BIOLOGY AND STOCK ASSESSMENT OF WESTERN AUSTRALIA'S COMMERCIALLY IMPORTANT SHARK SPECIES

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Contents

96/130 Biology and stock assessment of Western Australia's commercially important shark species.

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Objectives:

- To determine the distribution of nursery areas for juvenile whiskery sharks.
- To determine the stock structure of commercially important shark species.
- To determine biological parameters for adult dusky whaler sharks and to assess methods of measuring changes in breeding stock via recruitment to the fishery.
- To determine growth, movement, exploitation and mortality parameters for whiskery sharks, and to refine these parameters for juvenile dusky whalers.
- To determine the catch, size distribution and impact of all users of the commercially important shark resources in Western Australia.
- To improve the modelling techniques used, and the accuracy of the assessments produced, for the commercially important shark resources in southern Western Australia.

Non-technical summary

The purpose of this project was to improve the stock assessment advice available to the managers of the shark fishery in the southern half of Western Australia. The fishery is currently valued at approximately $7 million per year to fishers. Decreasing catch rates of dusky and whiskery sharks, and the introduction of reductions in fishing entitlements, required Fisheries WA to be able to accurately assess the status of key commercial shark species. A previous FRDC funded project had begun the collection of data and developed population modelling techniques. The current FRDC funded project collected biological and life-history data that was identified as critical to accurate stock assessment by modelling in the previous project. It also developed more complex population modelling techniques, introducing risk analysis to the whiskery shark assessment.

An extensive sampling was undertaken using specialised gear to determine the location of the nursery areas for whiskery sharks. This sampling provided a large amount of information on areas in which juvenile whiskery sharks do not occur. Only ten small juveniles were caught in 200 sets, indicating that the nursery is not in the area normally fished by the gillnet fleet. Instead, the nursery areas may be in deep water, or in unfishable habitat in continental shelf waters.

The Stock structure of gummy, whiskery and dusky sharks was also investigated by analysis of the elemental composition of their jaw cartilage. Analysis of this data

suggests that these sharks are mainly resident to the areas of their capture. This result is in good agreement with tag-recapture data collected for whiskery and dusky sharks.

Information was gathered on the diet, reproduction, and age and growth of dusky sharks. This species grows to a large size, reaching over 330 cm fork length (FL). The adults eat mostly bony fishes, but also cephalopods and elasmobranchs. Growth is slow, with juveniles growing 9 cm a year on average. However, there is considerable variation in growth rates between individuals. Males mature at 240 cm fork length, and females mature at 250 cm FL. These sizes at maturity correspond to ages at maturity of 22 years and 24 years in males and females, respectively. Females produce litters of approximately 12 young, but the periodicity is unknown.

Commercial catch rates of neonate dusky sharks were examined over the period of the project. These data were combined with data from a previously FRDC funded project, to provide data on changes in recruitment strength. There was no significant trend in the abundance of neonates over the five years, indicating that recruitment of dusky sharks remains stable, despite many years of fishing. Environmental factors did not appear to have a consistent impact on catch rates of juvenile dusky sharks in the south-west of Western Australia, but catch rates in some areas varied significantly depending upon the phase of the moon.

Research on the growth of whiskery sharks based on vertebral ageing and tag-recapture data indicated that growth after birth is rapid, but slows quickly as maturity is reached. The age at maturity was estimated to be 4.5 years in males and 6.5 years in females. The maximum age was estimated to be 15 years. Tag-recapture data was also used to investigate the movements of whiskery sharks. Most whiskery sharks were recaptured within 50 km of their point of release, but some moved as much as 400 km. Most individuals were recaptured in less than a year, and the longest time at liberty was over 1600 days.

Catch data supplied by commercial fishers, photographic surveys of commercial fish catches, and on-board observers, identified a number of fisheries in which there is significant shark bycatch that has the potential to impact upon shark fisheries in the southern half of Western Australia. This section of work also demonstrated that Fisheries WA's catch and effort database system is not currently capable of handling the diversity of sharks that are captured in the northern half of the state.

An age and sex structured model was developed for the stock assessment of the whiskery shark population. The model took account of the biology and life history of this species, and used fisheries data as an index of abundance. The results of the assessment indicate that total biomass is currently at 39% of virgin, and the mature biomass is currently at 23% of virgin. These levels indicate that the fishery has caused a significant decline in the population. Risk analysis indicates that future catches need to be kept below 190 tonnes (live weight) to meet the biomass target set by the management advisory committee. The model also indicates that the stock would fail if future annual catches are consistently in excess of 280 tonnes before 2011.

A novel demographic model was developed for the dusky shark fishery to incorporate life history data and tag-recapture data. The tag-recapture data was used to calculate the age-specific fishing mortality of juvenile dusky sharks. The results of the model indicate that current levels of fishing mortality in the gillnet fishery should not result in significant stock decline. However, if the mortality of larger fish (not targeted by the gillnet fishery) is greater than 4% then the model indicates that the stock will decline.

1. BACKGROUND

The gillnet fisheries of southern Western Australia exploit stocks of several species of sharks. The fishery on the south and lower-west costs were brought under formal management in 1988, while the fishery on the mid-west coast is currently being brought under management. The value of shark production in these two fisheries was approximately $6.8 million in 1993-94. In response to concerns about the status of the stocks a research project funded by the FRDC (project number 93/067) commenced in 1993 to provide biological data on dusky whaler, whiskery, gummy and to a limited extent thickskin sharks needed in order to develop population models for each of these species. This project has been very successful in providing an understanding of the biology of the life history stages targeted (ie juvenile dusky whalers, adult whiskery and gummy sharks) through biological sampling of commercial catches, feeding, age, growth, etc) and tagging (movements, stock structure, level of exploitation, mortality, etc.). The current project has also provided information on the fishery for these stocks through observation of commercial fisheries practices, experimental netting to determine size selectivity parameters for major species, refinement of the catch and effort data provided by all fishers, and collation of assessment techniques and age-structured population models to facilitate the development of future management options and the identification of areas where further research is required.

The stock assessments generated by FRDC Project 93/067 indicated that whiskery sharks are over-exploited, and that stocks of the other two species are fully exploited and may become over-exploited if catches are not reduced. The Western Australian Demersal Gillnet and Demersal Longline Fishery Management Advisory Committee (WADGDLFMAC) have used the stock assessment and population models to set out biomass targets for the major stocks and explore management options. As a result, effort levels in the fishery have been significantly reduced resulting in the commencement of a restructuring of the industry. While the models used in the preliminary assessments have been based on the best available data, more detailed data is now required to improve the accuracy of the forecasts for ongoing management. The proposed project will gather critical biological information while continuing to collect industry data to ensure that stock responses to management changes can be forecast with reasonable accuracy.

Assessment of the age-structured population models indicates that biological data (age, growth, reproduction, distribution, etc) from life-history stages not caught by the commercial fishery (eg adult dusky whalers and juvenile whiskery sharks) is essential to providing more accurate information for the modelling process. A proportion of the current information used in the models for these life-history stages currently comes from overseas studies of the species, or from closely related species. The assessment of dusky whalers would also be significantly improved by obtaining a better understanding of the impact that fishing has on the breeding stock.

The tagging of dusky whalers during FRDC Project 93/067 has begun to provide good data on the movement and level of exploitation on the juveniles of this stock. Tag returns from this project will continue to be monitored to provide the maximum amount of information possible since it is expected that the tags will persist in the population for many years to come. Whiskery and thickskin sharks were also tagged as part of FRDC Project 93/067. For whiskery sharks, however, low stock abundance and the low proportion of live animals in the nets has meant that insufficient numbers have been tagged to provide useful results. With field work on commercial vessels to continue during the proposed project it will be possible to continue to tag whiskery sharks, while using only minimal additional resources. The increased number of tagged animals will allow for more precise estimates of movement, exploitation and mortality parameters, as well as providing more vertebral specimens for age validation.

The age-structured population models developed as part of FRDC Project 93/067 assume that whiskery, gummy and dusky whalers in Western Australian waters represent single stocks. A recent study by the CSIRO Division of Fisheries has found that the gummy sharks on the south coast of WA are the same unit stock as those caught in the south -east shark fishery, but that those on the lower east coast are a separate stock. The stock structure of whiskery, thickskin and dusky whaler sharks has not been investigated in Western Australian waters. Information on the stock structure of these species needs to be obtained to validate the assumptions of the models.

The WADGDLFMAC has expressed concerns that the shark stocks are being exploited by non-gillnet fishers. These non-gillnet fishers have no management restrictions, while the gillnet fishers have had significant effort reductions. The non-gillnet sectors that catch most of the sharks are line-based fisheries. In particular the Western Australian Rock Lobster fishers catch significant amounts of large dusky whaler and thickskin sharks on line attached to lobster pots. These catches impact on the breeding stock of these species, a fact not accurately reflected in the current population models (which assumes all catches by gillnet). To provide information on the impact of non-gillnet fishers data on the catch and size composition of sharks needs to be collected from these sectors of the industry.

2. NEED

The stocks of key commercial sharks in the southern half of Western Australia are either over-exploited, or fully exploited, requiring catch reductions to ensure future sustainability. As a result significant reductions in effort levels have been introduced into the gillnet fishery on the south and lower west coasts. Effort reductions in the gillnet fishery on the mid-west coast will be introduced in the near future. Further effort reductions are likely in the future to achieve biomass targets set by the Western Australian Demersal Gillnet and Demersal Longline Fishery Management Committee. Given the state of the shark fisheries it is important that more accurate stock assessments, and models to analyse future management options, are developed. This will enable the effectiveness of the current management arrangements to be assessed and the need for further changes to be determined.

Information relevant to the ongoing sustainable management of the shark stocks is not only important to enable the continued viability of the commercial shark fisheries, but also for the conservation of shark stocks due to the recognition of their importance as apex predators in the marine ecosystem and their role in maintaining biodiversity.

3. OBJECTIVES

- To determine the distribution of nursery areas for juvenile whiskery sharks.
- To determine the stock structure of commercially important shark species.
- To determine the stock structure of whiskery, thickskin and dusky whaler sharks in Western Australian waters.
- To determine biological parameters for adult dusky whaler sharks and to assess methods of measuring changes in breeding stock via recruitment to the fishery.
- To determine growth, movement, exploitation and mortality parameters for whiskery sharks, and to refine these parameters for juvenile dusky whalers.
- To determine the catch, size distribution and impact of all users of the commercially important shark resources in Western Australia.
- To improve the modelling techniques used, and the accuracy of the assessments produced, for the commercially important shark resources in southern Western Australia.

4. METHODS

4.1 Nursery areas for whiskery sharks

Nursery areas for *Furgaleus macki* were investigated by sampling for juveniles using specially designed and constructed gillnets. Small juvenile *F. macki* are rarely caught by commercial fishers, which necessitated the use of specially designed nets. The nets were constructed of three panels of monofilament gillnet, one each of 5.1 cm, 7.6 cm, and 10.2 cm stretched mesh. Each panel was approximately 50 m in length.

The nets were attached to nets used by commercial gillnet vessels during routine field work undertaken by Fisheries WA research staff on these vessels. In addition some fishers agreed to use the nets as part of their normal operation for several weeks in 1997 and 1998. This allowed a greater range of areas to be assessed for the presence of juvenile *F. macki*.

The location, depth and date of capture of all juvenile *F. macki* caught in the net were recorded. Whole specimens were retained and stored frozen until examined. Fork length (FL, the straight line distance from the snout to the fork in the tail) and total length (TL, straight line distance along the centre-line of the body to a point perpendicular to the tip of the caudal fin, with the caudal fin in its natural position) were measured to the nearest centimetre, and the sex recorded. Stomach contents were recorded for diet analysis and a sample of vertebrae removed from the neck region for age and growth analysis.

The location of all sets of the small mesh gillnets, and the location of captures of juvenile *F. macki* were plotted on a GIS to assist in identifying nursery areas.

4.2 Stock structure of commercially important shark species

Elemental analyses and allozyne electrophoresis[1] were used to investigate the stock structure of the commercially important sharks.

Elemental analyses of the jaw cartilage from commercially important shark species from various locations was undertaken to determine if the pattern of element accumulation is specific to the location of capture. The assumption on which the technique is based is that trace elements are irreversibly deposited in the hard tissues (or, at least, have very long residence times) during the lifetime of the shark, and the accumulation revealed by analysis provides an integrated history of an individual fish directly related to the environment in which it has lived. Thus there is the possibility that the elemental accumulation is specific to the area in which the shark has lived, and that different elemental compositions for groups from different locations could be taken as evidence that the sharks form essentially non-mixing groups which presumably are spatially separated for a substantial amount, if not all, of their lives.

A previous study has shown the elemental composition of the jaw cartilage of gummy shark from three locations on the Western Australian coast to be specific to the location of capture of the fish (Edmonds *et al.* 1996). The study also related correlations between various elemental concentrations and discussed them in terms of changes that occur as the fish ages/grows and the cartilage calcifies. Sodium and potassium were suggested to act as counter ions to sulphate groups of the keratan and chrondroitin components of the proteoglycans and results in loss of sodium and potassium with calcification.

The current study explores further the work carried out by Edmonds *et al.* (1996), on the elemental composition of shark jaw cartilage and the ability of this technique to assess the stock structure of shark species.

4.2.1 Elemental analysis of shark jaw cartilage

Dusky, whiskery and gummy sharks were obtained from catches of commercial fishermen. The sharks were stored frozen at –20°C before being thawed in the laboratory and the jaws excised and substantially cleaned by the removal of adhering skin. A disc (12 mm diameter) was punched from the center of one mandible of the lower jaw with a titanium punch (so constructed with the object of limiting possible contamination of the sample to titanium). Remaining skin was removed from the upper and lower surfaces of the disc by scraping with glass knives. The thickness of each disc was then measured with a micrometer screw-gauge before the samples were transferred to acid-washed, weighed glass vials and dried at 40°C to constant weight (jaw weight). The discs were then placed into Teflon beakers and digested by heating (hotplate, 105°C) in redistilled nitric acid, which was subsequently removed by evaporation. The pale yellow residues were then dissolved in 10% redistilled nitric acid for analysis by ICP-AES using Daiani-Seiko JY48PV or JY38P instrumentation and by ICP-MS using a Yokogawa PMS 2000

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[1] During the second year of the project a PhD student based at the University of Western Australia undertook to use allozyne electrophoresis to further investigate the stock structure of whiskery, dusky and thickskin sharks. The required samples were collected, however during analyses the student became seriously ill. Thus analyses remain incomplete at the time of writing this report. Once the results become available, they will be forwarded to FRDC as an Appendix to this report.

instrument. B, Ca, K, Mg, Mn, Na, P, S, Sr were determined by ICP-AES and, in addition, Zn and Ba were determined by ICP-MS.

4.2.2 Statistical analysis of the elemental composition of shark jaw cartilage

Factor analysis was carried out to determine the differences in elemental composition of the cartilage samples from the locations sampled in the study. Factor analysis was performed using the *Factor Analysis* module of Statistica. The resultant factor scores 1 and 2 and the factors, location, sex and shark length were examined using analysis of covariance (ANCOVA). The two factors in the analysis were location and sex and were treated as fixed and orthogonal factors in the analysis. Shark length was used as a covariate in the analysis due to its variation with the age. Type III sums of squares were used to test the hypothesis of differences in the population means.

4.3 Biology of adult dusky whalers

4.3.1 Collection of specimens

Six collecting trips for adult dusky sharks were made aboard the *RV Flinders*, Fisheries Western Australia's 20 m research vessel (Table 4.1). Sampling was carried out using heavy drumlines baited with frozen Australian salmon. Each drumline consisted of an anchor, float, and one or two large shark hooks (Mustad 13/0 - 15/0 shark hooks) suspended from the float. Drumlines were normally set each afternoon and retrieved the following morning.

Table 4.1: Details of sampling trips for mature dusky sharks aboard the *RV Flinders*.

Trip no.	Dates	Sets	Location
1	22/8/96 – 9/9/96	16	North West Shelf, Ningaloo, Shark Bay
2	16/3/97 – 22/3/97	10	Rottnest Island, Abrolhos Islands
3	11/7/97 – 29/7/97	14	North West Shelf, Ningaloo, Shark Bay
4	24/3/98 – 4/4/98	10	Abrolhos Islands
5	25/9/98 – 5/10/98	9	North West Shelf, Ningaloo, Shark Bay
6	17/3/99 – 24/3/99	8	Abrolhos Islands

Sharks caught on drumlines were either kept for biological analysis, or tagged and released. Animals that were kept for biological analysis were identified, sexed, and measured - total length (TL, distance along the longitudinal axis of the body from the snout to a point perpendicular to the rear tip of the caudal fin, with the caudal fin in its natural position) and fork length (straight line distance from the snout to the fork of the caudal fin). The stomach fullness was scored on a scale from 0 to 4 (0, empty; 1, up to a quarter full; 2, one quarter to one half full, 3, one half to three quarters full, and 4, three quarters full to full) by suspending the stomach vertically and observing the proportion of the stomach containing food. Stomach content data were analysed using the occurrence method (Hyslop 1980). The contents of each stomach was recorded to the lowest possible taxon. Animals that were observed to have regurgitated during capture and handling were noted. Samples of vertebrae were removed from the region anterior to, or below, the first dorsal fin. Vertebrae were stored frozen until processed.

The clasper length of males (the distance from the tip of the clasper to its junction with the pelvic fin) was measured, and the presence of calcification of the clasper cartilage determined. Males were considered mature if the claspers were elongate and fully calcified. The presence or absence of substantial quantities of spermatozoa stored in the epididymis was determined by making a transverse cut across the midsection of the kidney.

To determine the stage of maturity for females the condition of the uterus was divided into six stages based on the criteria given by Lenanton *et al*. (1990) and Simpfendorfer and Unsworth (1998a) (Table 4.2). Females were considered mature if they had a uterus stage of 3 or greater. The number of embryos in the uteri of pregnant specimens was counted and their total lengths measured. The number of yolky ovarian follicles (yolky ova) was counted and the diameter of the largest was measured to the nearest millimetre to give maximum ova diameter (MOD). Where no obvious yolky ova existed, MOD was not measured.

Table 4.2: Uterus stage index used for dusky sharks.

Uterus stage	Description
1	Uterus very thin along its entire length, empty, immature.
2	Uterus very thin along most of its length, but enlarge posteriorly, empty, maturing.
3	Uterus enlarged along its entire length, empty, mature.
4	Uterus containing yolky eggs, no visible embryos on eggs, post-ovulatory.
5	Uterus containing visible embryos, pregnant.
6	Uterus enlarged and flaccid, appears to have just given birth, post partum

4.3.2 Preparation and reading of vertebrae

Samples of vertebrae were removed from the region anterior to, or below, the first dorsal fin. Vertebrae samples were stored frozen until processed. After defrosting, excess tissue was excised and individual centra separated before immersion in 5% sodium hypochlorite solution to remove any remaining flesh. Immersion times in hypochlorite varied with the size of the vertebrae and the age of the solution. Cleaned centra were dried in an oven at 50°C. Clean, dry centra were embedded in fibreglass resin and sectioned longitudinally using a diamond tipped blade. Sections were ground on wet and dry paper until approximately 300 microns thick. Micro-radiographs were made by placing sections on top of a light-proof bag containing Structrix D4 FW scientific grade film (Agfa) and exposing them in a soft x-ray machine (Hewlett-Packard Faxitron 43805) at 25 kV and 2 ma for 90 seconds. Films were developed using standard developing procedures.

Counts of the growth bands (defined as a dark band and the adjacent light band) were made for each of the three micro-radiographs from each individual. Counts were made without knowledge of the size, sex, or previous results for the individual. Three readers were used to make counts, reading each of the three micro-radiographs from each specimen. The birth mark was identified on each micro-radiograph and the number of full bands formed beyond this were counted. Each micro-radiograph was assigned a qualitative readability on a scale: 0, unreadable; 1, banding pattern visible but impossible to interpret accurately; 2, bands observable, but several difficult to interpret; 3, bands observable, but 1 or 2 difficult to interpret; 4, banding pattern unambiguous. The consensus count for each individual for each reader was determined by taking the count that matched in at least two of the three micro-radiographs. If the counts for each of the three micro-radiographs were all different that individual was excluded from analysis for that reader. The same approach was used to determine the final number of bands of a specimen, with a consensus reached between the final counts for each reader.

A von Bertalanffy growth curve was fitted to the length at age data by minimising the sum of squares. A modified form of the von Bertalanffy equation was used to ensure that the curve passed through the known size at birth:

$$L_T = L_0 + \left(L_\infty - L_0\right)\left(1 - e^{-KT}\right)$$

where L_0 is the length at time zero (size at birth = 75 cm FL), L_T is the length at time T, L_∞ is the asymptotic length, and K is the Brody growth coefficient. The time at length zero (t_0) was calculated by substituting $L_T = 0$ and solving for T. Only specimens which had a readability of two or higher were used in the length at age analysis.

Verification of age and growth parameters was undertaken by comparing the results of the vertebral ageing with the results of the analysis of tag-recapture (see 5.6.2).

4.4 Recruitment index for dusky whalers

4.4.1 Collection of field data

To produce a recruitment index for *C. obscurus* in south-western Australia data from the current FRDC project and FRDC project 93/067 were combined. In the current project the area in which neonate *C. obscurus* are born (Albany to Kalbarri) was divided into five regions (Table 4.3) and the catch rates of *C. obscurus* with open umbilical scars obtained from observations by Fisheries WA research staff on commercial gillnet vessels. Each region was sampled during periods when historical data suggested that neonate *C. obscurus* are most common. The main focus of the sampling was on the Albany, Augusta and Bunbury regions where the fishery for neonate *C. obscurus* in the autumn months (March to May) produces the majority of the annual catch.

Table 4.3: **Sampling regions and months for *Carcharhinus obscurus* with open umbilical scars aboard commercial gillnet vessels in south-western Australia. Geographic blocks refer to 1 degree statistical blocks used in the Fisheries WA Catch and Effort Statistics System (eg 3513 has it's NW corner at 35°S, 113°E).**

Region	Geographic blocks	Months sampled
Albany	3516 (part), 3517, 3518	March, April and May
Augusta	3416, 3516 (part), 3415, 3514, 3414	March, April and May
Bunbury	3314,3315,3215 (part)	March, April and May
Fremantle	3215,3115	July
Geraldton	2813, 2814, 2714	November

In the previous FRDC project similar fishing periods were used. The same vessels were used in each region each year for the current project to remove bias due to changing skippers and vessels. Each location was sampled for a minimum of nine days each month, normally either side of the full moon when commercial fishers report the best catch rates.

4.4.2 Data analysis

Data could not be collected from the two most northern sites (Fremantle and Geraldton) in all years, due mostly to changes in management policy in the West Coast Demersal gillnet and Demersal Longline Interim Managed Fishery. As a result the analysis was undertaken on the three southern sites that were sampled for three months each year. The data were analysed using a Generalised Linear Model (GLM) in Statistica using the Visual Generalized Linear Models module. The model included the categorical factor year, and the continuous factors depth and moon phase. Depth data were collected on board the vessel during sampling, while moon phase data were obtained from the US Navy moon phase tables (US Naval Observatory, Washington DC, 20392-5420).

Catch rate data for *C. obscurus* with open umbilical scars caught on sampling trips were calculated as the number of individuals caught per 1000 km hours of gillnetting (one kilometre hour is equivalent to one kilometre of gillnet set for one hour). Before analysis in the GLM catch rate data were ln (x+1) transformed. Catch rate data from 1994, although available, were not included in the analysis because not all *C. obscurus* were recorded during field work and so would have biased the results from this year.

To investigate if the recruitment index (the year factors from the GLM) was a reflection of the overall annual catch rates of *C. obscurus* in the gillnet fishery, it was correlated with annual catches. If the recruitment index from the current study was strongly correlated with the catch in zone 1 of the fishery then annual catches could be used as a longer index of recruitment (since 1975 as opposed to since 1995). However, if the recruitment index was not correlated with commercial catch rates then only a size year index would be available for further analysis.

The recruitment index (either the short-term index from sampling neonates from the commercial catch, or the commercial annual catch rates) were correlated with sea surface temperature and Leeuwin Current strength (as indexed by the Fremantle sea level). Both of these environmental factors have been shown to influence the catch rates of other marine organism along the Western Australian coast. Sea surface temperature data were obtained from the Reynold's temperature data (Reynolds and Smith, 1994). Fremantle sea level data were obtained from the National Tidal Facility, Flinders University of South Australia.

4.5 Biology of whiskery sharks

The study of the biology of *F. macki* was undertaken in three parts - a tag-recapture study for movement and growth data, analysis of vertebrae for age and growth data, and analysis of stomach contents for diet data. The reproductive biology was investigated as part of FRDC Project 93/067.

4.5.1 Tag-recapture study

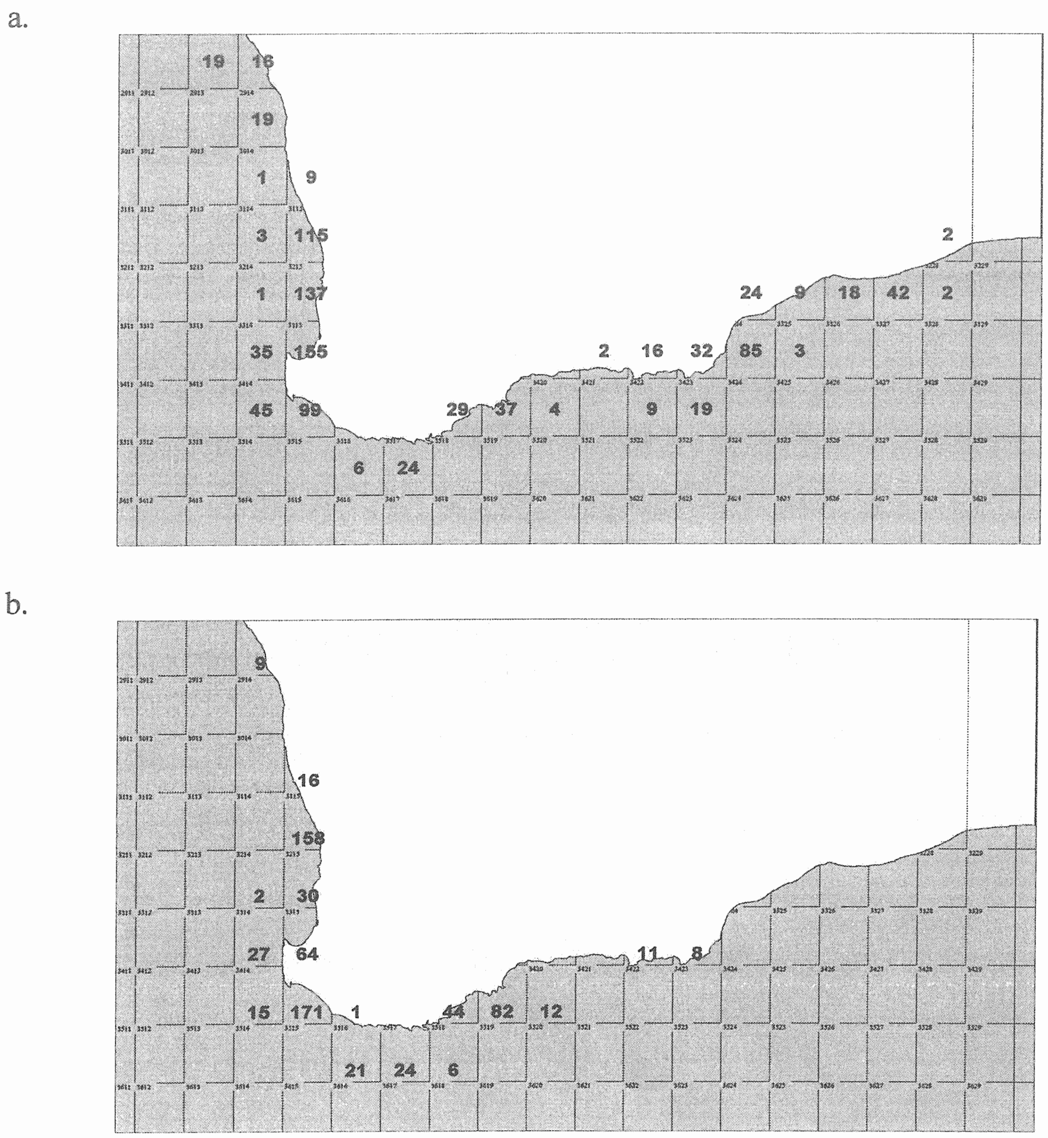
4.5.1.1 Data collection

Tagging of *Furgaleus macki* was continued from FRDC Project 93/067 to provide greater numbers of sharks for analysis. Tagging methods were the same for the current project, and details can be found in the Final Report for Project 93/067.

