/151 and 98/159) including:

- Commercial catches have been at historically high levels in Western Australia but have been decreasing in the Kimberley;
- There are no significant levels of mixing of Spanish mackerel across long lengths of coastline (eg. from Exmouth to Broome). However, despite limited alongshore mixing of juveniles and adults, genetic relationships are thought to span broader regions. Hence the effects of fishing in one zone are likely to have flow-on affects in the other zones;
- It would be inappropriate to manage the fishery by size limit alone, as mortality of released fish is likely to be high, as is mortality due to sharks, both of which may add substantially to the fishing pressure on the fish;
- This species schools in large numbers, in well-known locations, and hence can be captured in large quantities. Catch rates of schooling pelagic species can remain high until stock sizes have decreased significantly. This makes it vulnerable to fishing pressure; and
- Long-term commercial mackerel fishers had raised concerns about the mackerel stocks.

3RD FLOOR, THE ATRIUM
168 ST. GEORGES TERRACE
PERTH WESTERN AUSTRALIA 6000
TELEPHONE (08) 9482 7333
FACSIMILE (08) 9482 7389
WEBSITE http://www.fish.wa.gov.au
Email: headoffice@fish.wa.gov.au
ABN 55 689 794 771

This information was crucial in the approval of the Plan and continues to be crucial in the development of the Plan. The Research Division provided data from FRDC project 99/151 to the MIAP who in turn used the data as a basis for making its recommendations on possible management approaches. For example, when the MIAP was considering a Total Allowable Effort (TAE) arrangement, the Research Division provided concise data upon which it could base a decision.

FRDC project 99/151 complemented FRDC project 98/159 on the stock structure of *S. commerson* in WA, NT and QLD waters. The main beneficiaries of these projects will be fisheries managers, Management Advisory Committees, commercial and recreational fishers who target *S. commerson* along the WA coast and ultimately the Western Australian community with an interest in the long-term health of the fishery.

Future management and development of the WA mackerel fishery will be enhanced by:

Spanish mackerel

- Implementation of a fishery specific logbook to improve the monitoring of *S. commerson* catch and effort information (due to commence in 2004);
- Use of more sophisticated models that incorporate age structure information to enable more reliable examination of population dynamics and simulation of management options;
- Increased detail of *S. commerson* biology and ecology. Specific information that will provide more certainty in modelling and management decisions include: fecundity of larger females, habitat of *S. commerson* when not abundant on the coast, further understanding of the extent of spawning, site fidelity by individuals, and more rigorous validation of temporal periodicity of opaque zone formation in adult and juvenile otoliths.
- Further analysis of mortality. For example, with M this may be done by developing a more appropriate equation for tropical/subtropical species from a subset of the data used by Hoenig (1983) (N. Hall, Centre for Fish & Fisheries Research, Murdoch University, *pers. comm.*).
- Examination of the relationship between abundance of recruits and subsequent catches (i.e. stock-recruitment index). There is potential to do this with assistance from recreational fishers in the Dampier region.

Grey mackerel

- Provision of knowledge relevant to ecologically sustainable development requirements through collection of data on by-product and by-catch species in the troll fishery (noting that this fishery exports product to SE Asia). Data for grey mackerel (*S. semifasciatus*) is of particular importance since Grey mackerel are becoming an increasingly important component of the Spanish mackerel troll catch in WA. This species is only targeted for periods of one to two months each year and their importance varies between region and year. This species is valued on the export market and has become more vulnerable to fishing activities in recent years as fishing methods for this species are refined and become more widely known. Further information on the distribution and abundance of this species may also enhance the mackerel fishery.

The work undertaken in FRDC project 99/151 has provided the basis for developing the Total Allowable Commercial Catch (TACC) management system for the mackerel fishery in WA. The initial setting of a TACC in each zone of the WA fishery will be based on historical catch data and with the implementation of a fishery-specific log book in 2004, trends in catch rates following implementation of the mackerel management plan, will form the basis for TACC setting in the future.

Currently, temporal closures are being considered under the Plan, with advice from the Research Division, as a means of reducing management costs for the fishery (by reducing compliance and operating costs). Spatial and temporal closures will be more widely applied as information on the residency of the species becomes known.

FRDC project 99/151 provided detailed information on the biology of *S. commerson* and the associated WA troll-based mackerel fishery, which has, and will continue, to be used to ensure the sustainability of this fishery.

As is current practise for all fisheries management arrangements in WA, Research Division advice in relation to any studies into mackerel species, will be taken into consideration in developing and revising management arrangements for the fishery. The information gained through FRDC 99/151 has greatly enhanced the knowledge base within the Research Division with regard to mackerel. It has provided the basis for management advice, which will underpin mackerel management as the fishery moves to 'managed fishery' status.

Yours sincerely

Kristy Saville

FISHERIES MANAGEMENT OFFICER

14 August 2003