Tagging during the current project occurred during all trips on commercial gillnet fishing vessels. Tagging trips were conducted between Kalbarri (27°42'26"S, 114°10'14"E) on the west coast and Eucla (31°42'51"S, 128°53'02"E) on the south coast (Figure 4.1). Sampling trips were undertaken throughout the year, but were concentrated in Autumn (when staff were on vessels as part of the dusky whaler recruitment index study) and spring.

Tag returns were received from both commercial and recreational fishers. Recapture data requested included the date and location of capture, length, tag number, species, sex, and condition of the shark and tag. In order to standardise the information provided by commercial fishers, operators were provided with reporting forms and tape measures, and instructed on how to accurately measure and record data.

Figure 4.1: Distribution of tagging effort (number of gillnet sets for which Fisheries WA research staff were on board to tag sharks) during (a) FRDC Project 93/067, and (b) FRDC Project 96/130, by one degree statistical block.



4.5.1.2 Analysis of tagging data

4.5.1.2.1 Movement

To account for movement around the south-west corner of Western Australia a movement algorithm was developed. The algorithm included a number of turning points around the coast (see FRDC project 93/067 Final Report). The location of the turning points were determined such that a shark moving from point to point would remain close to the coast, but not move over land. Based on the release and recapture locations the algorithm calculated the distance from release to the nearest turning point (in the direction of the recapture), the distance from the recapture point to the nearest turning point (in the direction of the release), and the distance between each of the intervening turning points. The minimum "at sea" distance moved was the sum of these three distances.

4.5.1.2.2 Growth

Length data from tag-recaptures were analysed using the method of Francis (1988) that fits a modified form of the von Bertalanffy growth curve using a maximum likelihood technique. This model estimates six parameters - growth rates (g_α and g_β) at two sizes (α and β), standard deviation of the growth increment (ν), mean measurement error (m), standard deviation of the measurement error (s) and contamination probability(p_c). The standard deviation of the growth increment was assumed to be proportional to the time at liberty. The two growth rate parameters can be used to estimate the von Bertalanffy K and L_∞ values:

$$K = -\ln\left(1 + \left(\left(g_\alpha - g_\beta\right)/\left(\alpha - \beta\right)\right)\right)$$

$$L_\infty = \left(\beta g_\alpha - \alpha g_\beta\right)/\left(g_\alpha - g_\beta\right)$$

The value of t_0 was estimated by positioning the von Bertalanffy curve such that $L_0 =$ 22cm FL. Only recaptures for animals that had been at liberty for 60 days or more were used in the analysis.

4.5.2 Age and growth determination using vertebrae

Furgaleus macki were sampled onboard commercial gillnet vessels operating in south-western Western Australia, and from fish markets where the catch was sold, between April 1993 and October 1997. Commercial vessels used 16.5 cm or 17.8 cm stretched mesh gillnets with a height of approximately 2 m and lengths from 3.5 to 7.2 km. Nets were demersal and set for periods from 4 to 24 hours. The majority of specimens were obtained from the commercial nets during normal fishing operations. Samples of smaller *F. macki* were obtained using small mesh gillnets which were deployed from commercial fishing vessels. These nets were constructed to specifically target smaller *F. macki* (<90 cm FL) that were not caught by the larger mesh sizes used by the commercial fishery (see 4.1).

Onboard commercial vessels specimens were sexed, fork length measured to the nearest centimetre, and a section of the vertebral column from the neck region removed. Specimens obtained from fish markets had been partially processed when examined and the only length measure available was partial length (origin of first dorsal fin to dorsal origin of caudal fin). The relationship between partial length (PL) and fork length (FL), with measurements in centimetres is:

$$FL = 18.2 + 1.408PL$$

The removal of viscera, pelvic fins and claspers by fishers meant that the sex of specimens examined in the markets could not be determined.

Vertebrae were stored frozen until processed. After defrosting, excess tissue was excised and individual centra separated before immersion in 5% sodium hypochlorite solution to remove any remaining flesh. Immersion times in hypochlorite varied with the size of the vertebrae and the age of the solution. Cleaned centra were dried in an oven at 50°C. Clean, dry centra were embedded in fibreglass resin and sectioned longitudinally using a diamond tipped blade. Sections were ground on wet and dry paper until approximately 300 microns thick. Micro-radiographs were made by placing sections on top of a light-proof bag containing Structrix D4 FW scientific grade film (Agfa) and exposing them in a soft x-ray machine (Hewlett-Packard Faxitron 43805) at 25 kV and 2 ma for 90 seconds. Films were developed using standard developing procedures.

Micro-radiographs were prepared of three separate centra from each individual and were examined under a dissecting microscope with transmitted light. The radius of vertebrae were measured using an optical micrometer. The relationship between vertebral radius (*S*) and shark fork length (*FL*) was determined by fitting a power curve:

$$FL = uS^{v}$$

where u and v are constants. When the value of v equals one, the relationship is linear.

Counts of the growth bands (defined as a dark band and the adjacent light band) were made for each of the three micro-radiographs from each individual. Counts were made without knowledge of the size, sex, or previous results for the individual. Four readers were used to make counts, reading each of the three micro-radiographs from each specimen. Reader A was a biologist with experience in shark ageing, readers B and C were biologists without experience in shark ageing, and reader D was a laboratory technician with experience in ageing teleost fishes. The birth mark was identified on each micro-radiograph and the number of full bands formed beyond this were counted. Each micro-radiograph was assigned a qualitative readability on a scale: 0, unreadable; 1, banding pattern visible but impossible to interpret accurately; 2, bands observable, but several difficult to interpret; 3, bands observable, but 1or 2 difficult to interpret; 4, banding pattern unambiguous. The consensus count for each individual for each reader was determined by taking the count that matched in at least two of the three micro-radiographs. If the counts for each of the three micro-radiographs were all different that individual was excluded from analysis for that reader. The same approach was used to determine the final number of bands of a specimen, with a consensus reached between the final counts for each reader.

The Index of Average Percentage Error (IAPE) was calculated for the band counts of each reader using the method described by Beamish & Fournier (1981):

$$IAPE = \frac{1}{N}\sum_{j=1}^{N}\left(\frac{1}{R}\sum_{i=1}^{R}\frac{\left|X_{ij} - X_{j}\right|}{X_{j}}\right) \times 100$$

where N is the number of animals aged, R is the number of readings done, X_{ij} is the age of the *j*th animal at the *i*th reading, and X_j is the mean age of the *j*th fish from i readings.

The periodicity of band formation was determined using marginal increment analysis. The distance of the final band, and the penultimate band, from the edge of the centrum was measured using an optical micrometer on micro-radiographs that had clear band patterns and undamaged centrum edges. The marginal increment was taken as the distance from the last band to the edge of the centrum as a proportion of the distance between the last and the penultimate bands. Marginal increments were compared between months of capture.

A von Bertalanffy growth curve was fitted to the length at age data by minimising the sum of squares. A modified form of the von Bertalanffy equation was used to ensure that the curve passed through the known size at birth:

$$L_T = L_0 + \left(L_\infty - L_0\right)\left(1 - e^{-KT}\right)$$

where L_0 is the length at time zero (size at birth = 22 cm FL), L_T is the length at time T, L_∞ is the asymptotic length, and K is the Brody growth coefficient. The time at length zero (t_0) was calculated by substituting $L_T = 0$ and solving for T. Only specimens which had a readability of two or higher were used in the length at age analysis.

4.5.3 Stomach content analysis

Samples of *Carcharhinus obscurus* were collected on-board commercial gillnet vessels operating in Western Australian waters, between April 1993 and May 1998. Commercial shark fishing vessels operate year round using bottom set gillnets with mesh sizes between 16.5 cm and 17.8 cm (stretched). Sampling of the gillnet vessels occurred in all months, but was concentrated in the months from March to May to coincide with the pupping season of *C. obscurus*. In addition to specimens from gillnet vessels a small sample of larger *C. obscurus* was obtained from set lines used on research cruises between September 1994 and July 1997. Sets lines were anchored to the bottom and had one or two hooks (11/0, 13/0 or 14/0 Mustad shark hooks) suspended from a large surface float. Hooks were baited with Australian salmon or shark. Set lines were used to sample continental shelf waters between Cape Naturaliste (33.5°S) and Karratha (20.5°S).

A sub-sample of individuals caught in individual sets was used for stomach content analysis. Animals were sexed and measured (fork length , FL) and the stomach excised. The contents of each stomach were identified to the lowest possible taxon and counted on-board the vessel. Stomach content data were analysed using the occurrence method (Hyslop 1980). Baits from set lines were not included in the analysis of stomach contents

Diversity of the diets was calculated using the Shannon-Weiner Index (H'), and dietary overlap was estimated using the Simplified Morisita Index (C_H) (Krebs 1989). Calculations of H' and C_H were based on the occurrence of the prey groups: Annelid, Crustacean, Cephalopod, Gastropod, Echinoderm, Elasmobranch, Teleost, Reptile, Rock Lobster Bait, and Other.

4.6 Further analysis of dusky shark recaptures

Two thousand one hundred and ninety nine *Carcharhinus obscurus* were released as part of FRDC project 93/067. The methods of tagging, location of releases, months of releases and preliminary analysis are provided in the Final Report of Project 93/067.

Similar methods of analysing the movement data have been employed, however, more detailed analysis of the growth data have been undertaken and the methods are detailed below.

4.6.1 Analysis of growth rates from tag-recapture data

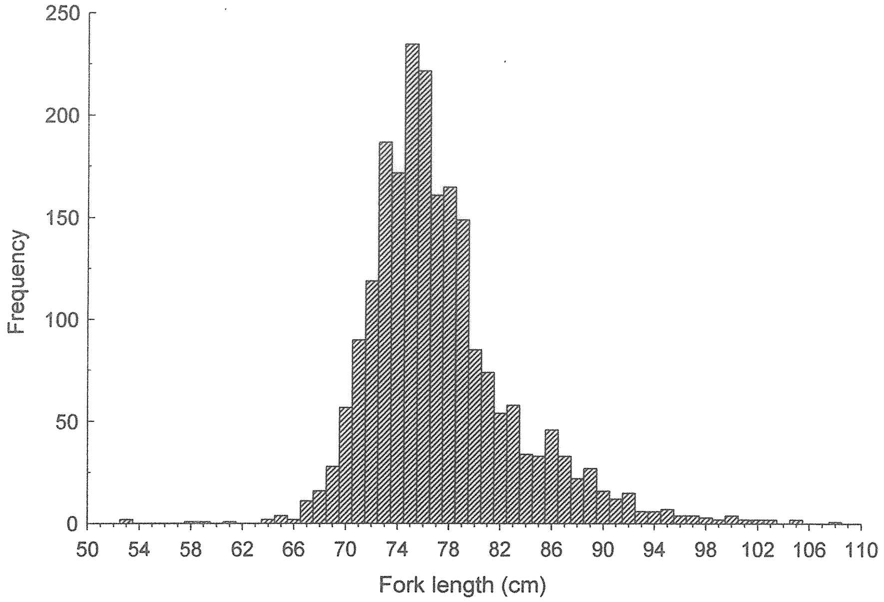
4.6.1.1 Tagging

Neonate and juvenile *C. obscurus* were obtained between March 1994 and June 1996 on-board commercial demersal gillnet vessels operating in south-western Australia. These vessels operate in continental shelf waters in depths from 7 to 100 m. The gillnets are constructed of 16.5 cm and 17.8 cm (stretched) mesh monofilament netting that is 1.5 m to 2.0 m deep. Nets are 3 km to 7 km in length, and are set on the sea floor for periods between four hours and 24 hours.

Individual *C. obscurus* were measured (fork length (FL), the distance from the tip of the snout to the caudal fork) to the nearest centimetre, sexed, examined for the presence of an open umbilical scar, and tagged with an individually numbered Jumbo Rototag (Dalton Supplies, Woolgoolga, New South Wales, Australia) in the first dorsal fin. Approximately one in every three animals was injected with OTC (25 mg kg^{-1}) to mark the centra for age validation studies.

A total of 2155 juvenile *C. obscurus* were released from March 1994 to June 1996 between the Western Australian – South Australian border (129°E) and Kalbarri (29°S) (see FRDC Final Report for project 93/067 Figure 12). Animals released ranged in size from 64 cm FL to 108 cm FL (Figure 4.2). One thousand seven hundred and thirty (78.7%) had open umbilical scars; 1062 were female, 1100 were male and 37 were of unknown sex; 879 were injected with OTC and 1320 were not injected. Information on tag-recaptures, including date, location and length were reported by commercial fishers and research observers operating in the demersal gillnet fishery. Fishers were provided with tape measures and trained how to measure fork length in an attempt to improve the accuracy of recapture data.

Figure 4.2: Size at release for 2155 juvenile *Carcharhinus obscurus* tagged off south-western Australia



4.6.1.2 Analysis

Growth rates of five groups of juvenile *C. obscurus* - males, females, OTC injected, non-OTC injected, and all groups combined - were estimated using four different methods.

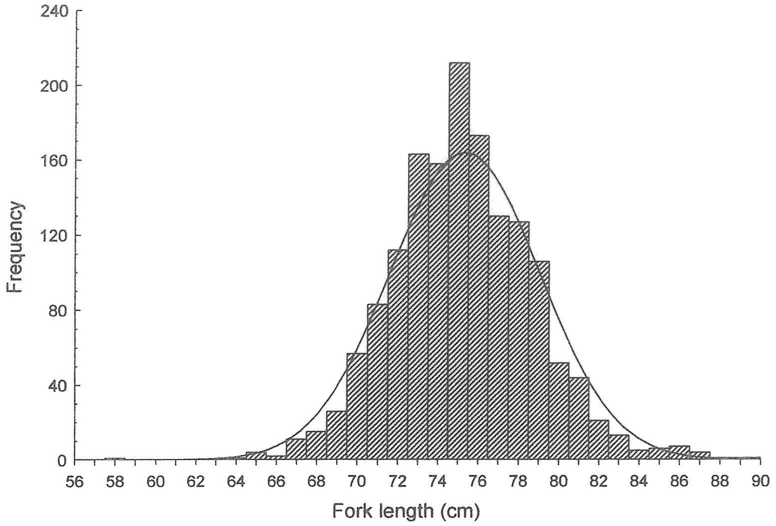
4.6.1.2.1 Gulland and Holt (1959)

The first method used was to construct plots of growth rate by average fork length (Gulland and Holt, 1959). The average fork length was calculated as the average of the fork length at release and recapture. Von Bertalanffy growth parameters are estimated by fitting a line through the data. The slope of the line is equal to $-K$, and the intercept with the x-axis is equal to L_∞. The value of t_0 was estimated by solving the function

$$L_T = L_0 + (L_\infty - L_0)(1 - e^{-KT}) \qquad (1)$$

for the value of T when the value of L_0 is the mean size at birth and $L_T = 0$ cm. The mean size at birth of *C. obscurus* from south-western Australia was estimated by fitting a normal probability function to a size frequency distribution of tagged individuals that had an open umbilical scar (Figure 4.3). From these data the mean size at birth was 75.3 cm.

Figure 4.3: Size frequency distribution of 1537 neonate *Carcharhinus obscurus* from south-western Australia with open umbilical scars. The line represents a normal distribution with a mean of 75.3 cm and a standard deviation of 3.75 cm.



4.6.1.2.2 Fabens (1965)

The Fabens (1965) method involves fitting the non-linear function:

$$L_R = L + (L_\infty - L)(1 - e^{-Kd}), \qquad (2)$$

where L_R is the length at recapture, L is the length at release, and d is the period at liberty. This function was fitted to the data using the non-linear estimation module in STATISTICA. The value of t_0 was estimated as for the Gulland and Holt (1959) method.

4.6.1.2.3 Francis (1988) method

This method uses a maximum likelihood approach to fitting a growth function that includes estimated growth rates (g_α and g_β) at two selected lengths (α and β), the coefficient of variation of growth variability (v), measurement error (assumed to be normally distributed with a mean, m, and standard deviation, s), and outlier probability (p). The estimated growth increment for an individual, i, is given by:

$$\Delta L_i = \left[\frac{\beta . g_\alpha - \alpha . g_\beta}{g_\alpha - g_\beta} - L_i\right]\left[1 - \left(1 + \frac{g_\alpha - g_\beta}{\alpha - \beta}\right)^{\Delta T_i}\right]$$

where L_i is the length at release and ΔT_i is the period at liberty. Francis (1988) suggested several methods of incorporating growth variability into the model. In this paper I assumed that growth variability was proportional to the growth increment.

The likelihood function is:

$$\lambda = \sum_i \log\left[(1-p)\lambda_i + p / R\right],$$

where $$\lambda_i = \frac{\exp\left(-0.5\left(\Delta L_i - \mu_i - m\right)^2 / \left(\sigma_i^2 + s^2\right)\right)}{\left[2\pi\left(\sigma_i^2 + s^2\right)\right]^{0.5}},$$

and R is the range of the observed growth increments.

The Solver function in Microsoft Excel was used to maximise the likelihood value of the model. When fitting the model it was assumed that growth rate decreased with increasing size, thus requiring the constraint $g_\alpha > g_\beta$. Although the growth model allowed the use of six parameters (eight if seasonal growth parameters are included, see Francis (1988)) the significance of using all of the parameters was tested using the Likelihood Ratio Test (LRT). As a minimum, three parameters (g_α, g_β and ν) were used. In addition to these three, the likelihood of the models with varying combinations of the remaining parameters was calculated. Using the LRT, a significant improvement in the model was achieved by the addition (or subtraction) of a parameter if the likelihood increased by 1.92 (Francis, 1988).

Bootstrapping was used to estimate 95% confidence intervals for parameter estimates. New growth increment values were generated by adding randomly selecting points from two normal distributions. The first distribution had a mean of the predicted growth increment and a standard deviation equal to $\nu\mu$, and represented growth and growth variability. The second distribution represented the measurement error and had a mean of m and a standard deviation of s. Five hundred bootstrapped data sets were created using each method and fitted using the technique described above. Ninety five percent confidence intervals were calculated from the 2.5th percentile and the 97.5th percentile of the resulting parameter distributions.

To allow comparison to other methods the von Bertalanffy growth parameters L_∞ and K can be calculated from the parameters of the Francis (1988) model, such that:

$$K = -\ln\left(1 + \left(\left(g_\alpha - g_\beta\right) / \left(\alpha - \beta\right)\right)\right),$$ and

$$L_\infty = \left(\beta g_\alpha - \alpha g_\beta\right) / \left(g_\alpha - g_\beta\right).$$

The value of t_0 was estimated as for the Gulland and Holt (1959) method.

4.6.1.2.4 Length-at-age for neonate releases

The use of length-at-age data is normally associated with ageing studies where the age of an individual is estimated from the number of bands on the vertebrae. Since the majority of animals tagged in this study had open umbilical scars it was possible to directly estimate the age of each of the recaptured animals based on the time at liberty and the rate of healing of the umbilical scar. There is limited information available on the time that it takes for the umbilical scar to close, but most estimates are in the magnitude of 4 to 6 weeks (Bass *et al.*, 1973; Simpfendorfer, unpublished data). Thus, if it is assumed that a shark with an open scar was tagged at the age of three weeks, the age at recapture is the time at liberty plus three weeks. The von Bertalanffy growth function:

$$L_t = L_\infty \left(1 - e^{-K(t-t_0)}\right)$$

was fitted to the data for animals released with open umbilical scars using the non-linear estimation module of Statistica.

4.7 Analysis of the impact of non-gillnet fishing on commercially important sharks species

Three approaches to investigating the catches of sharks by the non-gillnet fishing sector were employed - analysis of compulsory fishing returns, interviews with non-gillnet operators and fisheries compliance officers, and a photographic survey of shark catches.

4.7.1 Analysis of fishery returns and observer data

Data on the catch (kg, live weight) of sharks by fisheries other than the Southern Demersal Gillnet and Demersal Longline Limited Entry Fishery (SDGDLLEF) and the West Coast Demersal Gillnet and Demersal Longline Interim Managed Fishery (WCDGDLIMF) in Western Australia were extracted from Fisheries Western Australia's Catch and Effort System (CAES) for the years 1994/95 to 1997/98.

4.7.2 Photographic surveys

Photographic surveys were used to gather more information on the species composition of the elasmobranch catch in the Pilbara Fish Trawl Fishery and the Shark Bay Prawn and Scallop Trawl Fishery. These fisheries were chosen because Fisheries WA staff were present on vessels undertaking other research. Fisheries WA staff members were provided with disposable cameras and asked to photograph each of the elasmobranchs that were caught. Species were identified from the photographs.

4.7.3 Pilbara longline fishery

Information on the species composition of the Pilbara longline shark fishery was obtained from logbooks supplied by a vessel operating in this fishery between January 1998 and March 1998. The vessel was a Taiwanese longline vessel operating under a Fisheries WA North Coast Shark fishery permit. A set-by-set log was kept of the species composition as a license condition for the operation of this vessel. The operator used Last and Stevens (1994) as a standard identification guide. To provide a further check to the identification of individual animals two Fisheries WA researchers participated in one of the cruises of this vessel. Research staff compiled species composition data separately to the operator of the vessel. The results were compared and consistent difference corrected in the final logbook data. Research staff also instructed the operator on the correct identification of some species during this trip.

4.8 Population modelling

4.8.1 Whiskery sharks

The definitions of the symbols and notation used within equations in this paper are given in Appendix A.

4.8.1.1 Catch and effort data

Catch and effort data for use in the assessment of the status of the *F. macki* population were obtained from compulsory monthly fishing returns supplied by commercial fishers to Fisheries Western Australia. The amount of fishing effort (e.g. type of gear, quantity of gear, and number of days fished) and catches (by weight) of individual species, are reported monthly by one degree geographic blocks. These catch and effort data have been collected since 1975, although in some years compliance to the provision of catch returns was poor. To account for missing fishing returns the values of annual catch and effort were adjusted by the proportion of fishing returns not lodged. This resulted in catch and effort levels being increased by 25% in 1986, 35% in 1987, and 5% in all other years prior to the start of the 1989/90 season. Since the start of the 1989/90 season the provision of returns has been strictly enforced and no corrections were applied to this period.

To determine the level of catch and effort for *F. macki* the data for all vessels that captured sharks between 27°S and 128°E were extracted from the Western Australian catch and effort database. The catch data were corrected for fishers who did not accurately report the species composition of their catch. In most cases these fishers reported their catch simply as "shark" or "other shark". This practice was especially common in the years soon after the introduction of compulsory reporting of data by individual species. A number of quantitative criteria ("other shark" less than half of the total catch for a month, catch not recorded exclusively against one species, and either *F. macki* or *C. obscurus* recorded) were used to determine if a fisher had accurately reported the species composition of his catch. If a fisher's monthly return met these criteria then the record was considered a "good report" for that month. A record not meeting these criteria was considered a "bad report" for the month. The corrected total catch of each species, in each region (regions corresponded to the three management zones of the fishery), was

$$\hat{C}_{s,r} = C_r \cdot C^G_{s,r} / C^G_r \,, \qquad (1)$$

and the total catch of each species over all regions was

$$\hat{C}_s = \sum_r \hat{C}_{s,r} . \tag{2}$$

Since more than one fishing method is used to catch sharks, effort was standardised into gillnet equivalent units. Gillnet equivalent effort was calculated by taking the total shark catch of "good reports" using gillnets and calculating their gillnet CPUE by region

$$CPUE_r^{GN} = C_r^{GN} / E_r^{GN} , \tag{3}$$

and applying this CPUE to the total catch for a region to calculate the gillnet equivalent effort,

$$\hat{E}_r = C_r / CPUE_r^{GN} .$$

The total gillnet equivalent fishing effort was calculated by summing all regional values,

$$\hat{E} = \sum_r \hat{E}_r . \tag{4}$$

The abundance of *F. macki* was assumed to be proportional to the catch rate of the commercial fishery.

In calculating the average annual catch rate of *F. macki*, catch rates were first calculated for each one degree geographic block within the range of the fishery,

$$U_{j,t} = \sum_i C_{i,j,t}^G \Big/ \sum_i E_{i,j,t}^G . \tag{5}$$

Blocks in which there were less than 100 gillnet equivalent effort units had highly variable catch rates and were regarded as to imprecise for inclusion in the analysis. Catch rates were estimated as the average of a whole financial year (referred to from here on as a year) as fishing in many blocks was infrequent. The average annual catch rates (y_t) were obtained by fitting the multiplicative log-linear model,

$$\log\left(U_{j,t}\right) = u + y_t + A_j + e , \tag{6}$$

using the Generalised Linear Models procedure in SAS. The area effect (A_j) weighted the catch rates by the fishable area (depth less than 200m) within each one degree geographic block.

The average annual catch rates of *F. macki* were used to calculate effective effort, a measure of effort which is assumed to remain proportional to the fishing mortality regardless of changes in the distribution of fish and fishing effort (Gulland, 1983),

$$E_t^E = \hat{C}_t / y_t . \tag{7}$$

Effective effort was used as the measure of effort in the model described below. To take account of increasing efficiency in the fishery as a result of better equipment (e.g. larger vessels, GPS, and more effective net configurations), and increasing knowledge, a second calculation of effective effort was made based on the assumption that there was an annual 2% increase in efficiency. The efficiency increase was implemented by multiplying the effective effort by $1.00+(0.02\times t)$, where t is the number of years since 1975.

4.8.1.2 Model structure

The dynamics of the *F. macki* population were modelled using an age and sex structured simulation approach. Dynamics of the stock were assumed to be described by:

$$N_{a+1,g,t+1} = \begin{cases} N_{0,g,t+1} & a = 0 \\ \left(N_{a,g,t} - \hat{C}_{a,g,t}\right).e^{-M} & 1 \geq a > x_g \\ \left(N_{a,g,t} - \hat{C}_{a,g,t} + N_{a-1,g,t} - \hat{C}_{a-1,g,t}\right).e^{-M} & a = x_g \end{cases}, \qquad (8)$$

Recruitment to the fishery was assumed to follow a Beverton-Holt style stock-recruitment relationship,

$$N_{0,g,t} = \frac{S_t}{\left(b + c.S_t\right)}.P'''_{g=f}, \qquad (9)$$

where,

$$S_t = \sum_{a=m}^{x} N_{a,g=f,t}.P'_a.P''_a\,. \qquad (10)$$

The stock-recruitment parameters (b and c) were calculated from the known reproductive characteristics of the species, the virgin recruitment (R^*) and the proportion of R^* that recruits when S_t is 20% of the virgin level (Hilborn et al., 1994),

$$b = \frac{S^*.\left(1 - \frac{(z-0.2)}{(0.8z)}\right)}{R^*}, \qquad (11)$$

and,

$$c = \frac{z-0.2}{0.8\,z\,R^*}\,. \qquad (12)$$

The values of R^* and z were estimated in the model fitting process.

The catch in numbers of each sex, at each age, in each time period were calculated by:

$$\hat{C}_{a,g,t} = N_{a,g,t}.v_{a,g}.F_t, \qquad (13)$$

where the fishing mortality for each time period was:

$$F_t = Y_t / B_t^e, \tag{14}$$

and the exploitable biomass was:

$$B_t^e = \sum_g \sum_a N_{a,g,t} w_{a,g} v_{a,g} . \tag{15}$$

The use of gillnets in the fishery necessitated the inclusion of a vulnerability (selectivity) term in the model. Vulnerability was expressed as a gamma function following the method of Kirkwood and Walker (1986), and using stretched mesh size (*ms*) of the gillnets measured in inches:

$$v_{a,g} = \left(\frac{L_{a,g}}{\alpha\beta} \right)^{\alpha} .e^{\alpha - \frac{L_{a,g}}{\beta}} \tag{16}$$

where,

$$\alpha\beta = \theta_1 .ms, \tag{17}$$

$$\beta = -\tfrac{1}{2}\left((\theta_1 .ms) - \left(\theta_1^2 .ms^2 + 4\theta_2 \right)^{\frac{1}{2}} \right). \tag{18}$$

The values of θ_1 and θ_2 have known values based on the experimental work of Simpfendorfer and Unsworth (1998b).

Growth was assumed to follow the von Bertalanffy growth equation, with the length of age class and sex determined for the middle of the year:

$$L_{a,g} = L_{\infty,g} .(1 - e^{-(K_g(a+0.5-t_{0,g}))}). \tag{19}$$

The estimated catch rate in the model was calculated as a function of catchability and exploitable biomass,

$$\hat{U}_t = q_t .B_t^e . \tag{20}$$

Two values of *q* were used, one for the period from 1975 to 1981, and a second for the period from 1982 to 1997. During the first period fishermen mostly targeted *F. macki*, while from 1982 *C. obscurus* was the main target species (see Introduction). Both values of *q* were estimated in the model fitting process.

Total biomass for each year was calculated by:

$$B_t = \sum_g \sum_a N_{a,g,t} .w_{a,g} , \tag{21}$$

where,

$$w_{a,g} = lwa.L_{a,g}^{\;lwb},\tag{22}$$

with weights measured in kilograms and lengths measured in centimetres.

Similarly, the mature female biomass was calculated as:

$$B_t^m = \sum_{a=m}^{x} N_{a,g=f,t}.w_{a,g}\,.\tag{23}$$

4.8.1.3 Initial state

To account for the impact of fishing prior to the collection of detailed catch and effort information, the state of the population in 1975 was determined by:

$$N_{a+1,g,1975} = \begin{cases} R_0 P_g^{'''} & a = 0 \\ N_{a,g,1974}.e^{-(M+F_0)} & 1 \geq a > x_g\,, \\ N_{a,g,1974}.e^{-(M+F_0)} \big/ 1 - e^{-(M+F_0)} & a = x_g \end{cases}\tag{24}$$

where,

$$R_0 = \frac{X_0 - b}{X_0.c}\,.\tag{25}$$

The value of F_0 was estimated in the model fitting process and represents the estimated level of fishing mortality prior to 1975. The eggs per recruit in the pre-1975 population were calculated as:

$$X_0 = \sum_{a=m}^{x} N_{a,g,0}^{*}.P_a^{'}.P_a^{''}.P_{g=f}^{'''}\tag{26}$$

where,

$$N_{a+1,g,0}^{*} = \begin{cases} 1 & a = 0 \\ N_{a,g,0}^{*}.e^{-(M+F_0)} & 1 \geq a > x_g \\ N_{a,g,0}^{*}.e^{-(M+F_0)} \big/ 1 - e^{-(M+F_0)} & a = x_g \end{cases}\tag{27}$$

Virgin biomass is calculated as:

$$B_0 = \sum_g \sum_a N_{a,g,0}.w_{a,g}\tag{28}$$

where,

$$N_{a+1,g,0} = \begin{cases} R^* & a = 0 \\ N_{a,g,0} . e^{-M} & 1 \geq a > x_g \\ N_{a,g,0} . e^{-M} / 1 - e^{-M} & a = x_g \end{cases} . \tag{29}$$

Virgin mature female biomass was calculated by:

$$B_0^m = \sum_{a=m}^{x} N_{a,g=f,0} . w_{a,g} . \tag{30}$$

2.4 *Model fitting*

The model was fitted to catch rate data using the likelihood function:

$$LL = -\left(\frac{SSQ}{2\sigma^2}\right) - \left(n.\ln\left(\sqrt{\sigma^2 2\pi}\right)\right), \tag{31}$$

where,

$$SSQ = \sum_t \left[\log(U_t + 0.000001) - \log(\hat{U}_t + 0.000001)\right]^2 , \tag{32}$$

with $U_t = y_t$. The model was fitted using the Solver function in Microsoft Excel to provide estimates of five unknown parameters (R^*, z, F_0 , $q_{1975\text{-}1981}$, and $q_{1982\text{-}1996}$). Random starting values for each of the unknown parameters were used. The value of z was constrained to fall within the range of 0.205 (slightly greater than the 0.200 theoretical minimum) and an upper bound given by:

$$z_{\max} = \frac{S^*}{4R^* + S^*} . \tag{33}$$

The derivation of this constraint is given in Appendix B.

The calculation of *SSQ* required that the variance of the residuals was equal for the two time periods for which different q values were used (1975-1981 and 1982 to 1996). To achieve this an iterative approach to function maximisation was used. First, the function was maximised using no correction for variance. Next, the variance of the residuals for each of the periods were calculated. Residual values were standardised by dividing by the residual variance for the appropriate period. The function was then re-maximised. This process was repeated until there was no change in the residual variance values for both periods.

Confidence intervals for the parameter estimates were calculated using bootstrapping. New sets of catch rate data were generated by randomly sampling residuals from the original fitted model (with replacement), correcting for the variance for the appropriate period (see above) and the number of observations ($\sqrt{n+1/n}$), and adding them to the catch rates estimated by the model. The model was then re-fitted using the new catch rate data. Five hundred sets of bootstrapped data were created. Ninety five percent confidence intervals were calculated as the 2.5 and 97.5 percentiles of the resulting 500 sets of parameter estimates.

4.8.1.4 Projection of the fishery into the future

To determine the impact of future harvest strategies, the population was projected into the future using the model specified above. Recruitment was assumed to be variable, with a coefficient of variation (CV) of 0.2.

Future catches in the fishery were assumed to be held constant after 1997, with levels of annual future catch between 0 and 350 tonnes tested (constant annual yield harvest strategy). It was assumed that the fishery did not take exactly the designated catch each year, but rather come within 10%. To achieve this, a deviate to the catch calculated from a uniform random variate ranging from -10% to 10% was added to the designated catch each year (e.g. for 200 tonnes designated future catch, the actual catch ranged from 180 to 220 tonnes). This represents implementation error in the constant annual yield harvest strategy. To project the population into the future it was necessary to estimate the value of F_t required to make the actual catches. This was done by searching for the value of F_t that gave the required catch.

4.8.1.5 Biological parameters

Biological parameters utilised by the model were mostly taken from published information on *F. macki*. Simpfendorfer and Unsworth (1998a) have described the reproductive biology, Simpfendorfer *et al.* (in press) age and growth, and Simpfendorfer and Unsworth (1998b) the gillnet mesh selectivity parameters. The only parameter for which data were not available for *F. macki* is natural mortality (M). The value of M was estimated using the method of Hoenig (1983) that utilises a relationship between maximum age and total mortality. Simpfendorfer *et al.* (in press) examined age and growth in an exploited population, and based on this study it was assumed that in an unexploited population maximum age was 15 years for females and 13 years for males. The values of the biological parameters used in the model are given in Table 4.4.

Table 4.4: Biological parameters used in the age and sex structured model for *Furgaleus macki*.

Parameter	Value	Units	Source
Growth			Simpfendorfer et al. (in press)
Female			
K	0.369	year^{-1}	
L_∞	120.7	cm	
t_0	-0.544	year	
Male			
K	0.423	year^{-1}	
L_∞	121.5	cm	
t_0	-0.472	years	
Length-weight			Simpfendorfer and Unsworth (1998b)
lwa	1.63E-5		
lwb	2.733		
Selectivity			Simpfendorfer and Unsworth (1998b)
θ_1	173.70		
θ_2	26415		
Natural mortality			
M	0.27	year^{-1}	Hoenig (1983) relationship
Reproduction			Simpfendorfer and Unsworth (1998a)
P'_a	19		
P''_a	0.5		
$P'''_{g=m}$	0.5		
$P'''_{g=f}$	0.5		
Age			Simpfendorfer et al. (in press)
m	6	years	
x	15 (female)	years	
	13 (male)	years	

4.8.1.6 Sensitivity tests

To investigate the sensitivity of the assessment to variations in catch and effort, fishery and biological data, 15 scenarios with various combinations of parameters were tested (Table 4.5). The base case (scenario A) represents the best understanding of the population based on the currently available information. Scenarios B, C and D investigated the sensitivity of the model to variations in the catch and effort data (Table 4.5a). Risk assessment was not undertaken for scenarios B and C. Scenarios (E - K) investigate the sensitivity to variation in age, growth, natural mortality and reproduction (Table 4.5b). For scenarios E and F (variation in *M*) the maximum age and natural mortality (using the Hoenig (1983) method) were changed. The effect of varying the CV of recruitment for the risk assessments was tested with Scenarios L and M (Table 4.5c). Scenarios N and O examined the sensitivity to changes in mesh selectivity, with the high and low values taken as the upper and lower 95% confidence intervals given by Simpfendorfer and Unsworth (1998b) (Table 4.5c).

Table 4.5: Specification of scenarios for the assessment of the *Furgaleus macki* population. (a) models testing sensitivity to variations in catch and effort data; (b) models testing sensitivity to variations in biological parameters, and (c) models testing sensitivity to variations in gear and model specification parameters. Where parameters are not specified they were taken to be the same as those of the base case (scenario A).

(a)

Scenario	Name	Catch data	Effort data	Efficiency (% annual)
A	Base case	Corrected	Effective	2
B	Raw catch and nominal effort	Raw	Nominal	0
C	Nominal effort	Corrected	Nominal	0
D	No efficiency	Corrected	Effective	0

(b)

Scenario	Name	M (year^{-1})	m (years)	x (male/female) (years)	P''	K*
A	Base case	0.27	6	13/15	0.5	100%
E	Low M high x	0.23	6	16/18	0.5	100%
F	High M low x	0.35	6	10/12	0.5	100%
G	Double 0+ M	0.27 (0+ 0.54)	6	13/15	0.5	100%
H	Low m	0.27	4	13/15	0.5	100%
I	High m	0.27	8	13/15	0.5	100%
J	Annual breeding	0.27	6	13/15	1.0	100%
K	Low growth rate	0.27	6	13/15	0.5	80%

* proportion of value given by Simpfendorfer *et al.* in review

(c)

Scenario	Name	CV recruitment	θ_1	θ_2
A	Base case	0.2	173.70	26415
L	High CV	0.3	173.70	26415
M	Low CV	0.1	173.70	26415
N	Low selectivity	0.2	171.84	22000
O	High selectivity	0.2	175.52	31779

4.8.1.7 Risk assessment

Risk assessment was used to estimate the probability that a particular event would occur within a specified time given specified harvest strategies. The probability of three different events was assessed. Firstly, that the biomass target set by the Management Committee for the fishery would be met (i.e. total biomass at least 40% by 2010/11). Secondly, that the total biomass in 2010/11 would be equal to, or larger than, the total biomass in 1996/97. And thirdly, that the catch at any time during the period from 1996/97 to 2010/11would be equal to, or greater than, the exploitable biomass, indicating a failure in the fishery.

The *F. macki* population was projected forward using the results of each of the 500 bootstrapped data sets for each of the scenarios tested except B and C. Five hundred trials of each data set were used. The results from scenarios L and M were used to test the sensitivity of the results to the CV of recruitment. The overall probability of each of the specified events occurring, given a designated catch, was taken as the average of the results from the remaining scenarios (excluding B, C, L and M) assuming that each of the tested scenarios was equally likely.

4.8.2 Dusky whalers

4.8.2.1 Demographic techniques

Demographic analysis of the *C. obscurus* population in south-western Australia was undertaken using standard life table techniques (e.g. Krebs, 1985) to estimate values of reproductive rate per generation (R_o), generation time (G), intrinsic rate of population increase (r), population doubling time (t_{x2}), proportion reaching maturity (PM), and stable age distribution (C_x). Negative values of r indicate population decline. The value of fishing mortality providing the maximum sustainable yield (F_{MSY}) was calculated using the method of Ricker (1975) where $F_{MSY}=r/2$. This method assumes that fishing mortality is applied equally to all age classes.

4.8.2.2 Life history parameters

Life history parameters for use in the life tables were obtained from published data on *C. obscurus*. A number of authors have provided age and growth parameters for female *C. obscurus* (Lawler, 1976; Hoenig, 1979; Natanson, 1990; Natanson *et al.,* 1995). The most reliable of these are probably those of Natanson *et al.* (1995) for the western North Atlantic (L_∞ =349 cm fork length, K=0.039 year^{-1}, t_0=-7.04 years), and Natanson (1990) for South African waters (L_∞ =336cm fork length, K=0.054 year^{-1}, t_0=-4.87 years). There are currently no published growth parameters for Australian *C. obscurus.* The growth parameters from South Africa gave sizes at maturity that were the closest match to those observed in south-western Australia (C. Simpfendorfer, Fisheries Western Australia, unpublished data), and so these were used in the analysis. Natanson (1990) estimated the age at maturity for *C. obscurus* as 14-21 years, while Natanson *et al.* (1995) concluded that *C. obscurus* probably live over 45 years. Maximum age for the analysis was taken as 50 years, with sensitivity tests used to assess the impact of maximum ages of 40 and 60 years. Reports of litter sizes range from 6 to 14, with an average of 10 (Whitley, 1940; Bigelow and Schroeder, 1948; Clark and von Schmidt, 1965; Bass *et al.,* 1973; Heald, 1987; GSAFDF 1996). There have been no data published to suggest that litter size varies with the size of the mother (and hence age). An average litter size of ten for all mature females was used for the analyses, with sensitivity tests for litter sizes of eight and 12. Estimates of gestation period and breeding frequency remain scant. Recently it has been suggested (GSAFDF 1996) that the gestation period is approximately two years, with mature females producing a litter every three years. A reproductive periodicity of 3 years was used for the analyses, with sensitivity tests for 2 and 4 years.

Natural mortality (*M*) was estimated using the methods of Pauly (1980), Hoenig (1983), and Jensen (1996) (Table 4.6). The methods of Hoenig (1983) and Jensen (1996) gave estimates of *M* of just over 0.08 year^{-1}, and the method of Pauly (1980) a value of 0.11 year^{-1}. On the basis of the similarity of the majority of these estimates the value of *M* from the Hoenig estimate was used in the analyses because of its widespread use in other shark studies (e.g. Hoenig and Gruber, 1990; Cortes, 1995; Cortes and Parsons, 1996; Sminkey and Musick 1996). Scenarios using the estimate of *M* from the Pauly method, and a lower value (0.05 year^{-1}), were used to test the sensitivity of the analysis to variations in *M*.

Table 4.6: Estimates of natural mortality (*M*) for *Carcharhinus obscurus* using indirect methods from life history parameters. *K* and L_∞, parameters of the von Bertalanffy growth curve (units: *K*, *year*$^{-1}$, and L_∞, cm); *T*, average water temperature (units: degrees centigrade); t_{mat}, age at maturity (units: year); t_{max}, maximum age (units: years); *Z*, total mortality (units: year^{-1}).

Method	Relationship	Estimate of M (year^{-1})
Pauly (1980)	$\ln(M) = -0.0066 - 0.297.\ln(L_\infty) + 0.6543.\ln(K) + 0.4627.\ln(T)$	0.11
Hoenig (1983)	$\ln(Z) = 1.46 - 1.01.\ln(t_{max})$	0.083
Jensen (1996)	$M = 1.65/t_{mat}$	0.082
Jensen (1996)	$M = 1.5\ K$	0.081
Jensen (1996)	$M = 1.6\ K$	0.086

The normal life table assumes that natural mortality is independent of age. However, some authors have suggested that natural mortality is higher for age 0 animals (Hoenig and Gruber, 1990; Morrissey and Gruber, 1993; Sminkey and Musick, 1996; Cortes, 1998). To test the sensitivity of the analysis to increased levels of natural mortality for age 0 animals scenarios where tested where *M* was doubled for this group. The levels of *M* for which these tests were carried out were 0.083 year^{-1} and 0.05 year^{-1}.

4.8.2.3 Incorporating exploitation rates

The impact of fishing on the *C. obscurus* population in south-western Australia was assessed in the life tables by including age-specific exploitation rates from a tagging study. Details of the tagging study can be found in Simpfendorfer et al. (1996). *C. obscurus* with open umbilical scars were tagged with Jumbo Rototags from commercial gillnet vessels during Autumn (March to May) in 1994 and 1995. A total of 766 animals were released during the two tagging periods. To incorporate spatial differences in non-reporting rates into the tag-recapture analysis the fishery was divided into three regions that corresponded to management zones within the fishery (Simpfendorfer and Donohue

1998). Monthly estimates of the total number of tag recaptures by the commercial gillnet fishery were made for the fishery using the equation:

$$\hat{R}_{a,t} = \frac{\sum_{i=1}^{g} R_{a,i,t} / 1 - D_{i,t}}{e^{-S/12}}$$

where $\hat{R}_{a,t}$ is the estimated number of tags of cohort a caught in month t, $R_{a,i,t}$ is the number of tags reported from cohort a in region i during month t, g is the number of regions, $D_{i,t}$ is the non-reporting rate in region i for month t, and S is the annual tag shedding rate.

To estimate the non-reporting rate commercial gillnetters were classified as either "reporters" or "non-reporters" depending on whether they returned tag information. The non-reporting rate was estimated as the proportion of the total catch of a region, in a particular month, that was taken by "non-reporting" fishers. Catch figures were taken from compulsory monthly catch and effort returns supplied by all commercial fishers. The tag shedding rate of Jumbo Rototags was estimated using the method of Xiao (1996) for *C. obscurus* double tagged with Jumbo Rototags and Hallprint metal headed dart tags.

Age-specific exploitation rates for individual cohorts were calculated by summing the monthly values of $\hat{R}_{a,t}$ over a whole year (July to June) and dividing by the number tags estimated to be present at the start of each year. Tag recaptures made during the first four months (March to June) were not included in exploitation rate analyses to allow the tagged animals to mix into the population. Calculations were undertaken separately for the cohorts born in 1994 and 1995. Size composition data from the commercial fishery (Simpfendorfer *et al.* 1996), combined with growth data from tagged animals (C. Simpfendorfer, Fisheries Western Australia, unpublished data), indicated that individuals six years or older were not present in the catch. Since tag-recapture data were not available for all age-classes of each cohort it was necessary to estimate some age-specific exploitation rates. This was achieved by either using the estimate from the other cohort, or by estimating exploitation rates such that they declined steadily to zero at age six.

The exploitation rates experienced by the cohorts each year were incorporated separately into life tables by modifying the survival equation:

$$l_{x+1} = l_x(1 - P_x)e^{-M}$$

where l_x is the proportion of the recruits surviving at age x and P_x is the annual exploitation rate of the xth age class caught by the fishery. To test the sensitivity of the analysis to uncertainty in the exploitation rates scenarios were run with 10% and 20% greater exploitation rates in all ages up to six years.

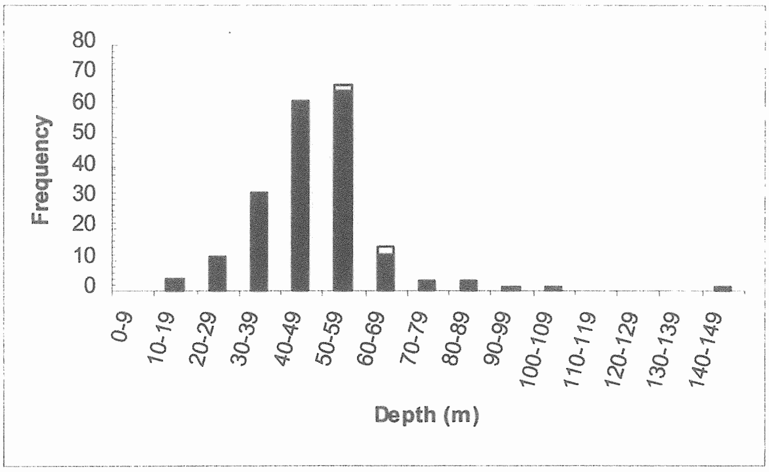
5. RESULTS

5.1 Nursery areas for whiskery sharks

A total of 198 sets of the experimental net were undertaken between March 1997 and November 1998 between Lancelin (31.5°S) and Chatham Island (116.5°E), with the majority between Mandurah (32.5°S) and Hamelin Bay (34°S) (Figure 5.1). Water depths of sets ranged from less than 10 m to 140 m, with the majority between 30 m and 50 m (Figure 5.2).

Figure 5.1: Map showing the location of exploratory sets of small mesh gillnets designed to catch small *Furgaleus macki*. Open circles indicate sets with no juvenile *F. macki*, filled circles show locations of sets with juvenile *F. macki*.

Figure 5.2: Depth distribution of sets of small mesh gillnet. Filled bars indicate sets in which no *F. macki* were caught; open bars indicate sets in which juvenile *F. macki* were caught.



A total of ten small *F. macki* were captured using the experimental net (Table 5.1). Specimens captured ranged in size from 50 to 86 cm FL. These captures were made in two areas: outer Geographe Bay and south of Augusta (Figure 5.1), and at depths between 20 m and 60 m (Figure 5.2). The highest proportion of successful sets were made in depths between 50 m and 60 m.

Table 5.1. Details of small *Furgaleus macki* caught in the experimental gillnet between March 1997 and November 1998.

Sex	Fork length (cm)	Date captured	Geographic Block	Depth (m)
F	50	6/5/97	3215	29
F	66	14/9/97	3415	47
M	65	14/9/97	3415	47
F	75	16/9/97	3415	50.6
F	85	20/10/98	3415	48.87
F	83	20/10/98	3415	48.87
M	74	20/10/98	3415	48.87
M	86	20/10/98	3415	48.87
F	70	20/10/98	3415	48.87
F	61	20/10/98	3414	30

Despite sampling over a wide geographic range and depth range few small *F. macki* were captured. This may have been the result of one or more of the following: (1) *F. macki* grows rapidly as juveniles making their capture less likely; (2) the nursery areas were in areas not fished by the commercial fishery, either because they were in areas deeper than regularly fished (the highest proportion of successful sets were in the 50-60 m range and few sets were over 60 m) or in habitats that are not fished (e.g. heavy inshore reefs); and (3) *F. macki* do not have specific nursery areas, but are rather widely dispersed and so sampling with limited resources would only catch a small number. Although this segment of the project did not provide a lot of information on *F. macki* nursery areas, it does give a good indication of areas in which they are unlikely to occur.

5.2 Stock structure of commercially important shark species

5.2.1 Location specific signatures for whiskery sharks

A total of 37 jaw cartilages from whiskery sharks were analysed for their elemental composition from three locations in southern Western Australia (Table 5.2). Results of elemental analyses, shark length, jaw thickness and jaw weight are summarised in Table 5.3.

Table 5.2: Summary of sampling locations for whiskery sharks.

Location	Date	Location code	n	Position
Albany	1995	ALB1995	16	35° 01’07”S, 117° 52’ 56”E
Bunbury	1995	BUN1995	15	33° 20’29”S, 115° 38’26”E
Cape Leeuwin	1995	Cle1995	6	34° 22’34”S, 115° 08’05”E

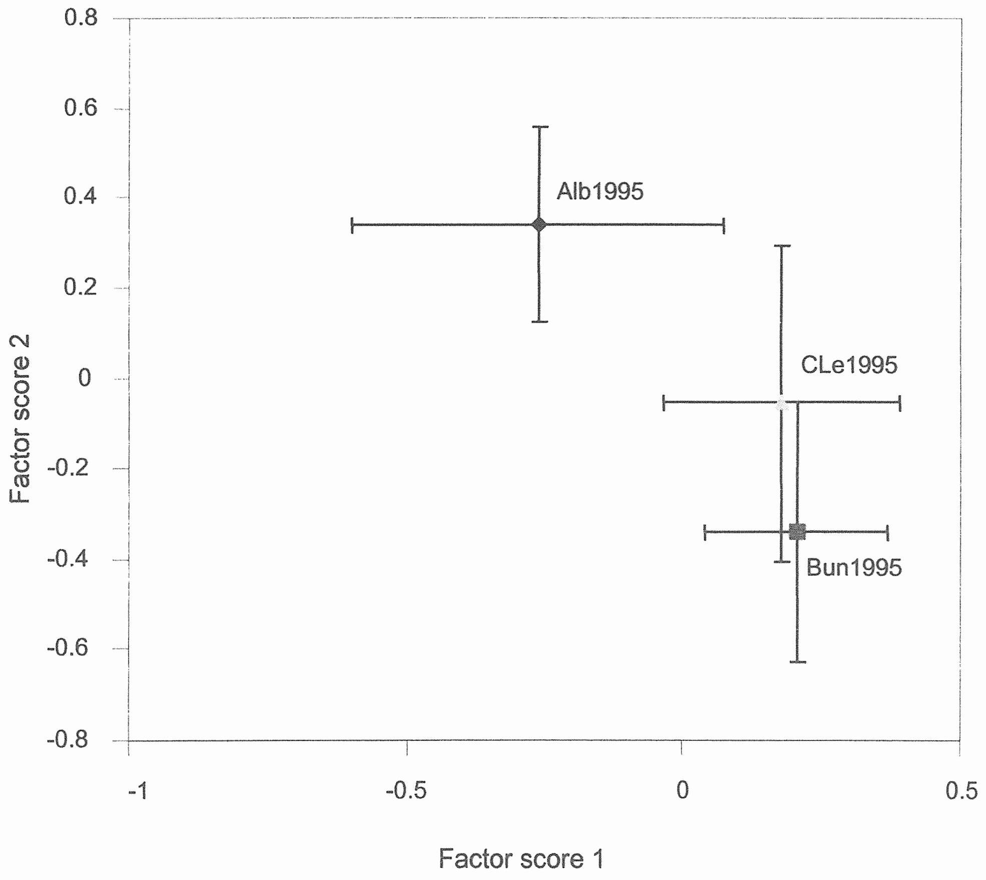
Table 5.3: Summary of size and elemental composition data for whiskery sharks for locations sampled.

Location/Year (Code)	Variable	n	Mean	Minimum	Maximum	Std.Dev.
Albany/1995 (ALB1995)	Shark Length (cm)	16	110.19	100.00	122.00	6.80
	Jaw Thickness (mm)	15	1.42	0.80	1.95	0.33
	Jaw weight (g)	15	0.11	0.06	0.12	0.02
	Mg	16	3318.78	2780.30	3662.90	245.77
	Mn	16	23.23	9.00	28.90	4.85
	Sr	16	812.08	648.60	936.10	97.31
	Zn	16	64.85	39.50	88.90	11.12
	S	16	14008.06	7090.00	25917.00	4181.54
	Ca	16	140317.25	110576.00	164961.00	16429.11
	P	16	74473.31	59107.00	83978.00	8121.96
	K	16	7685.88	5055.00	11794.00	1787.64
	Na	16	17470.00	11483.00	35440.00	5675.87
Bunbury/1995 (BUN1995)	Shark Length (cm)	14	110.64	97.00	122.00	7.86
	Jaw Thickness (mm)	15	1.44	1.10	2.05	0.26
	Jaw weight (g)	15	0.12	0.09	0.15	0.02
	Mg	15	3163.05	2825.40	3790.40	283.38
	Mn	15	25.09	18.90	31.90	4.28
	Sr	15	849.47	737.80	916.80	53.41
	Zn	15	66.11	53.40	81.00	7.64
	S	15	12225.07	5649.00	20329.00	3265.03
	Ca	15	145807.07	129495.00	156589.00	8614.05

	P	15	77934.60	69547.00	83432.00	4477.27
	K	15	9041.40	4114.00	12766.00	2104.83
	Na	15	15816.93	13109.00	20740.00	2407.39
Cape Leeuwin/1995 (CLe1995)	Shark Length (cm)	4	109.75	97.00	121.00	10.81
	Jaw Thickness (mm)	6	1.85	1.45	2.00	0.21
	Jaw weight (g)	6	0.13	0.11	0.15	0.01
	Mg	6	3177.98	2830.00	3704.50	287.58
	Mn	6	24.03	17.90	28.90	4.37
	Sr	6	860.92	813.50	943.40	46.49
	Zn	6	61.75	43.80	74.40	12.12
	S	6	11332.67	6972.00	14592.00	2877.27
	Ca	6	145592.17	139199.00	148604.00	3491.62
	P	6	78309.67	74874.00	80553.00	1939.81
	K	6	8514.17	7497.00	9182.00	736.77
	Na	6	15992.67	12504.00	19837.00	2780.74

The factor analysis for locations showed grouping and some separation of sharks from the sites sampled in this study (Figure 5.3). Analysis of covariance (ANCOVA) of factor 1 showed that the location differences accounted for a low proportion of the variability, explaining 3 % of the sum of squares. Whereas, shark length accounted for a higher proportion of the variability, explaining 15 % of the sum of squares (Table 5.4). Location, sex and location x sex interaction effects were not as significant.

Figure 5.3: **Mean factor score 1 (± standard error) versus factor score 2 (± standard error) for whiskery sharks.**



ANCOVA of factor 2 showed that the location differences accounted for a significant proportion of the variability, explaining 14 % of the sum of squares and shark length only accounted for 1 % of the sum of squares (Table 5.5). Sex and location x sex interaction effects were not as significant. However, ANCOVA of factor score 2 showed that location was a significant effect when the Cape Leeuwin samples were omitted from the ANCOVA.

Table 5.4: ANCOVA of factor score 1 based on elements concentrations in jaw cartilage of whiskery sharks.

Source	df	SS	MS	F	p
Location	2	1.1348	0.5674	0.5896	0.5615
Sex	1	0.0810	0.0810	0.0842	0.7739
Location x Sex	2	2.4289	1.2144	1.2620	0.2993
Shark Length	1	5.1828	5.1828	5.3856	0.0281
Residual (Error)	27	25.9830	0.9623		
Total	33	35.0998	1.0636		

Table 5.5: ANCOVA of factor score 2 based on elements concentrations in jaw cartilage of whiskery sharks.

Source	df	SS	MS	F	p
Location	2	4.9794	2.4897	2.7383	0.0826
Sex	1	0.6046	0.6046	0.6649	0.4220
Location x Sex	2	5.7185	2.8593	3.1448	0.0592
Shark Length	1	0.4656	0.4656	0.5121	0.4804
Residual (Error)	27	24.5485	0.9092		
Total	33	35.5525	1.0773		

Variations in factor score 1 for whiskery sharks were more attributable to shark length than location of capture (Table 5.4). However, the variation in factor 2 was more attributable to the location of capture. None of the locations were sampled over multiple years for whiskery sharks. The factor scores for the location showed some separation of whiskery sharks from these sites, however it is evident that the two sites with the greatest geographic distance between them (Albany and Bunbury) are statistically different (Figure 5.3). The close proximity of the areas sampled for whiskery sharks may limit the separation of these stocks using this technique, due to anticipated small differences in water chemistry and/or food source. However, the order of the locations on both factor scores reflected their relative geographic positions (Figure 5.3).

5.2.2 Location specific signatures for dusky sharks

A total of 102 jaw cartilages from dusky sharks were analysed for their elemental composition from six locations in Western Australia (Table 5.6). Results of elemental analyses, shark length, jaw thickness and jaw weight are summarised in Table 5.7.

Table 5.6: Summary of sampling locations for dusky sharks.

Location	Date	Location code	n	Position
Albany	1995	ALB1995	28	35° 01’07”S, 117° 52’ 56”E
Bunbury	1995	BUN1995	29	33° 20’29”S, 115° 38’26”E
Bunbury	1997	BUN1997	10	33° 20’29”S, 115° 38’26”E
Cape Leeuwin	1994	CLe1994	2	34° 22’34”S, 115° 08’05”E
Cape Leeuwin	1995	CLe1995	15	34° 22’34”S, 115° 08’05”E
Carnarvon	1995	CAR1995	5	24° 53’30”S, 113° 39’31”E
Geraldton	1995	GER1995	3	28° 46’49”S, 114° 36’47”E
Geraldton	1996	GER1996	3	28° 46’49”S, 114° 36’47”E
Perth	1997	PER1997	7	31° 51’30”S, 115° 44’57”E

Table 5.7: Summary of size and elemental composition data for dusky sharks for locations sampled.

Location/Year (Code)	Variable	n	Mean	Minimum	Maximum	Std.Dev.
Albany/1995	Shark Length (cm)	28	92.18	70.00	125.00	16.50
(ALB1995)	Jaw Thickness (mm)	28	1.46	0.90	2.50	0.42
	Jaw weight (g)	28	0.08	0.06	0.13	0.02
	Mg	28	3129.76	2550.60	4832.00	409.12
	Mn	28	9.34	4.80	15.50	2.88
	Sr	28	499.10	354.40	696.30	99.44
	Zn	28	50.19	39.00	67.00	6.79
	S	28	18270.64	8202.00	29341.00	4215.31
	Ca	28	100481.61	71880.00	127662.00	14863.99
	P	28	55538.75	38832.00	66546.00	6731.98
	K	28	8400.79	6274.00	13088.00	1946.92
	Na	28	24092.14	19016.00	30596.00	2890.82
Bunbury/1995	Shark Length (cm)	28	92.18	73.00	126.00	15.98
(BUN1995)	Jaw Thickness (mm)	29	1.55	1.10	2.50	0.33
	Jaw weight (g)	29	0.10	0.07	0.15	0.02
	Mg	29	3027.32	2373.80	3638.00	307.20
	Mn	29	9.88	6.50	14.00	2.06
	Sr	29	579.27	284.30	779.00	130.60
	Zn	29	47.92	36.40	58.00	5.54
	S	29	17715.10	8359.00	32487.00	6109.67
	Ca	29	109275.03	62081.00	146104.00	21371.09
	P	29	59401.28	36603.00	78360.00	10410.83
	K	29	11035.69	5224.00	15973.00	2473.19
	Na	29	20063.21	12451.00	27460.00	3763.96
Bunbury/1997	Shark Length (cm)	10	98.80	72.00	170.00	34.04

(BUN1997)	Jaw Thickness (mm)	10	1.91	1.21	4.51	0.97
	Jaw weight (g)	10	0.11	0.06	0.27	0.06
	Mg	10	3030.20	2471.00	3744.00	472.12
	Mn	10	9.11	7.10	11.70	1.46
	Sr	10	586.20	395.00	810.00	136.92
	Zn	10	45.50	40.00	54.00	5.08
	S	10	16563.90	13169.00	20268.00	2454.82
	Ca	10	112636.00	78160.00	144640.00	22055.46
	P	10	60264.00	42520.00	77040.00	10048.47
	K	10	11036.80	7076.00	17408.00	2858.00
	Na	10	18677.60	12884.00	27784.00	4509.10
Cape Leeuwin/1994	Shark Length (cm)	2	79.50	77.00	82.00	3.54
(CLe1994)	Jaw Thickness (mm)	2	2.53	2.40	2.65	0.18
	Jaw weight (g)	2	0.12	0.11	0.13	0.02
	Mg	2	2610.65	2421.70	2799.60	267.22
	Mn	2	12.10	10.90	13.30	1.70
	Sr	2	432.85	409.80	455.90	32.60
	Zn	2	38.50	37.80	39.20	0.99
	S	2	16444.50	11536.00	21353.00	6941.67
	Ca	2	79669.00	76000.00	83338.00	5188.75
	P	2	47864.50	43200.00	52529.00	6596.60
	K	2	13373.50	11217.00	15530.00	3049.75
	Na	2	23248.00	22908.00	23588.00	480.83
Cape Leeuwin/1995	Shark Length (cm)	15	98.73	73.00	200.00	35.34
(CLe1995)	Jaw Thickness (mm)	15	1.59	0.90	2.70	0.41
	Jaw weight (g)	15	0.11	0.07	0.23	0.04
	Mg	15	2823.83	2288.40	3245.70	311.75
	Mn	15	10.27	5.30	30.40	6.01
	Sr	15	546.83	328.10	962.40	223.23
	Zn	15	53.11	42.00	76.90	8.09
	S	15	16254.33	10051.00	25784.00	4744.26
	Ca	15	104927.93	71952.00	170619.00	35482.93
	P	15	57724.07	40664.00	88059.00	16187.49
	K	15	9105.33	4130.00	13024.00	2431.62
	Na	15	23484.40	12375.00	28879.00	5325.47
Carnarvon/1995	Shark Length (cm)	5	209.60	120.00	255.00	54.37
(CAR1995)	Jaw Thickness (mm)	5	1.51	1.23	1.73	0.20
	Jaw weight (g)	5	0.07	0.06	0.08	0.01
	Mg	5	3110.80	2957.00	3526.00	234.40
	Mn	5	9.60	8.60	10.50	0.78
	Sr	5	451.00	351.00	519.00	63.01
	Zn	5	49.00	43.00	62.00	7.75
	S	5	18144.80	16939.00	19537.00	1041.22
	Ca	5	89576.00	80360.00	98840.00	8736.75
	P	5	50848.00	45560.00	55880.00	4237.96
	K	5	10661.60	6016.00	15960.00	4179.34
	Na	5	22563.20	17524.00	28220.00	4929.54
Geraldton/1995	Shark Length (cm)	3	148.67	83.00	185.00	56.98
(GER1995)	Jaw Thickness (mm)	3	2.45	1.28	3.55	1.14
	Jaw weight (g)	3	0.17	0.09	0.22	0.07
	Mg	3	3093.33	3026.00	3195.00	89.58
	Mn	3	12.80	9.80	15.30	2.78

	Sr	3	729.67	618.00	918.00	164.04
	Zn	3	48.00	42.00	57.00	7.94
	S	3	14779.00	12522.00	17515.00	2530.73
	Ca	3	128600.00	110760.00	157760.00	25462.85
	P	3	68453.33	59120.00	83840.00	13425.79
	K	3	7912.00	6104.00	10552.00	2337.81
	Na	3	18132.00	14920.00	22404.00	3852.96
Geraldton/1996 (GER1996)	Shark Length (cm)	3	94.67	83.00	118.00	20.21
	Jaw Thickness (mm)	3	1.48	1.29	1.77	0.25
	Jaw weight (g)	3	0.10	0.85	0.13	0.03
	Mg	3	2969.00	2748.00	3144.00	201.97
	Mn	3	10.17	7.60	12.20	2.35
	Sr	3	617.00	551.00	740.00	106.62
	Zn	3	48.00	47.00	49.00	1.00
	S	3	16577.67	16215.00	17177.00	522.85
	Ca	3	113960.00	100800.00	128920.00	14146.15
	P	3	62360.00	57680.00	68840.00	5793.65
	K	3	10440.00	8840.00	11624.00	1437.87
	Na	3	17318.67	14940.00	18612.00	2062.61
Perth/1997 (PER1997)	Shark Length (cm)	7	74.14	69.00	82.00	4.67
	Jaw Thickness (mm)	7	1.28	1.14	1.43	0.11
	Jaw weight (g)	7	0.07	0.06	0.08	0.01
	Mg	7	2583.57	2236.00	3233.00	394.99
	Mn	7	13.54	10.10	20.70	3.87
	Sr	7	482.71	424.00	577.00	55.42
	Zn	7	49.29	42.00	61.00	6.05
	S	7	19809.71	16150.00	24853.00	2674.11
	Ca	7	97057.14	84440.00	109680.00	8490.99
	P	7	52314.29	46360.00	59080.00	4293.53
	K	7	9743.43	6052.00	12648.00	2541.66
	Na	7	20845.14	16844.00	30168.00	4459.97

The factor scores for locations showed grouping and separation for most of the locations sampled in this study (Figure 5.4). Analysis of covariance (ANCOVA) of factor score 1 showed that the location differences accounted for a high proportion of the variability, explaining 29 % of the sum of squares, however, shark length also accounted for a high proportion of the variability, explaining 40 % of the sum of squares (Table 5.8). Sex and location x sex interaction effects were not significant

ANCOVA of factor score 2 showed that the location differences accounted for a significant proportion of the variability, explaining 33 % of the sum of squares (Table 5.9). Shark length, sex and location x sex interaction effects were not significant.

Variations in the factor scores 1 and 2 were highly attributable to location. Although variations in factor score 1 for dusky sharks were more attributable to shark length than location of capture. However, the variation in factor score 2 was more attributable to the location of capture. Bunbury was sampled over two years and showed no significant difference in the factor scores over this period (Figure 5.4). It is evident from Figure 5.4 that of the locations studied that significant differences are apparent for all locations, except Carnarvon due to the small number of samples obtained from this location.

Figure 5.4: Mean factor score 1 (± standard error) versus mean factor score 2 (± standard error) for dusky sharks.

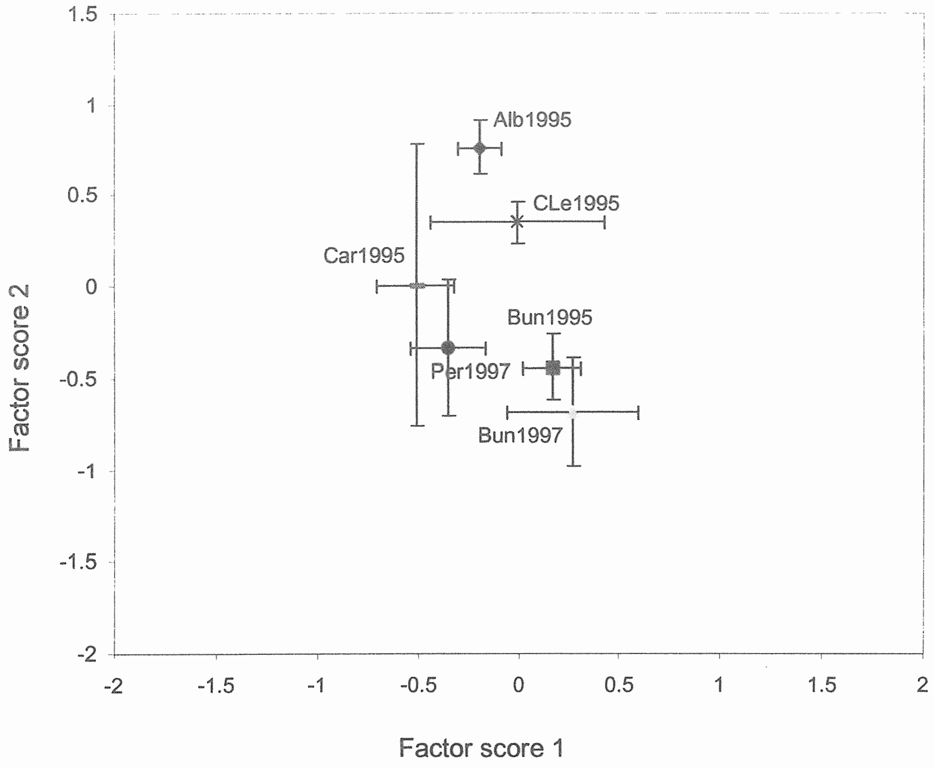


Table 5.8: ANCOVA of factor score 1 based on elements concentrations in jaw cartilage of dusky sharks.

Source	df	SS	MS	F	p
Location	6	25.8599	4.3100	7.4300	0.0000
Sex	1	0.0098	0.0098	0.0168	0.8971
Location x Sex	5	2.5462	0.5092	0.8779	0.4999
Shark Length	1	36.3849	36.3849	62.7245	0.0000
Residual (Error)	80	46.4060	0.5801		
Total	93	90.3381	0.9714		

Table 5.9: ANCOVA of factor score 2 based on elements concentrations in jaw cartilage of dusky sharks.

Source	df	SS	MS	F	p
Location	6	30.1868	5.0311	7.1702	0.0000
Sex	1	0.5016	0.5016	0.7149	0.4004
Location x Sex	5	6.5050	1.3010	1.8542	0.1117
Shark Length	1	1.3271	1.3271	1.8913	0.1729
Residual (Error)	80	56.1338	0.7017		
Total	93	91.9252	0.9884		

5.2.3 Location specific signatures for gummy sharks

A total of 189 jaw cartilages from gummy sharks were analysed for their elemental composition from eight locations in Western Australia and one location in Tasmania (Table 5.10). Results of elemental analyses, shark length, jaw thickness and jaw weight are summarised in Table 5.11.

Table 5.10: Summary of sampling locations for gummy sharks.

Location	Date	Location code	n	Position
Albany	1985	ALB1985	17	35° 01’07”S, 117° 52’ 56”E
Albany*	1988	ALB1988	9	35° 01’07”S, 117° 52’ 56”E
Augusta	1994	AUG1994	8	34° 18’49”S, 115° 09’28”E
Bunbury*	1989	BUN1989	26	33° 20’29”S, 115° 38’26”E
Bunbury	1994	BUN1994	21	33° 20’29”S, 115° 38’26”E
Cape Naturalist	1994	CNAT1994	2	33° 32’21”S, 115° 01’02”E
Esperance	1985	ESP1985	8	33° 51’30”S, 121° 55’08”E
Esperance	1986	ESP1986	14	33° 51’30”S, 121° 55’08”E
Esperance	1994	ESP1994	19	33° 51’30”S, 121° 55’08”E
Eucla*	1988	EUC1988	30	31° 42’51”S, 128° 53’02”E
Nornalup	1994	NOR1994	3	35° 00’29”S, 115° 43’33”E
Tasmania	1990	TAS1990	12	42° 00’06”S, 146° 45’31”E
Walpole	1990	WAL1990	20	34° 59’08”S, 116° 43’26”E

* data from Edmonds *et al.* (1996).

Table 5.11. Summary of size and elemental composition data for gummy sharks for locations sampled.

Location/Year (Code)	Variable	n	Mean	Minimum	Maximum	Std.Dev.
Albany/1985 (ALB1985)	Shark Length (cm)	17	118.06	99.00	164.00	21.43
	Jaw Thickness (mm)	17	2.24	1.50	3.10	0.51
	Jaw weight (g)	17	0.14	0.10	0.30	0.05
	B	17	10.00	3.00	21.00	5.45
	Ba	17	9.59	5.60	15.50	2.73
	Mg	17	3282.94	2700.00	4170.00	402.02
	Mn	17	21.82	9.00	57.00	11.60
	Sr	17	926.53	766.00	1210.00	106.63
	Zn	17	47.53	38.00	56.00	5.30
	S	17	12930.59	8420.00	15200.00	1605.35
	Ca	17	175058.82	149000.00	239000.00	22821.24
	P	17	86058.82	74000.00	113000.00	10021.67
	K	17	5044.71	2720.00	7620.00	1443.98
	Na	17	15588.24	11100.00	18800.00	1986.79
Albany/1988* (ALB1988)	Shark Length (cm)	9	110.17	98.00	141.00	13.12
	Jaw Thickness (mm)	9	2.55	2.27	2.82	0.21
	Jaw weight (g)	9	0.13	0.06	0.29	0.06
	B	9	28.78	17.00	48.00	9.63
	Ba	9	10.68	9.50	13.30	1.32
	Mg	9	2606.56	1735.00	3457.00	518.56

	Mn	9	23.42	9.40	42.00	9.47
	Sr	9	1020.67	655.00	1324.00	186.44
	Zn	9	66.89	48.80	87.60	14.45
	S	9	13905.00	7155.00	20250.00	3332.01
	Ca	9	161000.00	96000.00	235000.00	35647.58
	P	9	77055.56	45200.00	112000.00	17370.53
	K	9	7210.67	2820.00	9843.00	2010.76
	Na	9	12469.78	9628.00	14150.00	1436.77
Augusta/1994 (AUG1994)	Shark Length (cm)	8	135.63	113.00	148.00	11.03
	Jaw Thickness (mm)	8	3.29	2.75	4.75	0.71
	Jaw weight (g)	8	0.18	0.12	0.29	0.06
	B	8	21.00	13.00	27.00	4.17
	Ba	8	10.00	8.00	14.00	2.00
	Mg	8	2907.38	2596.00	3144.00	162.84
	Mn	8	26.66	11.30	48.00	13.00
	Sr	8	1127.88	926.00	1258.00	113.35
	Zn	8	39.63	30.00	47.00	5.26
	S	8	11531.00	10624.00	12864.00	862.97
	Ca	8	176243.25	145978.00	196850.00	18162.86
	P	8	89413.38	77193.00	98775.00	7964.53
	K	8	6126.00	3423.00	9022.00	2059.58
	Na	8	15271.50	12131.00	17154.00	1661.01
Bunbury/1989* (BUN1989)	Shark Length (cm)	26	124.88	102.50	176.00	17.96
	Jaw Thickness (mm)	0				
	Jaw weight (g)	26	0.14	0.09	0.27	0.05
	B	26	20.12	8.00	39.00	7.96
	Ba	26	9.04	4.00	16.00	3.38
	Mg	26	3007.85	2466.00	4113.00	364.11
	Mn	26	23.76	11.20	42.30	8.96
	Sr	26	983.73	754.00	1282.00	155.12
	Zn	26	57.77	34.30	80.40	12.55
	S	26	13497.58	8348.00	16400.00	2329.10
	Ca	26	165961.54	112000.00	235000.00	30585.59
	P	26	79603.85	57400.00	109000.00	13440.37
	K	26	5700.19	1441.00	9641.00	1808.76
	Na	26	13508.08	11260.00	15720.00	1325.99
Bunbury/1994 (BUN1994)	Shark Length (cm)	21	132.05	115.00	165.00	11.62
	Jaw Thickness (mm)	21	2.72	1.75	3.25	0.37
	Jaw weight (g)	21	0.15	0.07	0.23	0.04
	B	21	18.86	10.00	31.00	5.87
	Ba	21	9.14	5.00	15.00	2.90
	Mg	21	3304.24	2737.00	3925.00	265.66
	Mn	21	25.57	12.00	46.00	10.28
	Sr	21	1102.19	806.00	1442.00	172.43
	Zn	21	39.24	25.00	64.00	10.85
	S	21	11548.00	6148.00	17952.00	2787.04
	Ca	21	179629.24	115247.00	218413.00	31229.83
	P	21	91267.00	62299.00	107859.00	13781.79
	K	21	6657.52	3508.00	15302.00	2874.42
	Na	21	13217.33	11080.00	17315.00	1474.19
Cape naturalist/1994 (CNAT1994)	Shark Length (cm)	2	128.00	127.00	129.00	1.41
	Jaw Thickness (mm)	2	3.23	2.90	3.55	0.46

	Jaw weight (g)	2	0.20	0.20	0.20	0.00
	B	2	19.50	19.00	20.00	0.71
	Ba	2	10.50	10.00	11.00	0.71
	Mg	2	3489.50	3463.00	3516.00	37.48
	Mn	2	27.50	27.00	28.00	0.71
	Sr	2	1298.50	1230.00	1367.00	96.87
	Zn	2	36.50	33.00	40.00	4.95
	S	2	11368.00	10696.00	12040.00	950.35
	Ca	2	196694.00	185367.00	208021.00	16018.80
	P	2	99526.00	94943.00	104109.00	6481.34
	K	2	3384.00	3377.00	3391.00	9.90
	Na	2	14049.00	13292.00	14806.00	1070.56
Esperance/1985 (ESP1985)	Shark Length (cm)	8	119.88	102.00	152.00	18.67
	Jaw Thickness (mm)	8	2.16	1.60	3.30	0.54
	Jaw weight (g)	8	0.12	0.10	0.18	0.03
	B	8	19.63	12.00	33.00	7.87
	Ba	8	9.34	4.80	14.10	3.18
	Mg	8	4274.13	2900.00	7010.00	1462.05
	Mn	8	18.45	8.60	27.00	6.63
	Sr	8	798.13	724.00	899.00	64.88
	Zn	8	45.75	37.00	59.00	7.85
	S	8	14226.25	12010.00	16300.00	1765.97
	Ca	8	150250.00	135000.00	179000.00	13604.10
	P	8	78125.00	70000.00	91000.00	6854.35
	K	8	4161.25	950.00	8570.00	2613.05
	Na	8	14538.75	8150.00	17100.00	2927.26
Esperance/1986 (ESP1986)	Shark Length (cm)	14	128.71	109.00	149.00	11.20
	Jaw Thickness (mm)	14	2.49	1.95	3.05	0.35
	Jaw weight (g)	14	0.14	0.10	0.27	0.04
	B	14	7.14	0.00	15.00	4.20
	Ba	14	7.98	4.60	14.20	2.32
	Mg	14	2794.29	2460.00	3320.00	230.14
	Mn	14	26.21	19.00	42.00	6.35
	Sr	14	817.79	663.00	990.00	109.36
	Zn	14	36.21	27.00	43.00	5.28
	S	14	13175.71	7360.00	15900.00	2358.41
	Ca	14	161285.71	133000.00	228000.00	29350.48
	P	14	82071.43	70000.00	109000.00	11743.83
	K	14	6333.57	3690.00	8130.00	1111.38
	Na	14	14142.86	11400.00	16600.00	1816.89
Esperance/1994 (ESP1994)	Shark Length (cm)	19	121.42	102.00	146.00	12.78
	Jaw Thickness (mm)	0				
	Jaw weight (g)	19	0.13	0.09	0.19	0.03
	B	19	26.79	16.00	44.00	7.86
	Ba	19	15.79	10.00	27.00	3.91
	Mg	19	3064.00	2426.00	4096.00	352.19
	Mn	19	29.32	12.00	91.00	19.84
	Sr	19	999.00	758.00	1224.00	133.89
	Zn	19	42.11	27.00	53.00	6.94
	S	19	13817.47	10912.00	17604.00	2201.04
	Ca	19	155405.05	108648.00	202320.00	26820.34
	P	19	80191.63	58822.00	101800.00	12558.21

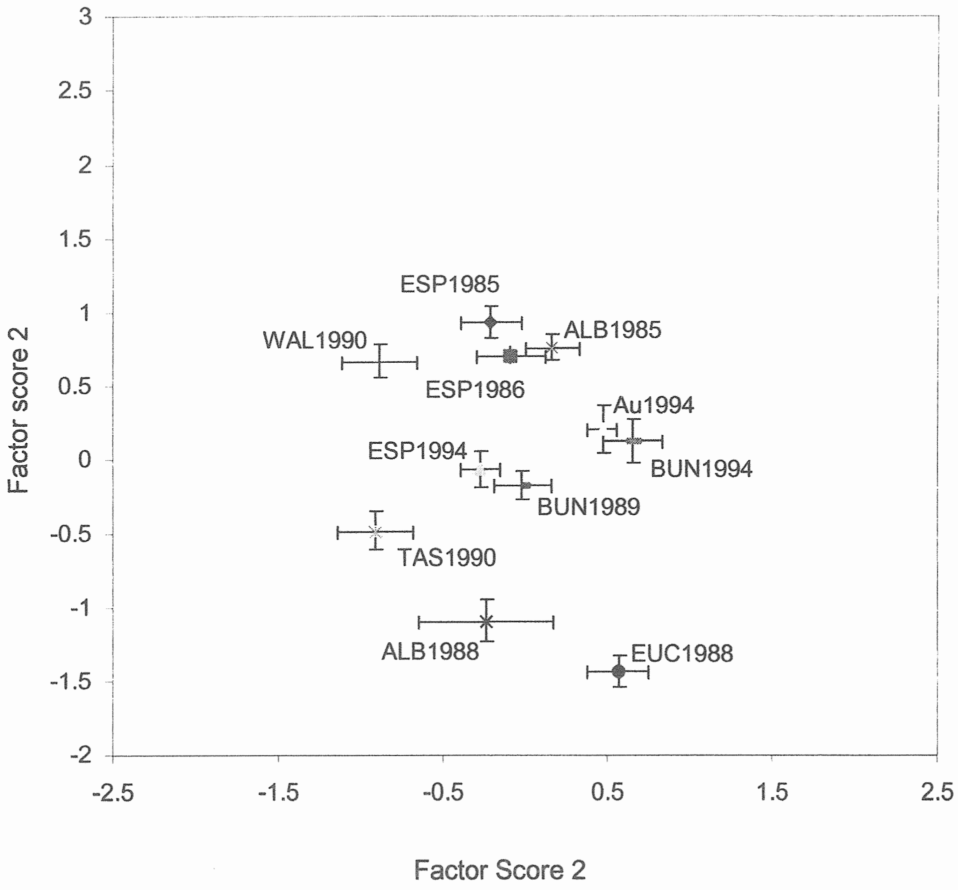
	K	19	7389.32	4005.00	12595.00	2388.54
	Na	19	15322.00	12466.00	18453.00	1662.37
Eucla/1988*	Shark Length (cm)	30	125.88	108.00	152.50	13.89
(EUC1988)	Jaw Thickness (mm)	30	2.79	2.14	3.34	0.35
	Jaw weight (g)	30	0.15	0.08	0.26	0.044
	B	30	35.13	20.00	54.00	11.18
	Ba	30	10.90	5.30	20.40	3.71
	Mg	30	2960.00	2588.00	3469.00	231.90
	Mn	30	17.33	5.90	30.00	6.08
	Sr	30	1206.07	794.00	1537.00	193.47
	Zn	30	65.57	42.00	98.80	17.01
	S	30	12216.97	7243.00	15980.00	2176.71
	Ca	30	187050.00	124000.00	258000.00	33558.58
	P	30	90583.33	67600.00	120000.00	14329.60
	K	30	7213.43	4730.00	10200.00	1382.49
	Na	30	10787.23	8164.00	15050.00	1707.37
Nornalup/1994	Shark Length (cm)	3	101.67	99.00	107.00	4.62
(NOR1994)	Jaw Thickness (mm)	3	2.47	2.05	3.15	0.60
	Jaw weight (g)	3	0.12	0.11	0.14	0.02
	B	3	26.00	24.00	29.00	2.65
	Ba	3	24.00	12.00	31.00	10.44
	Mg	3	2874.33	2391.00	3374.00	491.70
	Mn	3	7.67	6.00	9.00	1.53
	Sr	3	858.67	596.00	1134.00	269.22
	Zn	3	56.00	46.00	72.00	14.00
	S	3	15112.00	8944.00	21504.00	6283.00
	Ca	3	136589.33	88754.00	180128.00	45838.28
	P	3	69045.00	45304.00	89667.00	22345.36
	K	3	7538.67	4957.00	9075.00	2249.23
	Na	3	15488.00	10406.00	21029.00	5326.35
Tasmania/1990	Shark Length (cm)	12	71.70	59.50	90.20	10.15
(TAS1990)	Jaw Thickness (mm)	12	1.52	1.30	1.90	0.19
	Jaw weight (g)	12	.07	0.05	0.09	0.01
	B	12	17.25	0.00	41.00	15.67
	Ba	12	14.99	3.70	24.50	6.19
	Mg	12	2758.33	2080.00	4410.00	573.27
	Mn	12	17.67	9.00	34.00	6.75
	Sr	12	952.25	767.00	1260.00	134.07
	Zn	12	61.17	47.00	75.00	7.70
	S	12	16316.67	10000.00	18900.00	2524.37
	Ca	12	134083.33	111000.00	177000.00	19133.30
	P	12	71666.67	57000.00	88000.00	9208.03
	K	12	8055.00	2060.00	10300.00	2099.31
	Na	12	14241.67	11900.00	16900.00	1432.39
Walpole/1990	Shark Length (cm)	20	95.42	78.00	115.00	13.52
(WAL1990)	Jaw Thickness (mm)	20	1.90	1.65	2.50	0.22
	Jaw weight (g)	20	0.09	0.06	0.13	0.03
	B	20	20.80	4.00	38.00	9.91
	Ba	20	26.81	10.40	59.80	14.08
	Mg	20	2614.00	2230.00	3540.00	324.04
	Mn	20	7.11	4.00	12.00	2.62
	Sr	20	842.95	707.00	1260.00	126.95

	Zn	20	51.75	36.00	74.00	11.89
	S	20	14126.00	7490.00	17300.00	3035.70
	Ca	20	153000.00	124000.00	244000.00	28015.03
	P	20	74300.00	60000.00	117000.00	13318.37
	K	20	3296.50	1710.00	4640.00	913.40
	Na	20	17120.00	6700.00	22500.00	4220.45

* data from Edmonds *et al.* (1996).

The factor scores for locations showed grouping and some separation of sharks from the sites sampled in this study (Figure 5.5). ANCOVA of factor score 1 showed that the location differences accounted for 9 % of the sum of squares. Shark length accounted for a higher proportion of the variability, explaining 13 % of the sum of squares (Table 5.12). Sex and location x sex interaction effects were not significant.

Figure 5.5: Mean factor score 1 (± standard error) versus mean factor score 2 (± standard error) for gummy sharks.



Analysis of covariance of factor score 2 showed that the location differences accounted for a high proportion of the variability, explaining 45 % of the sum of squares (Table 5.13). Shark length was not significant and sex and location x sex interaction effects were not as significant.

Table 5.12: ANCOVA of factor score 1 based on element concentrations in jaw cartilage of gummy sharks.

Source	df	SS	MS	F	p
Location	10	15.1528	1.5153	2.6914	0.0045
Sex	1	0.7069	0.7069	1.2556	0.2641
Location x Sex	7	6.1585	0.8798	1.5626	0.1501
Shark Length	1	22.7159	22.7159	40.3471	0.0000
Residual (Error)	162	91.2080	0.5630		
Total	181	171.6785	0.9485		

Table 5.13: ANCOVA of factor score 2 based on element concentrations in jaw cartilage of gummy sharks.

Source	df	SS	MS	F	p
Location	10	66.0740	6.6074	31.0306	0.0000
Sex	1	0.8750	0.8750	4.1092	0.0443
Location x Sex	7	5.0905	0.7272	3.4152	0.0020
Shark Length	1	0.0101	0.0101	0.0474	0.8279
Residual (Error)	162	34.4949	0.2129		
Total	181	148.2959	0.8193		

Variations in factor score 1 for gummy sharks were more attributable to shark length than location of capture (Table 5.12). Whereas variations in factor score 2 were more attributable to location of capture (Table 5.13). Sampling of gummy sharks was carried out over multiple years for some locations. Samples that were taken over multiple years include Esperance (1985, 1986 and 1994), Albany (1985 and 1988) and Bunbury (1989 and 1994). Of these locations sampled over multiple years, the Esperance factor scores remained relatively constant over a period of two years, but changed considerably over a longer period such as eight years (Figure 5.5). Significant differences were also found in the values for the factor scores for samples taken at Albany in 1985 and 1988, and Bunbury in 1989 and 1994. It is interesting to note the large difference in the factor scores observed for the sharks sampled at Albany for the years 1985 and 1988. This time period in Albany coincides with an increased fishing effort during the late 1980's, which may have impacted on the available food sources for the sharks in this area.

Comparison of the location specific signatures is more difficult in the case of gummy sharks due to the large range of years investigated and the observed change in the elemental composition of shark jaw cartilage with time. However, groups of locations with comparable years include:

Group 1.	Esperance 1985, Esperance 1986 and Albany 1985.
Group 2.	Bunbury 1989, Albany 1988, Eucla 1988, Walpole 1990 and Tasmania 1990.
Group 3.	Augusta 1994, Bunbury 1994, Esperance 1994.

From comparison of the factor scores for the locations sampled in group 1 it is evident that there is little difference in the Albany and Esperance locations. In contrast, all of the locations in group 2 (Bunbury, Albany, Eucla, Walpole and Tasmania) show significant differences based on their factor scores. Whereas the locations in group 3 show significant differences in their factor scores for Esperance and Augusta/Bunbury.

5.2.4 Interpretation of location signatures of shark jaw cartilage

This study has shown that the accumulation patterns of elements in the jaw cartilage of dusky, whiskery, gummy sharks from sites off the southern Australian coast are specific to location and timing of capture. However, only a limited number of whiskery sharks from locations of relatively close proximity were available for this study. Therefore, while some separation is apparent for whiskery shark stocks it is difficult to gauge the significance of the separation in these stocks. Dusky and gummy shark stocks showed significant separation of locations based on the ANCOVA of the factor scores of the elemental concentrations in their jaw cartilage. The elemental composition of shark jaw cartilage for locations sample over a two year period showed no significant variation, however, samples taken over a longer period of time showed significant differences. These differences are likely to be reflecting changing environmental conditions (water chemistry, temperature), and possibly available food organisms, in the different areas. Clearly, if this technique is to be used for the purpose of stock delineation that samples should be taken from locations in the same year or at least within two years.

A strong correlation was also observed between calcium and strontium concentrations in the cartilage (Table 5.14) and it is well known that strontium (and possibly barium) will, because of their similar chemical and physical properties, replace calcium to some extent in calcified biological tissues. The degree of replacement will depend upon their relative availabilities and the extent to which the organism can discriminate them. Calcium and strontium are present in seawater at concentrations of 0.4123 and 0.0081 g/kg respectively (Ripley and Tiongudai 1967). Thus calcium predominates over strontium by a factor of 112 on a molar basis. The ratio of calcium to strontium in gummy shark cartilage (Table 5.14) is 364:1 (molar basis), whiskery shark cartilage (Table 5.14) is 375:1 (molar basis) and dusky shark cartilage (Table 5.14) is 422:1 (molar basis). These values are similar to calcium:strontium values of 353:1 and 357:1 (molar basis) for the jaw cartilage of gummy shark (Edmonds *et al*. 1996) and the cartilage for the ray *Raja batis* (Mauchline and Templeton1966), respectively. However, calcium to strontium ratios in bones of a range of teleost fish from Japanese waters of about 300:1 (molar basis) Ueda *et al.* (1973); and 484-697:1 (molar basis) in teleosts from the Irish Sea (Mauchline and Templeton, 1966) are not greatly different from those recorded in this study for these shark species. Significant correlation for elements reported for gummy shark (Edmonds *et al*. 1996) were also observed in this study for strontium and phosphorus and a significant negative correlation for strontium and sulphur. These presumably again reflect the relative rates of accumulation of calcium and strontium (Edmonds *et al.* 1996).

The diet of gummy, whiskery and dusky sharks has been shown to consist mainly of cephalopoda and crustacea for gummy sharks (pers. comm. Rory McAuley), cephalopoda for whiskery sharks (Table 5.17) and teleosts for dusky sharks (Table 5.15). The common elemental compositions reported for these diets shows that the concentrations of zinc and copper in crustacea and cephalopoda are much greater than those of teleosts. While copper was not measured in this study, zinc concentrations measured for the jaw cartilage of these sharks was found to be highest in whiskery sharks and lowest in the dusky sharks (Table 5.14), which is the expected trend for the diet being responsible for the zinc concentration in the jaw cartilage. These results support the assumption that some elements that make up composition of shark jaw cartilage may be dependent on the available food source. Furthermore, if the elemental composition of the shark jaw cartilage is partially dependent on the sharks diet then this technique may also provide information about the changing dietary habits of shark species at locations, due to changing environmental factors.

Another key factor that may influence the elemental composition of shark jaw cartilage is the retention time of the elements in the cartilage. In contrast with aragonitic carbonate otoliths from teleost fish it can reasonably be assumed that once laid down material in the otolith is not reworked. In the case of shark cartilage such assumptions cannot reasonably be made. Furthermore, the elemental composition of carbonate otoliths are likely to reflect the hydrology of a specific location which may remain constant for significant periods of time. However, this may not be the case with the jaw cartilage were the elemental composition may reflect the available food source which may vary more rapidly due to natural and/or anthropogenic effects.

It is evident from this study that the elemental composition of shark jaw cartilage does persist through time for periods up to two years. However, the elemental composition shark jaw cartilage does vary significantly for periods greater than two years, which is likely to be due to changing environmental conditions (water chemistry, temperature), and/or the available food organisms, in the different areas. Nevertheless this study has shown that cartilage from sharks from different areas can have dissimilar chemical characteristics, suggesting that these stocks are non-mixing. However, further research is necessary to ascertain the ability of this technique as a stock delineation tool and whether this technique can be used to monitor changes in the available food organisms for shark species.

Table 5.14: Summary of shark size and elemental composition data for sharks.

	Gummy		Whiskery		Dusky	
	Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev.
n	189		37		102	
Shark Length (cm)	117.97	21.21	110.32	7.49	99.87	36.92
Jaw Thickness (mm)	2.42	0.60	1.50	0.32	1.59	0.52
Jaw weight (g)	0.13	0.05	0.12	0.02	0.09	0.03
Mg	3063.68	610.13	3232.81	271.47	2997.20	380.44
Mn	21.00	11.54	24.11	4.51	10.04	3.37
Sr	1000.77	195.55	835.15	76.08	542.48	141.73
Zn	50.85	15.06	64.86	9.84	48.89	6.82
S	13238.98	2665.15	12851.38	3704.53	17581.89	4563.46
Ca	166885.27	31813.80	143398.24	12265.93	104764.64	22107.67
P	82890.01	14219.57	76498.65	6247.65	57344.39	10307.40
K	5983.53	2395.45	8369.73	1878.59	9822.52	2691.01
Na	14261.64	3203.86	16560.27	4171.65	21727.25	4458.78
B	20.95	12.03				
Ba	12.38	7.91				

5.3 Biology of adult dusky whalers

5.3.1 Feeding of dusky sharks

Eighteen *C. obscurus* over 200 cm in length had non-empty stomachs. Teleosts were the most commonly observed prey (61.1%), while cephalopods (44.4%) and elasmobranchs (22.2%) were also relatively common (Table 5.15). Teleosts consumed included Aleulidae, Cheilodactylidae, Clupeidae, Monacanthidae, Plotosidae and Scombridae. Elasmobranchs consumed included Heterodontidae and Dasyatididae.

Table 5.15. Occurrence of prey in the stomachs of 18 specimens of *Carcharhinus obscurus* over 200 cm FL. Values in italics indicate totals for groups.

Prey group	n	%
5.3.2 Mollusca		
Cephalopoda	*8*	*44.4*
Unidentified cephalopoda	5	27.7
Cuttlefish	1	5.6
Octopus	2	10.2
5.3.3 Chordata		
Elasmobranchii	*4*	*22.2*
Shark	*3*	*16.7*
Unidentified shark	2	11.1
Heterodontidae		
Heterodontus portusjacksoni	1	5.6
Batoid	*1*	*5.6*
Dasyatididae		
Dasyatis sp.	1	5.6
Teleostei	*11*	*61.1*
Unidentified teleost	4	22.2
Albulidae		
Albula neoguinaica	1	5.6
Cheilodactylidae		
Nemadactylus valenciennesi	1	5.6
Clupeidae		
Sardinops neopilchardus	1	5.6
Labridae	1	5.6
Plotosidae		
Cnidoglanis macrocephalus	1	5.6
Scombridae		
Thunnus maccoyii	1	5.6
Thunnus sp.	1	5.6

5.3.4 Reproductive biology of dusky whalers

5.3.4.1 Female

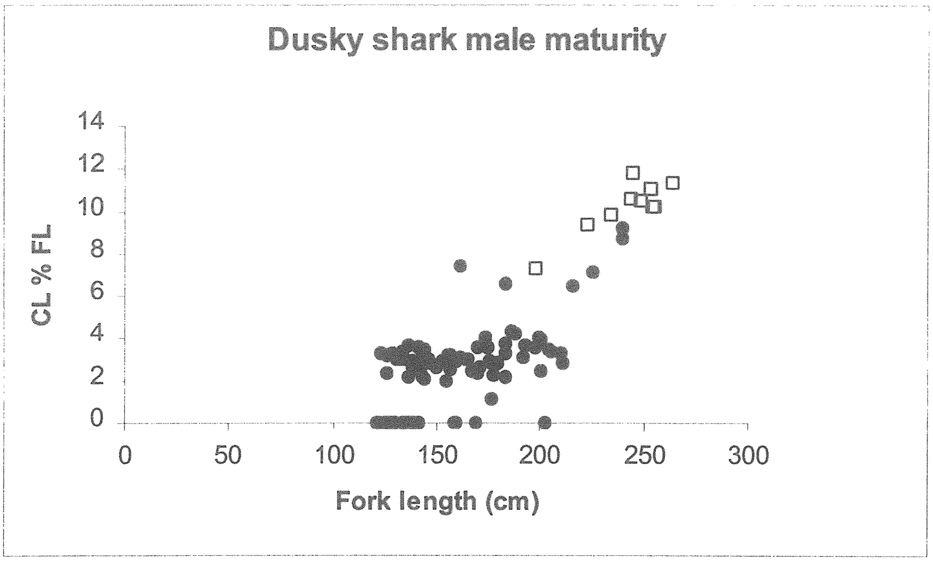
The smallest mature female captured was 220cm FL, and the largest 282 cm FL. Few females over 230 cm FL were immature, but the largest immature female was 269 cm FL. On the basis of these data the size at 50% maturity is approximately 250 cm FL. Three pregnant females were captured, all approximately 270 cm FL. All were full term litters caught between February and June, one of which aborted during capture. The two un-aborted litters both contained 12 embryos between 71 and 75 cm in length. Three additional mature females that had fresh placental scars in the uterus, indicating they had recently given birth, were caught between February and April. On the basis of the data from full-term and post-partum females pupping of *C. obscurus* in Western Australia occurs in between February and June. All full-term and post-partum females were caught south of the Abrolhos Islands, indicating pupping occurs in the southern half of Western Australia.

Two mature females caught in July 1997 had enlarged yolky ova in their ovaries – one had twenty three 20 mm ova, and the other had nine 45 mm ova. Both of these animals were non-pregnant. Both of these animals were captured in the waters of the Northwest Shelf off the Pilbara coast of Western Australia. The results of the reproductive studies indicate that mature female *C. obscurus* may undergo migrations from Western Australia's Pilbara coast (where they spend winter, spring and early summer), and then migrate south to give birth in the south-west of the state.

5.3.4.2 Male

Clasper elongation in male *C. obscurus* begins at around 200 cm FL, with the smallest male with calcified claspers being 225 cm FL (Figure 5.6). The largest male with uncalcified claspers was 240 cm FL. The size at 50% maturity was approximately 240 cm FL. Mature males with running sperm in the epididymis were caught between March and September, with most caught after May. The occurrence of males with running sperm suggests that mating may occur in winter.

Figure 5.6: Maturity of male *Carcharhinus obscurus* as indicated by size and condition of claspers. Solid points indicate uncalcified claspers and open points indicate fully calcified claspers.

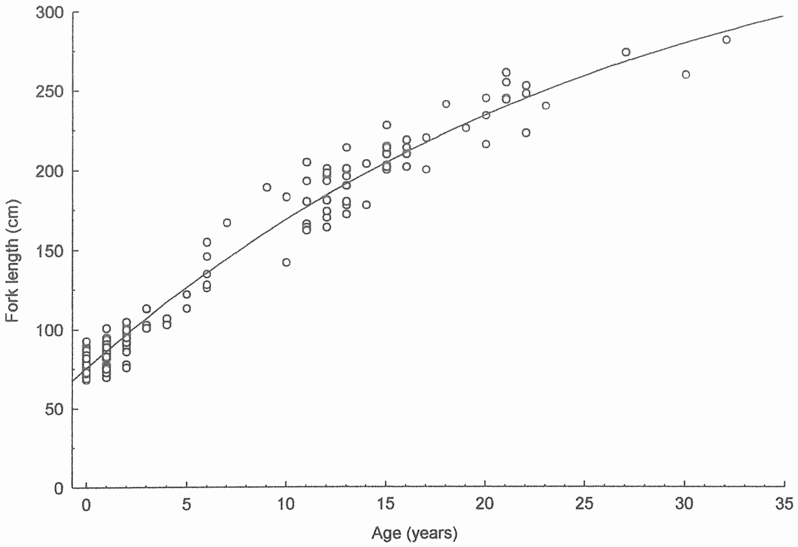


5.3.5 Age and growth of dusky whalers

Vertebrae from 374 *C. obscurus* were sectioned and micro-radiographs produced. Consensus counts between three readers were obtained from 294 specimens ranging in size from neonates 65 cm FL to mature females up to 280 cm FL. Natanson *et al.* (1995) and Natanson and Kohler (1996) demonstrated that the periodicity of growth band formation in *C. obscurus* from the western North Atlantic Ocean and southwest Indian Ocean was most likely to be annual on the basis of marginal increment analysis. Assuming the growth bands of *C. obscurus* from south-western Australia are also formed annually, then the maximum age for *C. obscurus* from south-western Australia reliably aged (consensus counts reached between three readers) was 32 years.

The results of fitting a von Bertalanffy growth curve to the data for males and females combined, using a size at birth of 75 cm FL, were: $L_\infty = 386.8$ cm FL, $K = 0.036$ year^{-1} and $t_0 = -6.08$ years (Figure 5.7). These values are similar to those estimated for other populations of *C. obscurus* using vertebral ageing. The growth rates of tagged juvenile *C. obscurus* in south-western Australia had similar rates of growth as estimated by vertebral ageing providing further verification that growth bands were formed annually.

Figure 5.7: Length-at-age plot for 294 *Carcharhinus obscurus* from south-western Australia. The line represents the von Bertalanffy growth curve for the parameters given in the text.



On the basis of the von Bertalanffy growth curve the age at maturity of males is 22 years, and for females is 24 years. However, high variation in the growth rates of *C. obscurus* probably results in maturity being reached between 15 and 27 years.

5.4 Recruitment index for dusky whalers

5.4.1 Generalised linear model

The recruitment index for *C. obscurus* was calculated based on the catch rate of neonates in three regions (Bunbury, Augusta and Albany) over the years from 1995 to 1999. The results of the GLM are given in Table 5.16 and Figures 5.8. Catch rates were significantly different between years, regions and moon phase. Catch rates did not differ significantly with depth, and there was a significant interaction between regions and years.

Catch rates were significantly different between years (Table 5.16), but there was no obvious trend over time with mean catch rates over time around 13 sharks/1000 km hour (Figure 5.8). Catch rates were significantly higher in the Augusta region than in the Bunbury or Albany regions (Figure 5.9, Table 5.16). Catch rate trends over time varied significantly between regions (Table 5.16), but none showed a consistent trend (Figure 5.10). The influence of moon phase on catch rates was significant (Table 5.16), but appeared to differ between regions. Highest catch rates were observed around the time of the full moon in the Augusta region, at moon phases around 0.8 in the Albany region, while in the Bunbury region there was no clear peak (Figure 5.11).

Table 5.16: Results of the GLM for neonate *Carcharhinus obscurus* in south-western Australia. Astrices in probability column (p) indicate significant effects.

	d.f.	Wald statistic	p
Intercept	1	35.15763	.000*
Depth	1	1.59732	.206
Moon phase	1	8.50903	.004*
Year	4	9.70122	.046*
Region	2	62.50866	.000*
Year*Region	8	73.12690	.000*

Figure 5.8: Marginal mean values estimated by the GLM for the five years used in the *Carcharhinus obscurus* recruitment index. Error bars represent one standard error.

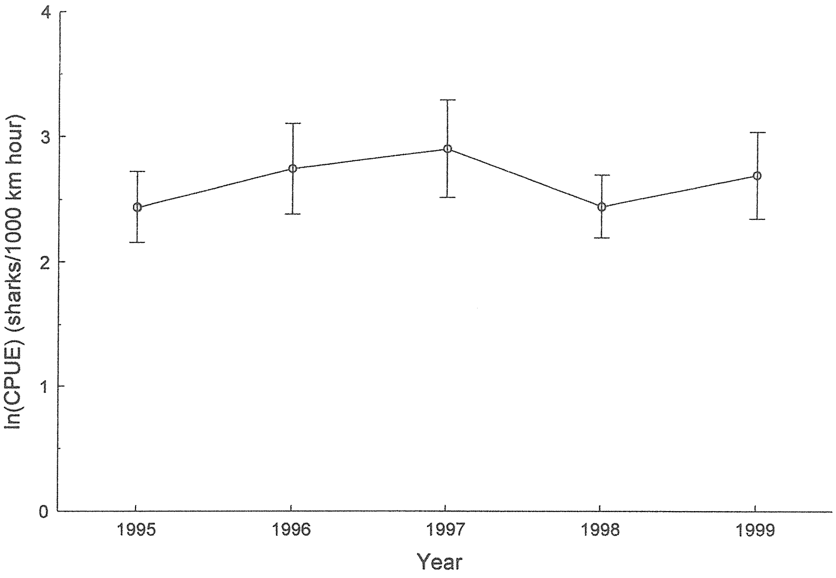


Figure 5.9: **Marginal mean values estimated by the GLM for the three regions used in the *Carcharhinus obscurus* recruitment index. Error bars represent one standard error.**

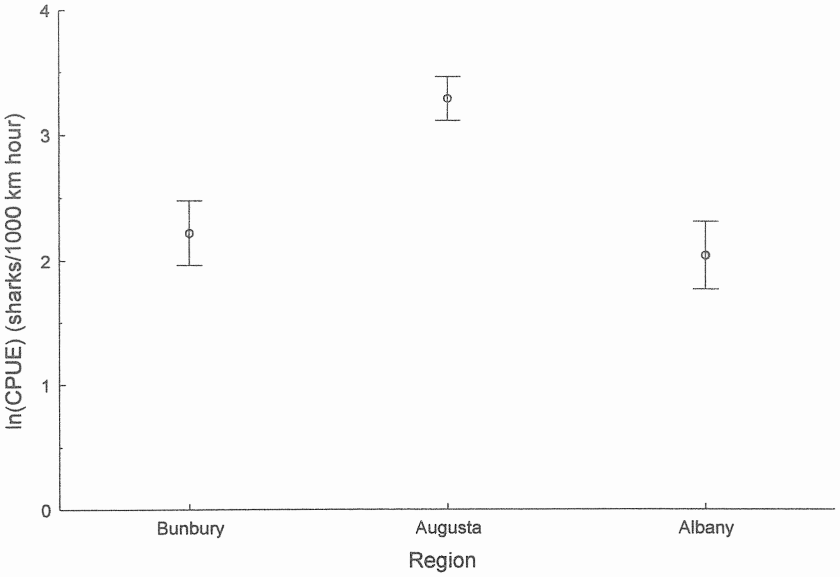


Figure 5.10: **Marginal mean values estimated by the GLM for each of the three regions in each of the five years used in the *Carcharhinus obscurus* recruitment index. Error bars represent one standard error.**

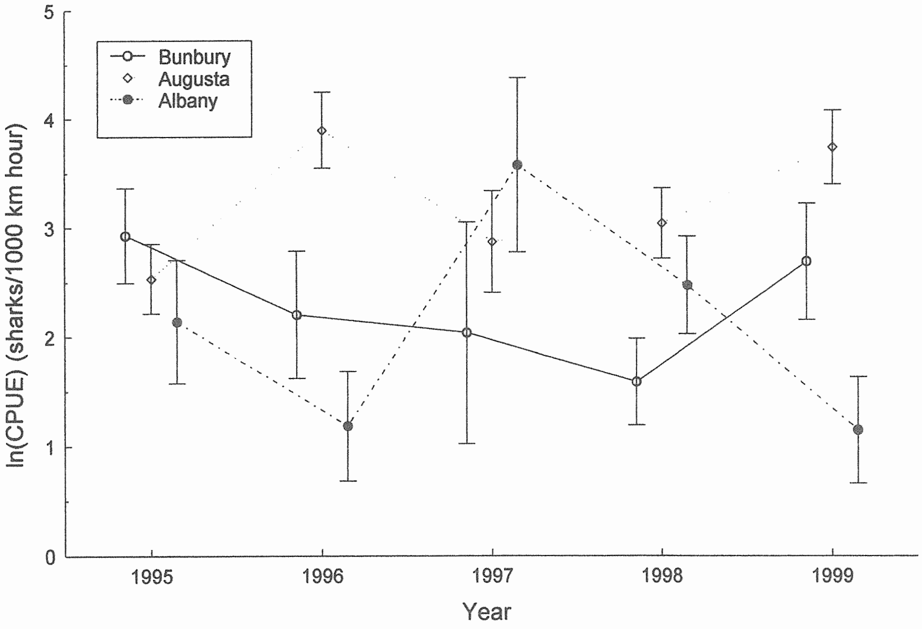
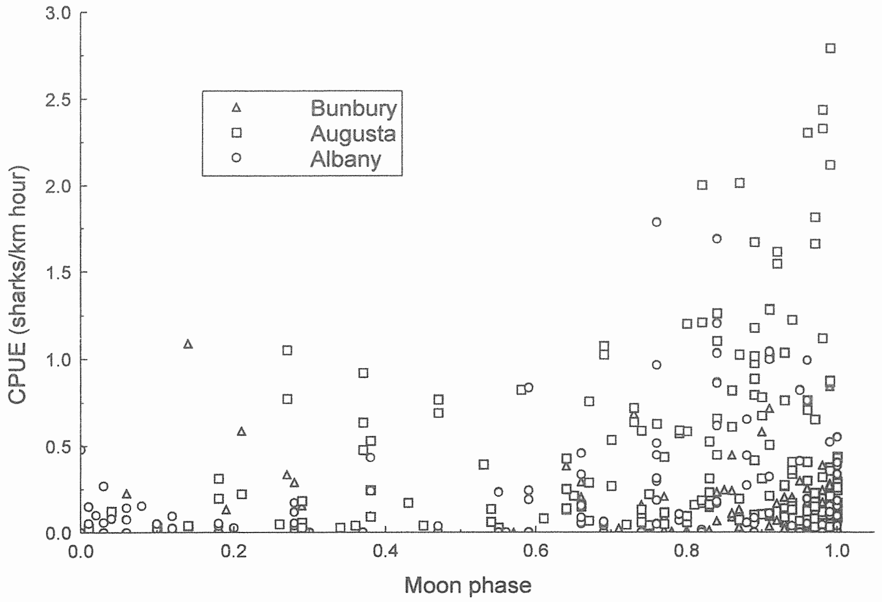
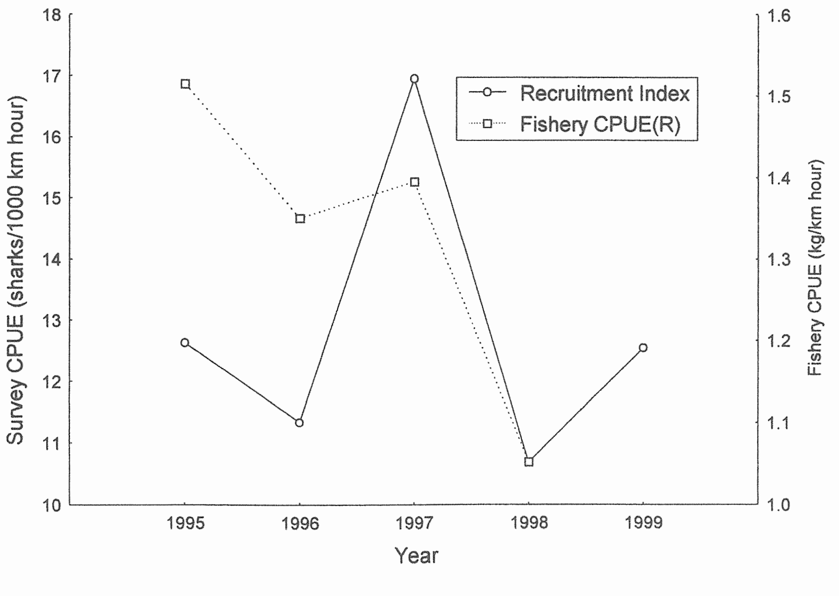


Figure 5.11: **Catch rates by moon phase for the three regions used in the calculation of *Carcharhinus obscurus* recruitment index.**



Comparison of the recruitment index to the annual catch rate of the gillnet fishery in the area where the bulk of *C. obscurus* pupping occurs (the Augusta and Bunbury regions) indicates that the index reflects, at least in part, the catch rates in the fishery (Figure 5.12). The correlation coefficient was 0.477, indicating a relatively low level of correlation. Thus it is unlikely that the annual catch rate of the fishery fully reflects the recruitment in the fishery. The correlations with environmental parameters discussed below are thus likely to reflect influences on the stock as a whole and/or the fishery.

Figure 5.12: **Comparison of the *Carcharhinus obscurus* recruitment index and the annual catch rate for zone 1 (Bunbury to Augusta) of the Southern Demersal Gillnet and Demersal Longline Limited Entry Fishery. At the time of writing data were not available for the commercial fishery for 1999.**

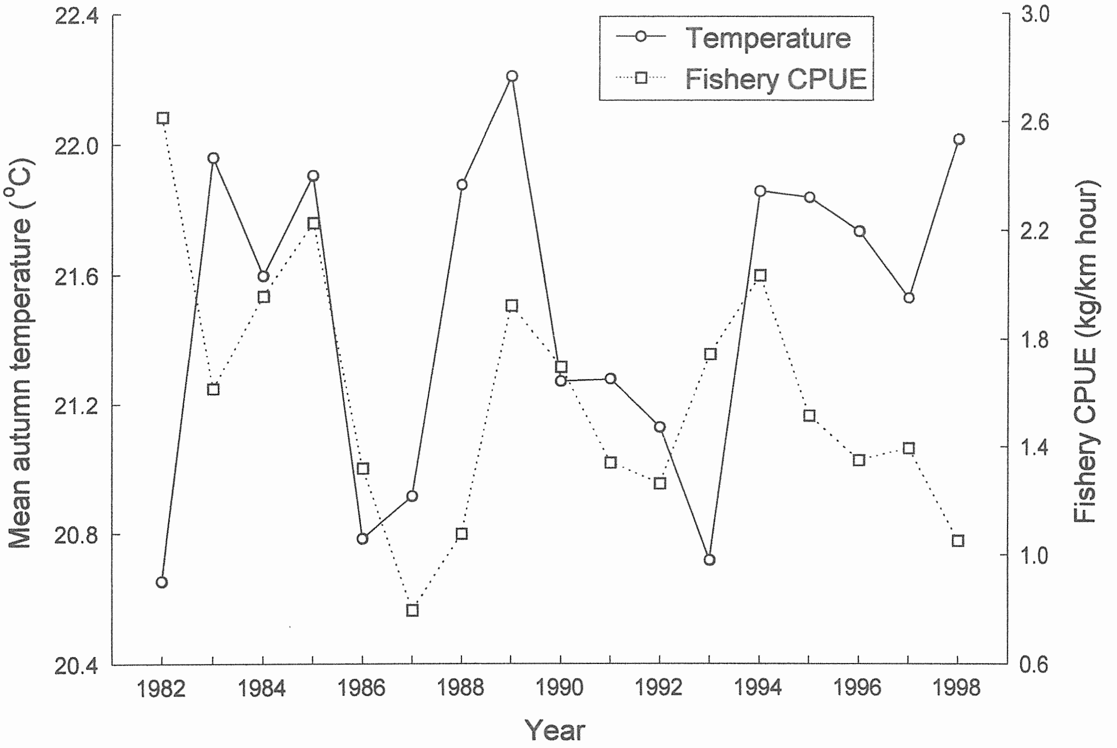


5.4.2 Environmental influences

5.4.2.1 Temperature

Comparison of annual commercial catch rates from the fishery in the area where the majority of *C. obscurus* pupping occurs to mean sea surface temperatures for the main pupping season (March to May) indicates that there is no significant effect (Figure 5.13). The correlation coefficient (r) was -0.0093, indicating that sea surface temperature explains approximately 0.009% of the variation in catch rate.

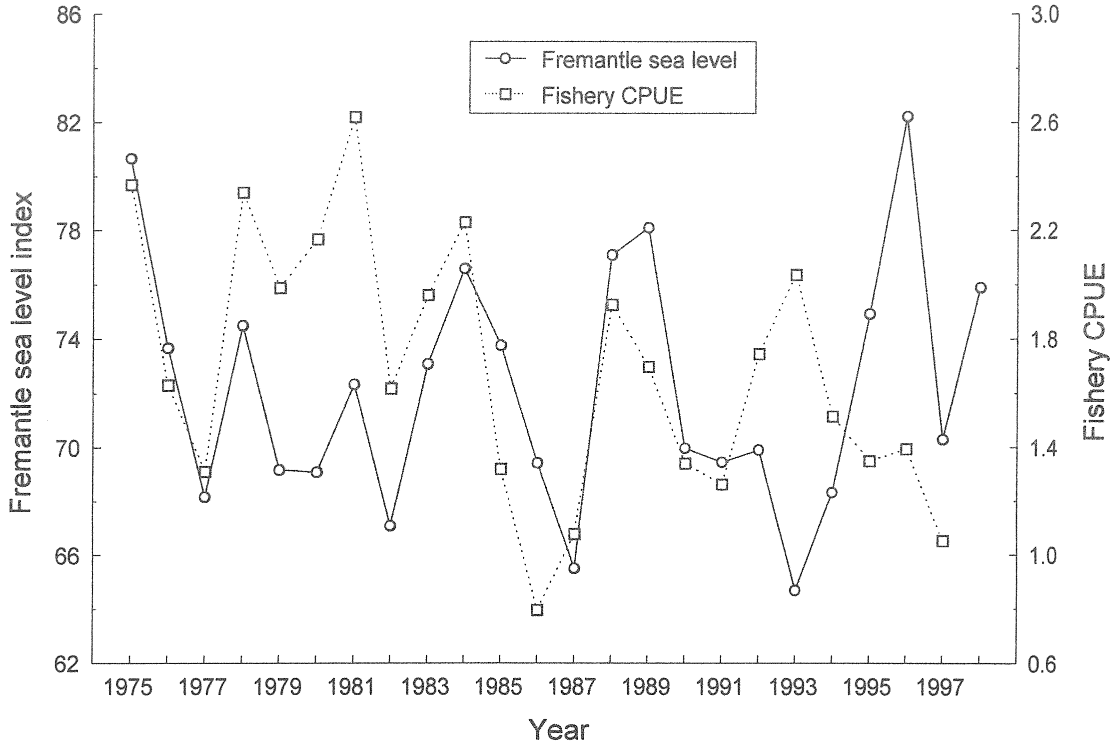
Figure 5.13: Annual catch rates of *Carcharhinus obscurus* from zone 1 (Bunbury to Augusta) of the Southern Demersal Gillnet and Demersal Longline Limited Entry Fishery and mean sea surface temperature for the same area during the main pupping period (March to May) from the Reynold's temperature data.



5.4.2.2 Leeuwin Current

Comparison of annual commercial catch rates from the fishery in the area where the majority of *C. obscurus* pupping occurs to annual Fremantle sea level (an indicator of the strength of the Leeuwin Current, higher values indicate a stronger current) indicates that there is no significant effect. The correlation coefficient (r) was 0.284, indicating that Fremantle sea level explains approximately 8% of the variation in catch rate. Visual examination of the time-series data (Figure 5.14) from the 1970s and 1980s suggested that Fremantle sea level and catch rate may be correlated, however, during the 1990s the complete opposite occurs, with catch rates showing the opposite trend to Fremantle sea level.

Figure 5.14: Annual catch rates of *Carcharhinus obscurus* from zone 1 (Bunbury to Augusta) of the Southern Demersal Gillnet and Demersal Longline Limited Entry Fishery and annual Fremantle sea level index since 1975.



5.5 Biology of whiskery sharks

5.5.1 Diet of whiskery sharks

The diet of *F. macki* consisted almost exclusively of cephalopods (95.7% of stomachs with food present) (Table 5.17). The cephalopod prey group was comprised of octopus (70.2%), unidentified cephalopods (22.3%), and cuttlefish and squid for the remainder (Table 5.17). Unidentified crustaceans a hermit crab (0.8%) and teleosts (4.8%) were the only non-molluscan prey consumed by *F. macki* . A specialised cephalopod diet was exhibited throughout the size range and by both sexes.

Table 5.17: Stomach contents of 372 *Furgaleus macki* caught off Western Australia by commercial gillnetting. Stomach contents are expressed as occurrence (n) and percentage occurrence (%). Numbers in italics indicate summary totals for broad prey groups.

Prey items	n	%
Arthropoda		
Crustacea	*3*	*0.8*
Unidentified crab	2	0.6
Paguridae	1	0.3
Mollusca		
Cephalopoda	*356*	*95.7*
Unidentified cephalopod	83	22.3
Cuttlefish	3	0.8
Octopus	261	70.2
Squid	9	2.4
Chordata		
Teleostei	*18*	*4.8*
Unidentified teleost	14	3.8
Monacanthidae	3	0.8
Mullidae	1	0.3
Others		
Unidentified food	1	0.3

5.5.2 Age and growth of whiskery sharks

5.5.2.1 Vertebral ageing

Vertebrae from 598 *F. macki* were processed and micro-radiographs produced. The length of specimens varied in size from 50 to 140 cm FL, with the majority between 100 and 130 cm FL (Figure 5.15). The radius of vertebrae ranged from 3.4 to 8.1 mm, with the majority between 5.0 and 7.3 mm (Figure 5.16). The relationship between radius and fork length for 534 individuals was allometric, with the 95% confidence interval of v being 0.53 to 0.63.

Figure 5.15: **Length frequency distributions of (a) male, (b) female, and (c) combined sexes (including individuals for which sex could not be determined) *Furgaleus macki* from which vertebrae were used in age determination.**

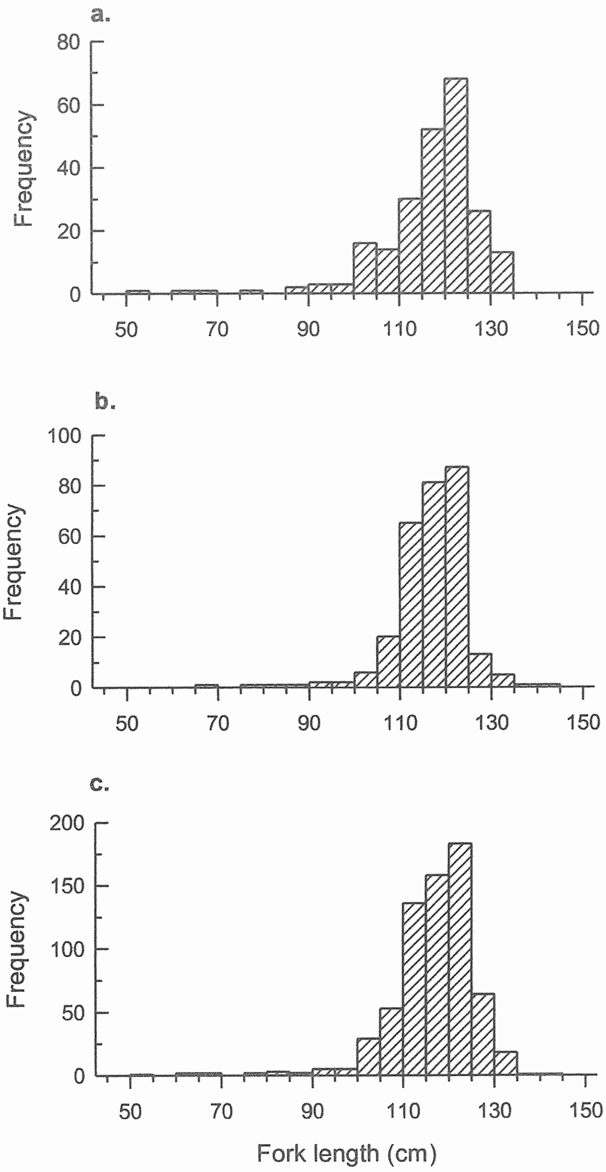
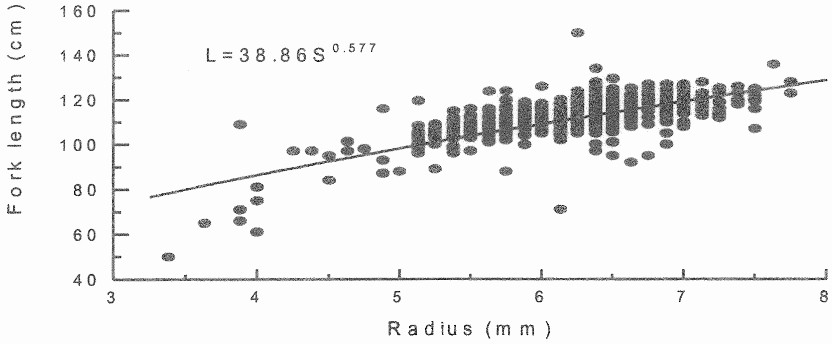


Figure 5.16: Relationship between centrum radius and fork length of 534 *Furgaleus macki* from south-western Australia.



The clarity of bands on centra varied considerably between individuals. The readability of micro-radiographs from 102 (17%) individuals had a readability of less than two, and so were excluded from the analysis of age. Of the remaining 496 vertebrae 308 (62%) had a readability of 2, 184 (37%) had a readability of 3, and 2 (1%) had a readability of 4.

Band counts varied between readers. The average band counts were similar for readers A, B, and D, but were at least 1.5 bands higher for reader C (Table 5.18). The IAPE of band counts for each reader did not differ greatly, and was lowest for reader A and highest for reader D (Table 5.18). The number of specimens for which consensus counts could be reached were highest for reader A and lowest for reader C (Table 5.18). Final band counts across all Readers were obtained for a total of 277 individual *F. macki*, 258 of which were from specimens with readability values of 2 or greater. Individual readers contributed differentially to the final counts. Reader A had the highest level of agreement between consensus and final counts, readers B and D had similar levels of agreement, and reader C had a low level of agreement (Table 5.18).

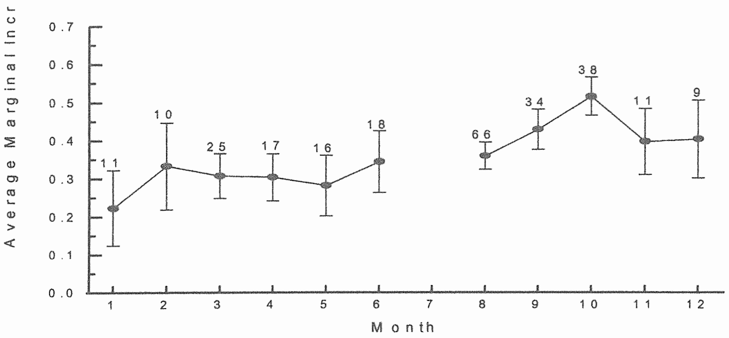
Table 5.18: Assessment of band counts for *Furgaleus macki* from south-western Australia by individual readers.

Reader	Average count	IAPE	Number of consensus counts	% agreement with all final counts (n=277)	% agreement with final counts for vertebrae with readability ≥ 2 (n=258)
A	6.33	8.46	452	70.4	75.2
B	6.01	9.60	412	57.0	61.2
C	7.95	9.39	413	29.6	29.2
D	6.44	10.20	317	62.4	67.0
Final	6.57	-	277	-	-

Marginal increments were measured from 146 individual *F. macki*. Lowest monthly mean marginal increments were recorded in January, with an increasing trend throughout the year (Figure 5.17). This indicated that a single band was formed each year between

December and January in *F. macki*. Since parturition occurs from August to October (Simpfendorfer and Unsworth, 1998a) the first band would have been formed either at an age of 3 to 5 months, or 15 to 17 months. Given the size of individuals that had a single band (50-61 cm FL) it was assumed that the band was formed after 15-18 months as growth to these sizes within 3-6 months was not consistent with the growth rates of other species of triakid sharks (e.g. Yudin and Cailliet 1990; Moulton *et al.*, 1992; Rountree and Able, 1996).

Figure 5.17: Mean monthly marginal increments of opaque bands for *Furgaleus macki* from south-western Australia. Error bars represent ± one standard error. Numbers above each month indicate sample sizes.



The majority of specimens that had consensus counts were aged between 4.5 years and 10.5 years. The maximum age of an individual from final counts (consensus between readers) was 10.5 years from males, and 11.5 years for males. The maximum age based on the consensus for a single reader (but not between readers) was 12.5 year, with the highest individual band count by any reader being 16 (=16.5 years).

Von Bertalanffy growth curves were fitted to the length-at-age data assuming that bands were formed annually after the first band was completely formed after 18 months (Figure 5.18). Growth of males and females appeared to be rapid over the first three or fours years, but subsequently slowed. There appeared to be little or no increase in length after four or six years of age for males and females, respectively. The von Bertalanffy growth parameters for males, females and combined sexes were similar (Table 5.19), with *K* values slightly larger for males and combined sexes, than for females.

Figure 5.18: Von Bertalanffy growth curves for (a) male, (b) female, and (c) combined sexes (including individuals for which sex could not be determined) *Furgaleus macki* from south-western Australia. Dashed line on (c) represents the von Bertalanffy growth curve estimated from tag-recapture data using the Francis (1988) model

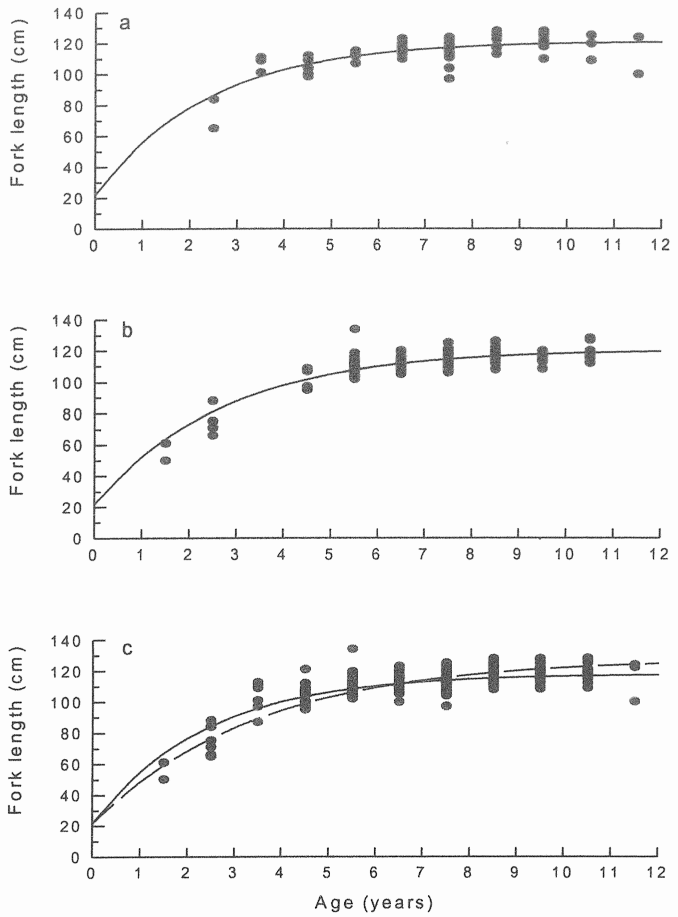


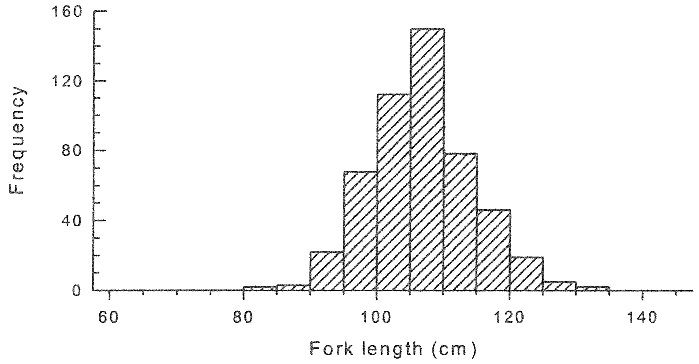
Table 5.19: Von Bertalanffy growth parameters for *Furgaleus macki* from south-western Australia estimated using length-at-age data.

	Male	Female	Combined sexes
L_∞ (cm FL)	121.5	120.7	118.1
K (year^{-1})	0.423	0.369	0.420
t_0 (years)	-0.472	-0.544	-0.491
n	67	112	258

5.5.2.2 Tag-recapture data

A total of 512 *F. macki* ranging from 81 to 135 cm FL, with most between 95 and 120 cm FL, were tagged and released in south-western Australia (Figure 5.19). Fifty tagged *F. macki* were recaptured after periods at liberty between 1 and 1226 days, and ranged in size from 98 to 134 cm FL. Growth analysis was conducted on 29 individuals that had sufficient recapture data, and had been at liberty at least 60 days (25 were at liberty greater than 300 days).

Figure 5.19: Length frequency distribution of 512 tagged *Furgaleus macki* released in south-western Australia.



The results of the analysis of the tag recapture data using the Francis (1988) model are given in Table 5.20. The von Bertalanffy growth parameters derived from the g_α and g_β values were $K = 0.288$ year^{-1} and $L_\infty = 128.2$ cm FL. By fixing the size at birth at 22 cm FL the t_0 value was estimated to be -0.654 years. The growth curve described by these parameters is similar to that of the combined sexes growth curve derived from the vertebral ageing data (Figure 5.18c).

Table 5.20: Estimates of parameters from the Francis (1988) growth model for 29 tagged and recaptured *Furgaleus macki* from south-western Australia.

Parameter	Estimated value
g_α	7.05 cm FL year^{-1}
g_β	2.04 cm FL year^{-1}
v	0.13 cm FL year^{-1}
m	0.14 cm FL
s	1.18 cm FL
p_c	0.20

5.5.3 Movement of whiskery sharks

A total of 618 *F. macki* were released in southern Western Australia between March 1994 and June 1999. To date a total of 70 have been recaptured. The time at liberty for most animals was less than 400 days, but was as high as 1700 days (Figure 5.20). This is likely to increase with further recaptures and the estimated maximum age of *F. macki*. The majority of recaptures were made at distances less than 50 km from the point of release (Figures 21 and 22). However, some animals moved distances up to 550 km, including between the south and west coasts (Figure 5.21). There was little relationship between the distance moved and the time at liberty, with several animals having moved long distances (>300 km) in less than 400 days (Figure 5.23).

Figure 5.20: Time at liberty histogram for *Furgaleus macki* tag recaptures in southwestern Australia.

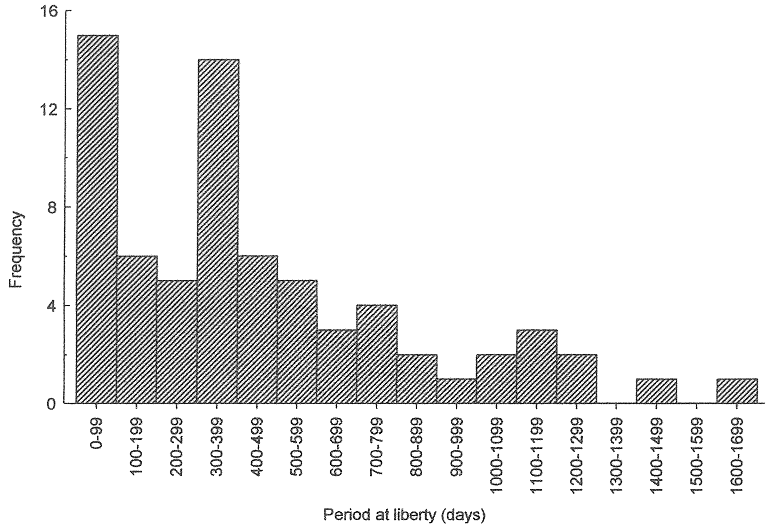


Figure 5.21: Movements of *Furgaleus macki* from tag-recapture data in south-western Australia

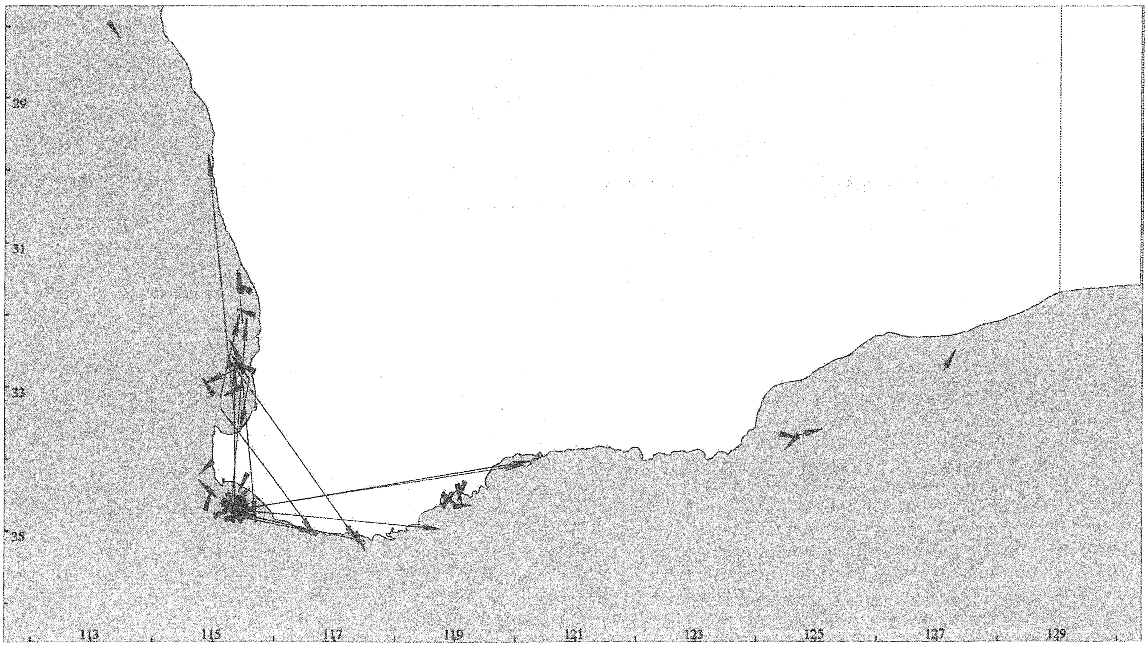


Figure 5.22: **Histogram of distance moved for *Furgaleus macki* tag recaptures from southwestern Australia. Distances have been calculated as distanced moved around the coast, not straight-line distances.**

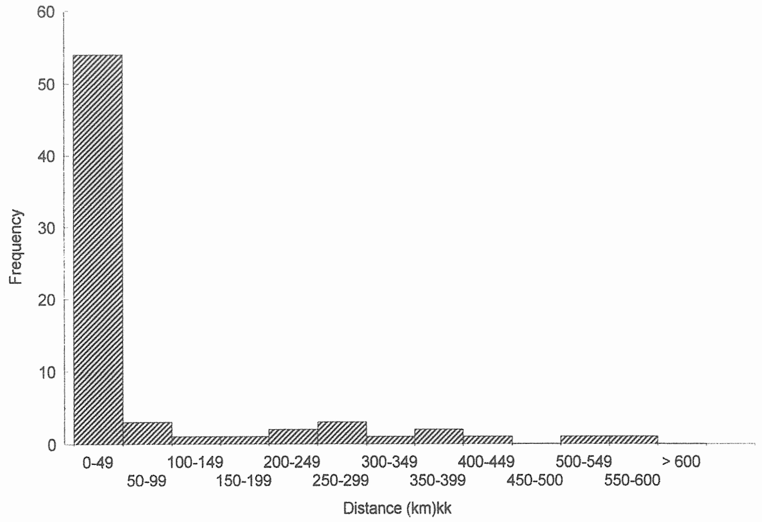
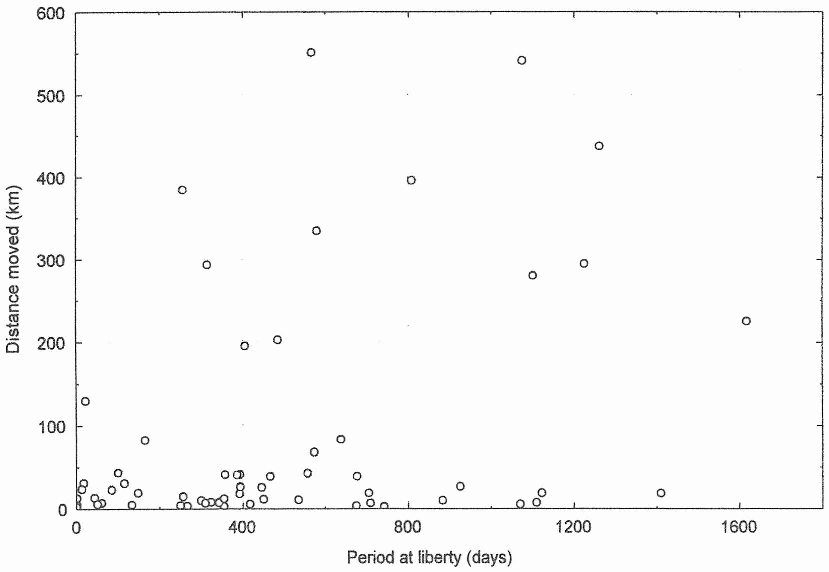


Figure 5.23: **Time distance plot for *Furgaleus macki* recaptures in southwestern Australia.**



5.6 Further analysis of dusky whaler recaptures

5.6.1 Movements of dusky whalers

Since the completion of FRDC project 93/067 103 more recaptures of *C. obscurus* have been reported, making a total of 442 reported recaptures. The periods at liberty range from 0 to 1706 days, with the majority caught in the first 400 days after release (Figure 5.24). Many of the animals tagged have moved between the west and the south coasts in both directions (Figure 5.25). Most recaptures have been made at distances less than 100 km from the point of release, but over 150 have been recaptured at distances between 100 and 600 km from the point of release (Figure 5.26). The longest distance moved has been 2205 km. There is little relationship between the time at liberty and the distance moved (Figure 5.27).

Figure 5.24: Time at liberty histogram for *Furgaleus macki* tag recaptures in southwestern Australia.

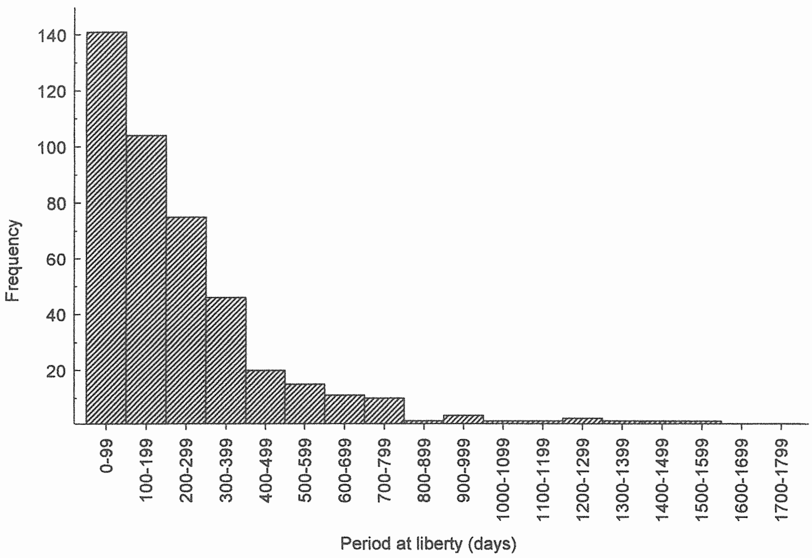


Figure 5.25: **Movements of *Carcharhinus obscurus* from tag-recapture data in south-western Australia**

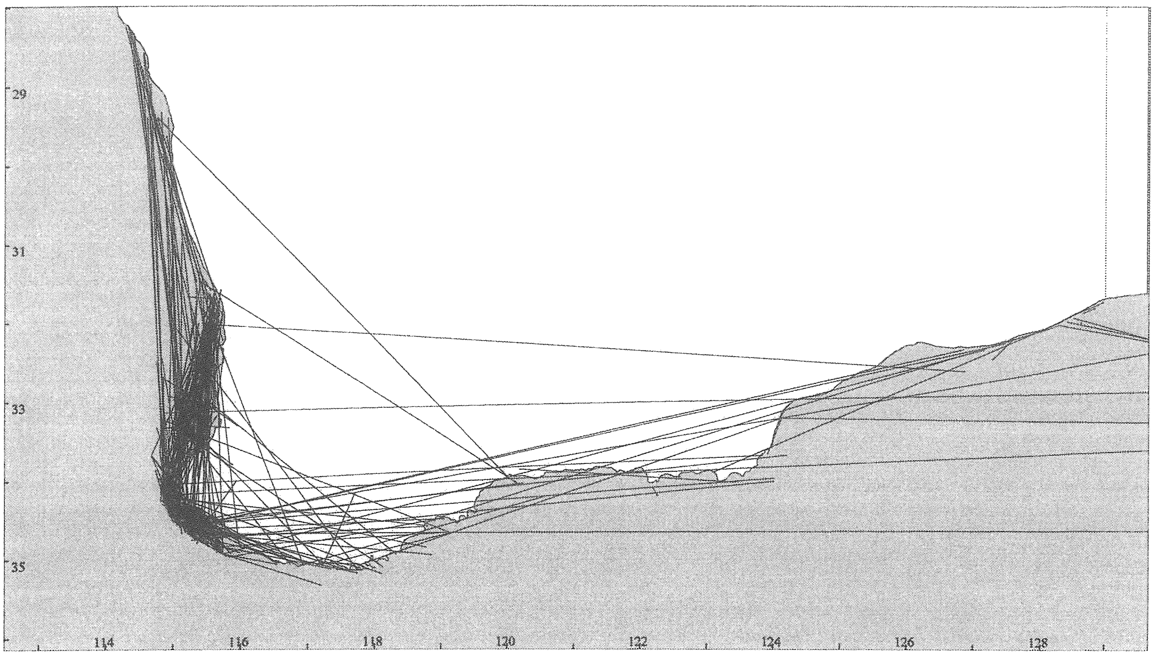


Figure 5.26: **Histogram of distance moved for *Carcharhinus obscurus* tag recaptures from southwestern Australia. Distances have been calculated as distanced moved around the coast, not straight-line distances.**

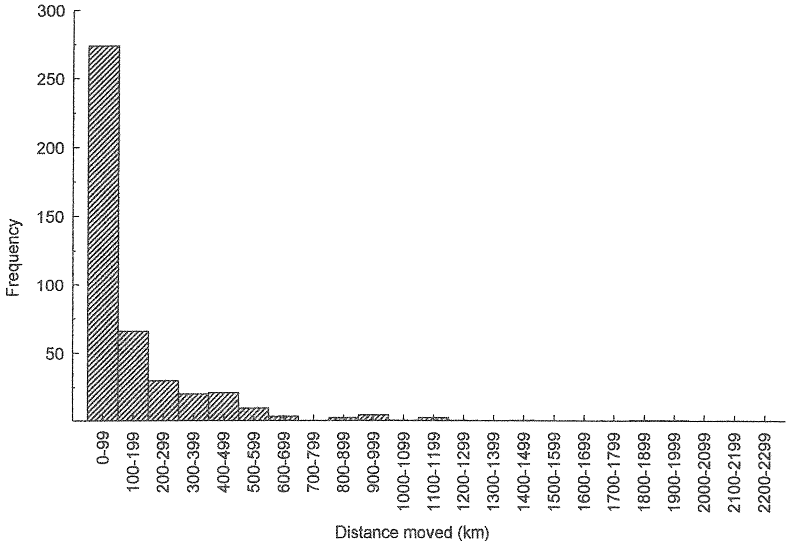
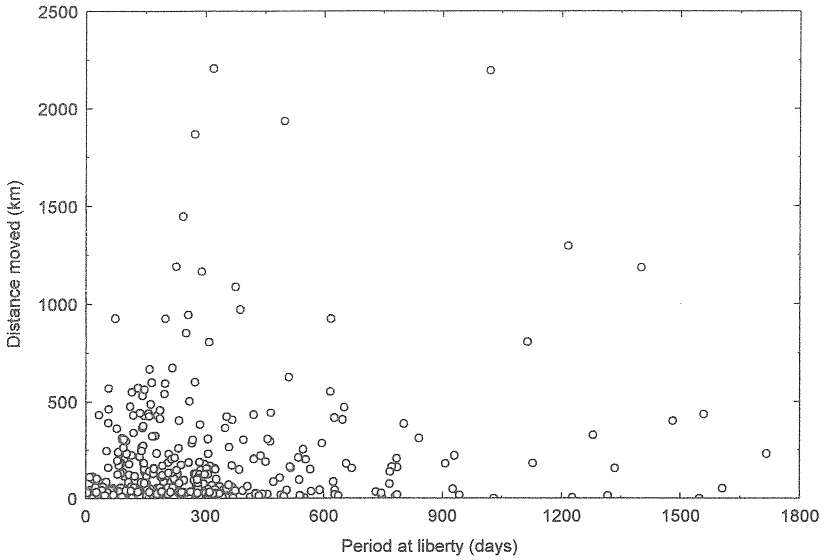


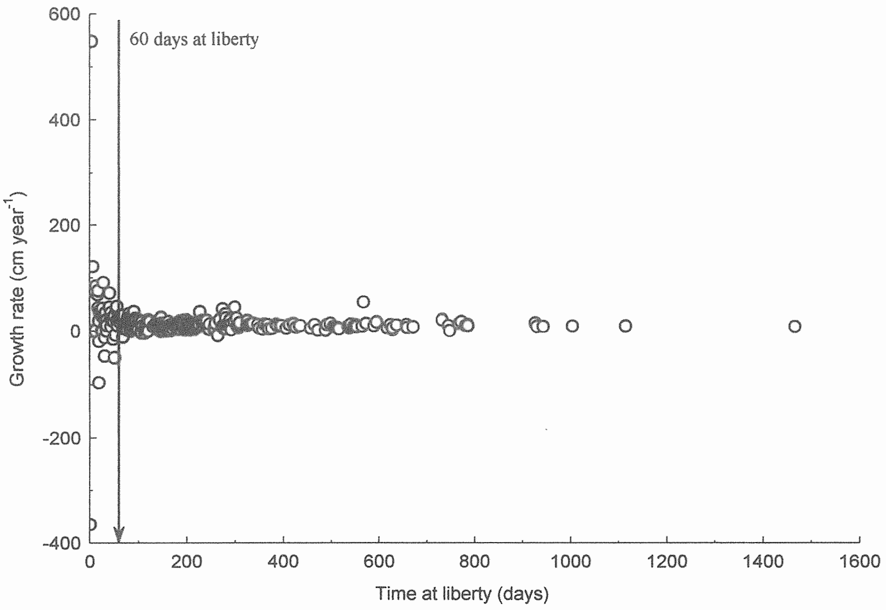
Figure 5.27: Time distance plot for *Carcharhinus obscurus* recaptures in southwestern Australia.



5.6.2 Growth of dusky whalers

A total of 473 recaptures were reported to September 1998, of which 339 had useable length-at-recapture data. Animals without useable length data were excluded from this study. Recaptured animals were at liberty between 0 and 1716 days (4.7 years), with 7 at liberty greater than 3 years. Tag-recapture data from individuals that were at liberty for more than 60 days were used in the analysis of growth. Individuals at liberty less than 60 days were excluded as many individuals had growth rates that were beyond those considered reasonable because of the short period at liberty (Figure 5.28). The size at recapture ranged from 68.5 cm FL to 147 cm FL. There were 274 recaptures with useable data that were at liberty for 60 days or more, including 137 males, 130 females, 111 animals injected with OTC, and 160 non-injected animals.

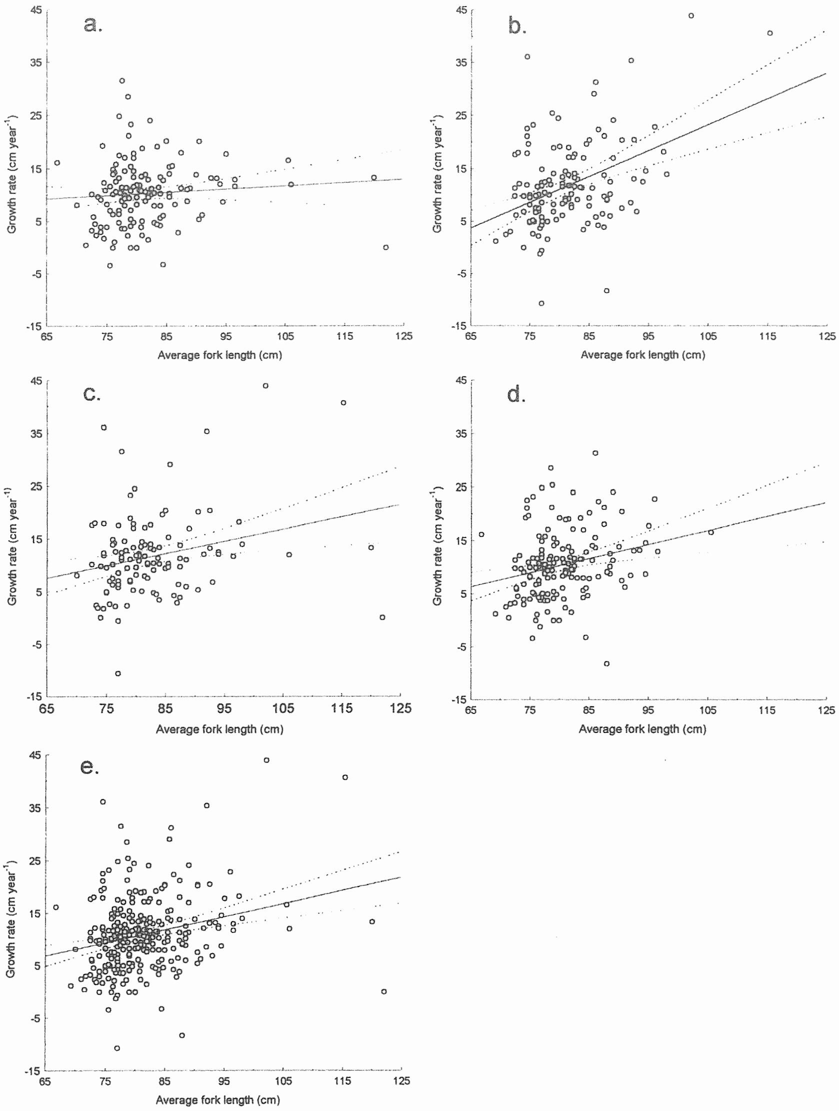
Figure 5.28: Growth rates of recaptured juvenile *Carcharhinus obscurus* from south-western Australia as a function of time at liberty. The line indicates 60 days at liberty, the time below which individuals were excluded from analysis.



5.6.2.1 Gulland and Holt (1959) method

Linear regressions fitted to the plots of growth rate versus average fork length (Figure 5.29) produced negative estimates of *K* and $L_\infty = \infty$ for each of the five groups examined. These results indicate that this method was unable to estimate growth parameters for juvenile *C. obscurus*.

Figure 5.29: Gulland and Holt (1959) plots for (a) male, (b) female, (c) injected, (d) non-injected, and (e) all, *Carcharhinus obscurus* from south-western Australia. Solid lines represent linear function fitted to data, and dotted lines indicate 95% confidence intervals.



5.6.2.2 Fabens (1965) method

Von Bertalanffy growth parameters estimated by the Fabens (1965) method varied widely (Table 5.21). All of the groups, except the non-injected individuals, produced estimates of K between 0.092 year^{-1} and 0.187 year^{-1}, and estimates of L_∞ between 142 cm FL and 194 cm FL. For the non-injected individuals the estimate of K was 0.031 and L_∞ was 379 cm FL. Values of r^2 for all groups were relatively high, indicating that the von Bertalanffy parameters explained most of the variation in the data.

Table 5.21: Estimates of von Bertalanffy growth parameters using the Fabens (1965) method for juvenile *Carcharhinus obscurus* from south-western Australia.

Group	L_∞ (cm)	K (year^{-1})	r^2
All	177	0.111	0.74
Male	195	0.092	0.80
Female	142	0.187	0.67
Injected	156	0.167	0.73
Non-injected	379	0.031	0.72

5.6.2.3 Francis (1988) method

The results of the LRTs for the group containing all of the useable recaptures indicate that the addition of parameters in most situations increased the likelihood of the result (Table 5.22). The simplest model, containing three parameters had the lowest likelihood. The models with all six parameters, and that with all of the parameters except the mean measurement error, had the lowest likelihood and were not significantly different. For consistency, and for ease of comparison between groups, the model with all six parameters was used in all situations.

Table 5.22: Growth parameter estimates using the Francis (1988) method for models with different combinations of the model parameters, and the results of likelihood ratio test comparing the increased significance of the results. Results are displayed in order of increasing likelihood. Results are for the group containing all useable recaptures of juvenile *Carcharhinus obscurus* from south-western Australia. ** following likelihood value indicates a significantly better fit based on the results of the likelihood ratio test.

Model	g_{75}	g_{100}	v	s	m	p	Likelihood
A	11.4	8.3	0.69	-	-	-	-834.98
B	10.5	7.8	0.75	-	0.50	-	-834.17
C	11.3	8.2	0.62	1.54	-	-	-831.06**
D	10.8	7.9	0.65	1.49	0.29	-	-830.85
E	10.8	8.7	0.58	-	-	0.03	-806.37**
F	8.8	8.2	0.68	-	1.01	0.03	-802.07**
G	10.2	10.0	0.36	2.14	-	0.03	-779.76**
H	9.4	9.4	0.39	2.10	0.63	0.03	-778.07

The Francis (1988) method produced similar parameter estimates between all of the groups examined (Table 5.23). There were no significant differences in parameter values between groups, except that males had a significantly lower contamination probability than females, and females had a significantly high value of *s* than males.. Values of g_{70}

and g_{100} were very similar for all groups, indicating little or no change in the growth rate over this size range of *C. obscurus* examined in this study.

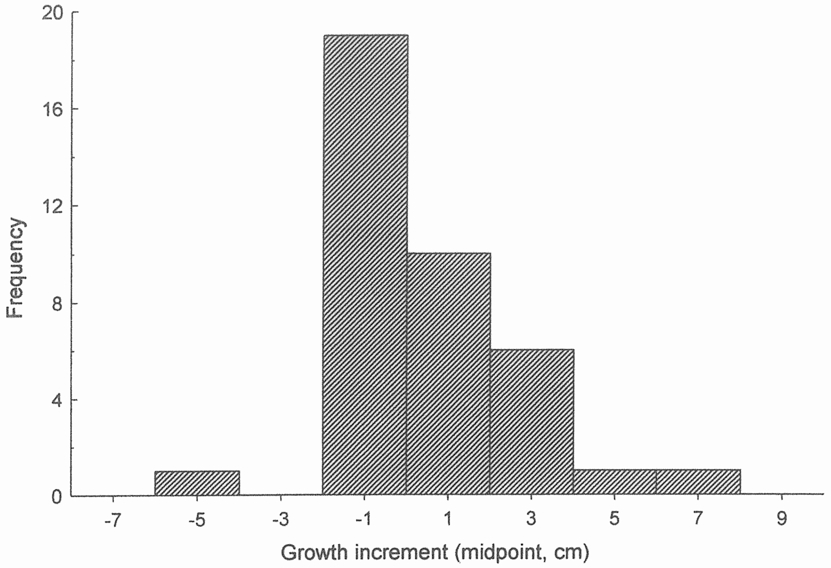
Table 5.23: Growth parameter estimates for *Carcharhinus obscurus* from south-western Australia using the Francis (1988) method with six parameters. Figures in parentheses after estimates are 95% confidence intervals calculated by bootstrapping. The values of *K* and L_∞ based on parameter estimates are given for comparison to other methods.

Parameter	All	Male	Female	Injected	Non-injected
g_{70} (cm year^{-1})	9.36 (8.5-10.5)	9.26 (7.8-11.1)	8.67 (6.9-10.6)	10.87 (9.4-13.1)	8.26 (7.0-9.8)
g_{100} (cm year^{-1})	9.35 (7.7-10.4)	9.25 (6.8-10.6)	8.66 (5.3-10.1)	10.41 (7.8-11.9)	8.25 (5.1-9.6)
v	0.39 (0.31-0.46)	0.43 (0.30-0.54)	0.40 (0.25-0.53)	0.28 (0.16-0.38)	0.44 (0.31-0.58)
s	2.10 (1.6-2.5)	0.28 (0.2-0.4)	2.20 (1.4-2.8)	2.26 (1.5-2.9)	1.98 (1.3-2.5)
m (cm)	0.63 (-0.1-1.2)	0.51 (-0.5-1.4)	1.13 (0.07-2.1)	0.09 (-1.3-1.2)	1.04 (0.1-1.9)
p	0.03 (0.01-0.07)	0.0 (0.0-0.01)	0.09 (0.03-0.2)	0.07 (0-0.09)	0.04 (0-0.09)
K (year^{-1})	0.00037	0.00037	0.00035	0.018	0.00033
L_∞ (cm)	25099	25092	25114	660	25095

The value of g_{70} was 2.61 cm year^{-1} higher in the injected versus non-injected groups (Table 5.23). This difference was not significant at the 95% level, however, the results of the bootstrapping indicated only 13% overlap in estimates. There was a much greater overlap in bootstrap estimates of g_{100} between the injected and non-injected groups.

The values of *v*, the coefficient of variation of growth variability, indicated a high level of individual variation in growth for all groups examined (Table 5.23). Mean measurement error varied between 0.086 cm (injected) and 1.12 cm (female) (Table 5.23). The standard deviation of the measurement error, however, was very similar between groups, varying only from 1.87 cm to 2.26 cm. If it is assumed that animals at liberty less than 30 days did not grow significantly, then the observed growth increment should provide an approximation of the measurement error. The mean difference in size for 38 *C. obscurus* at liberty less than 30 days was 1.17 cm FL, and the standard deviation was 2.09 cm (Figure 5.30). These values are similar to those estimated from the model for most of the groups.

Figure 5.30: Differences between release and recapture lengths for 38 juvenile *Carcharhinus obscurus* at liberty less than 30 days off south-western Australia.



5.6.2.4 Length-at-age for neonate releases

Parameter estimates based on the length-at-age for neonate releases (Figure 5.31) varied considerably between groups (Table 5.24). However, all groups had similar growth rates up to four years of age. The groups containing all, males and non-injected animals had very large L_∞ values and low K values. There were substantial differences in parameters between males and females, and injected and non-injected animals. Values of r^2 indicate that the von Bertalanffy parameters explain approximately 50% of the variation in length for each of the groups. Results of all methods that provided useable answers are illustrated in Figure 5.32.

Figure 5.31: **Length-at-age plots for (a) male, (b) female, (c) injected, (d) non-injected, and (e) all, *Carcharhinus obscurus* from south-western Australia. Lines represent von Bertalanffy growth curves based on parameters given in Table X.**

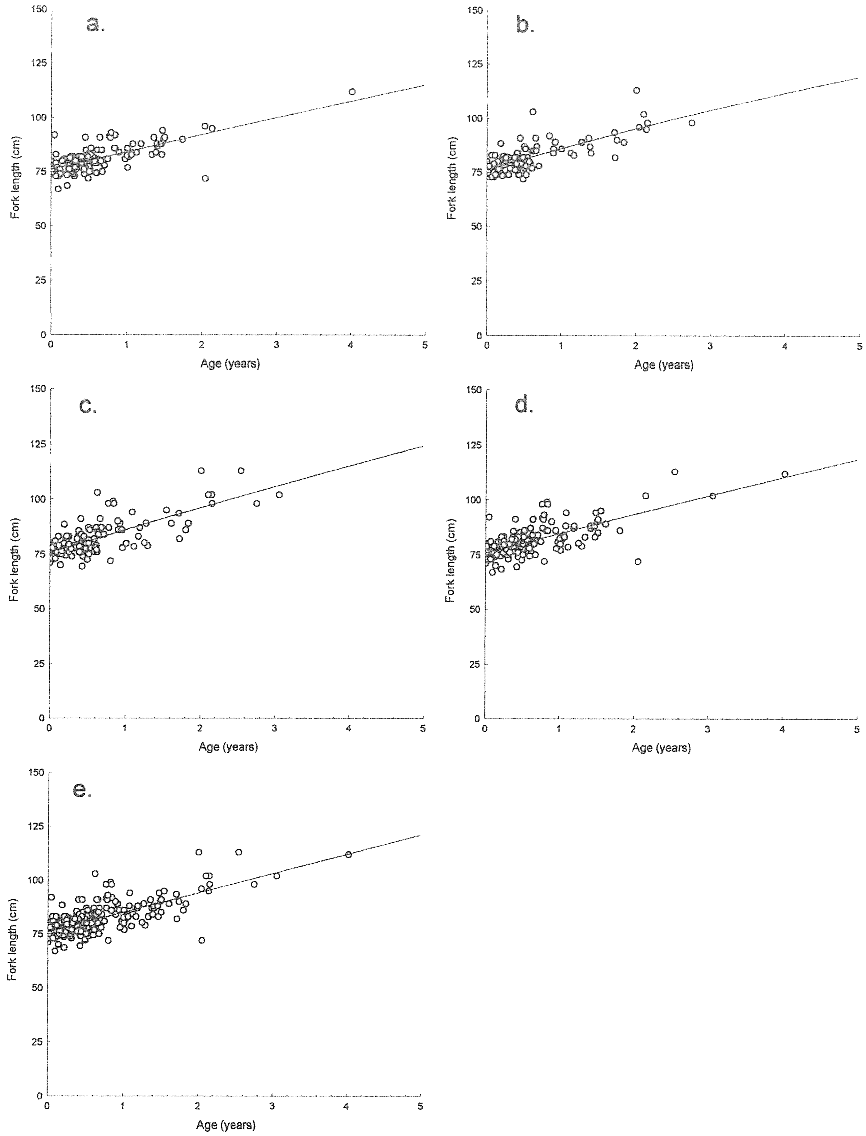
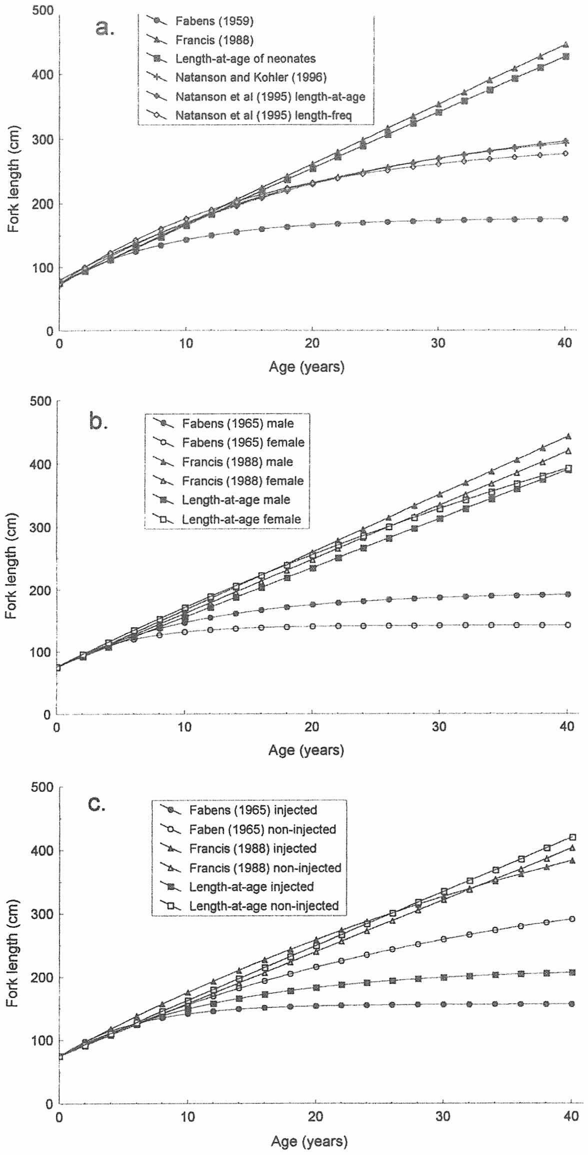


Table 5.24: **von Bertalanffy growth parameter estimates for juvenile *Carcharhinus obscurus* based on length-at-age data for neonate releases.**

Group	n	L_∞ (cm)	K (year^{-1})	t_0 (years)	r^2
All	241	6139.9	0.0015	-8.34	0.52
Male	117	6834.9	0.0012	-9.43	0.50
Female	120	840.0	0.013	-7.09	0.54
Injected	92	213.8	0.075	-5.83	0.58
Non-injected	149	12965.9	0.00068	-8.68	0.49

Figure 5.32: **Comparison of von Bertalanffy growth curves produced by three different estimation techniques from tag-recapture data for *Carcharhinus obscurus* caught off south-western Australia. Growth curves from previous studies are also shown. (a) all group and comparison to previous studies, (b) males and females, and (c) injected and non-injected.**



5.7 Analysis of the impact of non-gillnet fishing on commercially important shark species

5.7.1 Analysis of fishery returns

Catches of sharks reported by non-gillnet Western Australian managed fisheries are given in Table 5.25. Most fisheries had a limited bycatch of sharks, with only 5 of 30 fisheries catching more than 10 tonnes in 1996/97. The five fisheries that took greater than 10 tonnes of shark were the Exmouth Gulf Beach Seine Fishery (gillnet operators), Exmouth Gulf Prawn Fishery, Pilbara Fish Trawl Fishery, West Coast Rock Lobster Fishery (dropline fishing) and Open West Coast License Fishery. In addition one operator took a large amount of shark (>100 tonnes in 1996/97) in an unclear licensing situation. This fishermen has several permits and the algorithm that divides the catch by fishery was unable to assign the catch to any one fishery. Annual catches by non-gillnet fisheries around Western Australia were over 300 tonnes for the three years analysed. This level of catch represents about a quarter of the gillnet shark catch in the south and west coast shark fisheries. These catches do not include those made by illegal foreign fishing vessels in the Kimberley region, by Commonwealth licensed vessels, or unreported catches by Western Australian licensed fishers. As a result the non-gillnet catch makes up a significant proportion of the total catch of sharks in Western Australia.

Table 5.25: Catches of shark reported by commercial fishermen in various Western Australia fisheries for the fishing years 1994/95, 1995/96 and 1996/97.

Fishery	Fishing method	Catch (kg)		
		1994/95	1995/96	1996/97
Cockburn Sound Fish Net Fishery	Gillnet	0	0	1132
Cockburn Sound Line and Pot Fishery	Handline	114	153	529
	Dropline	0	104	86
	Longline	2091	1653	2796
	Pot	0	477	0
Exmouth Gulf Beach Seine Fishery	Beach seine	0	0	32
	Gillnet	1528	10094	23972
	Handline	0	599	37
	Haul net	350	0	0
Exmouth Gulf Prawn Fishery	Trawl	6755	9010	10355
Kimberley Demersal Line Interim Fishery	Dropline	0	0	180
	Handline	0	94	3710
	Longline	0	0	263

Kimberley Gillnet and Barramundi Fishery	Gillnet	4022	12252	9157
	Handline	73	120	223
Kimberley Prawn Fishery [1]	Trawl	0	171	0
Kimberley Trap Fishery	Fish trap	1271	83	9
Nickol Bay Prawn Fishery	Trawl	999	0	506
Onslow Prawn Fishery	Trawl	772	185	803
Pilbara Fish Trawl Fishery	Trawl	41163	58070	62900
Pilbara Fish Trap Fishery	Fish trap	177	483	0
Shark Bay Seine Mesh Net Fishery	Beach seine	80	419	78
	Haul net	17	0	0
Shark Bay Prawn Fishery	Trawl	3230	3055	2428
Shark Bay Pink Snapper Fishery	Dropline		103	6
	Handline	987	969	849
Shark Bay Scallop Fishery	Trawl	0	135	37
South Coast Salmon Fishery	Beach seine	119	232	76
	Haul net	8	0	304
Southern Rock Lobster Fishery	Pot	44	41	0
South West Coast Salmon Fishery	Beach seine	0	0	143
South west Inshore Trawl Fishery	Trawl	888	501	466
West Coast Rock Lobster Fishery [2]	Pot	0	21	32
	Dropline	5040	3764	10899
	Gillnet	1335	567	0
	Handline	2051	1983	3241
	Longline	210	795	267
Windy Harbour Rock Lobster Fishery	Pot	167	0	0
South Coast Estuarine Fisheries	Beach seine	3	0	0
	Gillnet	162	125	435
	Handline	0	0	48
	Haul net	0	5	7
Inner Shark Bay Handline Fishery	Dropline	0	0	21

	Handline	0	19	0
South Coast Trawling Endorsement	Trawl	3585	0	172
General Fish Trapping	Fish trap	0	0	32
South West Coast Estuarine Fisheries	Gillnet	211	0	0
Midwest Coast Purse Seine Fishery	Purse seine	0	0	23
Leatherjacket Trap Fishery	Fish trap	73	18	0
Ningaloo Fisher Trawl Fishery	Trawl	0	0	289
Open West Coast License	Dropline	29795	24140	30721
	Gillnet	16957	9833	16329
	Handline	21342	17578	21149
	Longline	41841	16621	11793
	Trolling	14055	11198	2110
No authority to fish	Dropline	404	13	223
	Gillnet	140992	118659	105673
	Handline	1270	4877	363
	Longline	1338	0	0
Total		336883	302110	310497

1. Catches mostly reported to the Commonwealth
2. Catches of lobster fishers by other methods are given separately

5.7.2 Photographic surveys

The species composition of the elasmobranch bycatch of the Pilbara Fish Trawl Fishery as recorded by photographic survey is given in Table 5.26. The catch was dominated by carcharhinid sharks (whaler sharks), hemigaleid sharks (weasel sharks), the leopard shark, shovel nose rays and stingrays. The limited survey of the Shark Bay Prawn Trawl Fishery indicated that the weasel shark, *Hemigaleus microstoma* dominated the catch (Table 5.27).

The wide variety of elasmobranch species caught in these fisheries could not be recorded on the Fisheries Western Australia catch and effort database system because many of the northern species do not have a species code. As such it has not been possible for these fishers to accurately report their catch, or for researchers to accurately assess the species composition from catch returns.

Table 5.26: Species composition of catches from the Pilbara fish trawl fishery based on photographic data from 1996 to 1998.

Species	Number
Stegastomatidae	
Stegastoma fasciatum	5
Hemigaleidae	
Hemigaleus microstoma	3
Hemipristis elongata	4
Carcharhinidae	
Carcharhinus plumbeus	8
Carcharhinus dussumieri	3
Carcharhinus sp.	2
Loxodon macrorhinus	1
Sphyrnidae	
Sphyrna lewini	3
Rhinobatidae	
Rhinobatos sp.	1
Rhynchobatidae	
Rhynchobatus djiddensis	8
Pristidae	
Anoxypristis cuspidata	1
Dasyatidae	
Dasyatis leylandi	2
Dasyatis sp.	1

Table 5.27: Species composition of catches from the Shark Bay trawl fishery based on photographic data from 2 October 1996 to 7 October 1996.

Species	Number observed
Hemiscyllidae	
Chiloscyllium punctatum	1
Hemigaleidae	
Hemigaleus microstoma	16
Rhynchobatidae	
Rhynchobatus djiddensis	3

5.7.3 Pilbara longline fishery

The logbook records of the Chuan Cheng indicate that a wide variety of sharks are caught by the Pilbara shark fishery (Table 5.28). The dominant species are *Carcharhinus plumbeus (*thickskin shark), *Carcharhinus amboinensis* (pigeye shark), (*Carcharhinus sorrah*) spot-tail shark) and *Galeocerdo cuvier* (tiger shark). As with the Pilbara Fish Trawl Fishery, the Pilbara Shark Fishery operators presently cannot accurately report their catch to Fisheries WA since the recording system does not have species codes for the wide variety of sharks present in the northern half of the state.

Table 5.28: Species composition of from the longline vessel Chuan Cheng from logbook data, January 1998 to March 1998.

Species	n	%
Heterodontidae		
Heterodontus sp.	3	0.14
Stegastomatidae		
Stegastoma fasciatum	11	0.51
Ginglymostomatidae		
Nebrius ferrugineus	12	0.56
Odontaspididae		
Carcharias taurus	14	0.66
Triakidae		
Mustelus sp.	7	0.33
Carcharhinidae		
Carcharhinus altimus	2	0.09
Carcharhinus amblyrhynchoides	4	0.19
Carcharhinus amblyrhynchos	1	0.05
Carcharhinus amboinensis	339	15.86
Carcharhinus brevipinna	1	0.05
Carcharhinus cautus	0	0
Carcharhinus falciformis	1	0.05
Carcharhinus melanopterus	2	0.09
Carcharhinus plumbeus	655	30.65
Carcharhinus sorrah	266	12.45
Carcharhinus tilstoni	69	3.23
Galeocerdo cuvier	198	9.27
Loxodon macrorhinus	24	1.12
Negaprion acutidens	147	6.88
Rhizoprionodon acutus	3	0.14
Sphyrnidae		
Eusphyra blochii	1	0.05
Sphyrna lewini	1	0.05
Sphyrna mokarran	222	10.39
Rhinobatidae		
Unidentified	7	0.33
Rhynchobatidae		
Rhynchobatus djiddensis	19	0.89
Pristidae		
Unidentified	2	0.09
Other	95	4.44

5.8 Population modelling

5.8.1 Whiskery sharks

5.8.1.1 Catch and effort data

Catches of *F. macki* reported by commercial fishers in Western Australian waters since 1975 have varied between 94 tonnes and 508 tonnes (Table 5.29). Catches adjusted for fishers who did not provide species specific data on their returns have varied between 162 tonnes and 611 tonnes. The proportion of catch attributed to "good reporters" has increased steadily since the mid 1970s, from 50-60% to nearly 91% in 1996/97. Catches of *F. macki* between 1979/80 and 1992/93 were between 380 and 500 tonnes, except for 1981/82 when the catch was 611 tonnes and 1987/88 when the catch was 583 tonnes. Since 1993/94 the catches have fallen, ranging between 261 and 216 tonnes.

Table 5.29: Catch, effort and catch rate values for *Furgaleus macki* by financial year from 1975/76 to 1997/98.

Year	Raw catch (kg)	Adjusted catch (kg)	% catch from good reports	Nominal effort (km.gn.hr)	Effective effort (no efficiency) (km.gn.hr)	Effective effort (2% efficiency) (km.gn.hr)	Catch rate (no efficiency) (kg km.gn.hr^{-1})	Catch rate (2% efficiency) (kg km.gn.hr^{-1})
1975/76	94,262	161,679	58.3	64,691	65,756	65,756	2.46	2.45
1976/77	138,716	213,652	64.9	67,610	77,105	78,647	2.77	2.71
1977/78	177,868	345,587	51.5	98,053	119,877	124,720	2.88	2.75
1978/79	186,557	272,754	68.4	100,825	95,395	101,234	2.86	2.67
1979/80	267,180	388,509	68.8	144,173	160,165	173,368	2.43	2.23
1980/81	290,992	413,099	70.4	165,128	193,103	213,201	2.12	1.93
1981/82	508,382	610,879	83.2	198,634	299,465	337,246	2.04	1.79
1982/83	390,068	492,804	79.2	270,775	340,466	391,088	1.45	1.25
1983/84	289,807	388,645	74.6	295,477	346,702	406,217	1.12	0.95
1984/85	278,405	399,089	69.8	439,543	344,571	411,794	1.16	0.97
1985/86	318,428	481,429	66.1	572,425	569,115	693,748	0.85	0.69
1986/87	336,291	441,362	76.2	600,743	628,075	780,933	0.70	0.56
1987/88	412,168	583,127	70.7	786,687	749,161	950,117	0.78	0.61
1988/89	324,644	447,028	72.6	665,386	497,416	643,461	0.90	0.70
1989/90	314,268	409,592	76.7	557,851	570,149	752,299	0.72	0.55
1990/91	402,835	493,594	81.6	516,733	501,489	674,939	0.98	0.73
1991/92	367,946	433,264	84.9	434,428	443,969	609,474	0.98	0.71
1992/93	297,808	371,513	80.2	445,135	504,432	706,327	0.74	0.53
1993/94	186,179	226,905	82.1	381,944	421,647	602,215	0.54	0.38
1994/95	211,291	261,291	80.9	350,226	401,521	584,940	0.65	0.45
1995/96	192,011	233,802	82.1	331,149	355,849	528,773	0.66	0.44
1996/97	196,750	216,748	90.8	327,306	338,324	512,786	0.64	0.42
1997/98	185,449	231,843	80.0	309,795	293,136	453,182	0.79	0.51

Nominal fishing effort (i.e. that reported by fishers) increased more than an order of magnitude from the mid 1970s to a peak in 1987/88 (Table 5.29). Since reaching this peak, nominal effort has fallen steadily as a consequence of management decisions, and in 1997/98 was much less than half of the maximum level reported historically. Effective effort calculated without any efficiency increase showed a similar trend to that of nominal effort. However, the effective effort calculated with a 2% annual efficiency factor resulted in a higher peak effort level and higher current levels of effort. The catch rate calculated using the adjusted catch and effective effort with the 2% annual efficiency factor fell steadily during the late 1970s and early 1980s (Table 5.29). Since the mid 1980s the catch rate has remained relatively stable.

5.8.1.2 Model fit

The predicted catch rates from the model provided a good fit to the observed data (Figure 5.33). In most cases the observed values fell within the 95% confidence interval for the predicted value. The size of the confidence intervals was greater in the period from 1975 to 1981 than for the period from 1982 to 1997. Comparison of the residuals between these two periods showed that the variation was higher for the later period (Figure 5.34a), confirming the need for correction of the residuals in the fitting process. After correction the distribution of residuals was similar for both periods (Figure 5.34b).

Figure 5.33: **Observed catch rate data for *F. macki* in south-western Australia (circles) and predicted catch rates from the model for the base case (scenario A) (solid lines) and 95% confidence intervals (dashed lines).**

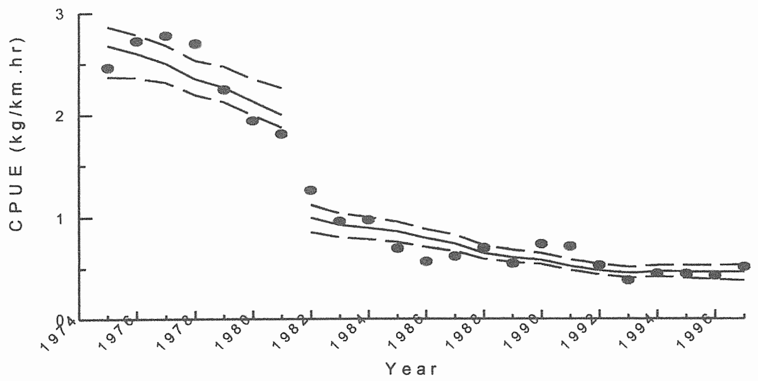
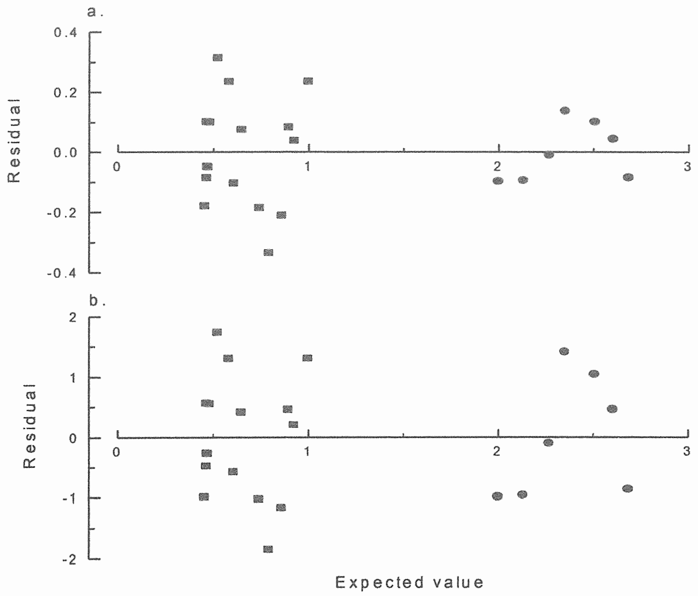


Figure 5.34: Residual plots for the base case model (scenario A) for 1975 to 1981 (circles) and 1982 to 1997 (squares), (a) without correction for period variance, and (b) with correction for period variance. See text for details of correction for variance and fitting procedure.



The population parameters (R^*, z and F_0) that provided the best fit for each of the scenarios tested, and their 95% confidence intervals (CI), are given in Table 5.30. Values of $q_{1975-1981}$ and $q_{1982-1997}$ are not presented as they are scaling parameters. In all scenarios $q_{1975-1981}$ was greater than $q_{1982-1997}$.

Table 5.30: Population parameters from 13 different scenarios for *Furgaleus macki* population off south-western Australia. Values indicated are the best estimate and 95% confidence interval calculated from the solutions of 500 bootstrapped data sets (in parentheses).

Scenario	R^*	z	F_0
A	284,700 (273,000 - 591,200)	0.496 (0.205* - 0.496*)	0.0032 (0.0002 - 0.0499)
B	1,602,700 (860,000 - 10,000,000*)	0.340 (0.205* - 0.496*)	0.0739 (0.0000 - 0.1490)
C	643,200 (223,400 - 5,689,700)	0.276 (0.205* - 0.496*)	0.0181 (0.0000 - 0.0856)
D	326,900 (290,200 - 843,500)	0.468 (0.205* - 0.496*)	0.0027 (0.0000 - 0.0472)
E	214,800 (190,300 - 290,200)	0.562 (0.205 - 0.591*)	0.0042 (0.0003 - 0.0490)
F	555,000 (519,700 - 2,972,800)	0.326 (0.205* - 0.326*)	0.0011 (0.0000 - 0.0583)
G	406,700 (387,400 - 1,126,700)	0.428 (0.205* - 0.428*)	0.0022 (0.0000 - 0.0509)
H	284,900 (217,400 - 1,000,000*)	0.342 (0.205* - 0.558)	0.0015 (0.0000 - 0.0778)
I	401,600 (376,300 - 2,710,200)	0.362 (0.205* - 0.362)	0.0011 (0.0000 - 0.0443)
J	263,300 (231,800 - 506,100)	0.565 (0.205* - 0.663*)	0.0045 (0.0000 - 0.0561)
K	363,400 (316,700 - 628,800)	0.410 (0.205 - 0.496*)	0.0019 (0.0000 - 0.0700)
N	284,800 (273,000 - 540,000)	0.496 (0.206 - 0.496*)	0.0032 (0.0002 - 0.0489)
O	284,200 (272,600 - 562,000)	0.496 (0.205* - 0.496*)	0.0032 (0.0000 - 0.0493)

* indicates that range was constrained by limits placed on the optimising procedure

Values of R^* varied considerably between scenarios. The base case (A), low age at maturity (H), and both mesh selectivity sensitivity tests (N and O) had very similar values, all towards the low end of the range from all scenarios. Two scenarios had lower values of R^* - low M and high x (E), and annual breeding (J). All other scenarios had R^* values greater than that of the base case. Highest values occurred for the two scenarios where uncorrected catch and/or effort was used (B and C). In all scenarios the best estimate of R^* was towards the lower end of the 95% CI. In only two scenarios (B and H) did the 95% CI of the R^* values reach limits set during the optimising procedure. On the basis of the 95% CI there were no significant differences between R^* in scenarios A, C, D, G, H, I, J, K, N and O. The value for scenario B was significantly higher than that for A, D, E, J, K, N and O; while scenario F had a significantly higher value than J and E. Scenario E had a significantly lower R^* value than B, D, F, G, I and K.

Values of z varied less between each of the scenarios than did R^* (Table 5.30), mainly due to the constraints placed on the fitting procedure. Unlike the limits for R^* which were used to eliminate values that appeared to be unreasonable and speed the fitting process, the limits on z were imposed because of biological constraints. In all but four of the scenarios the 95% CI reached both the upper and lower limit set. In all scenarios the best estimate of z was at, or near, the upper limit of the allowable range. On the basis of the 95% CI there were no significant differences between z values for any scenarios.

Estimates of F_0 for all scenarios were less than 0.08 (Table 5.30). Highest values of F_0 were for the scenarios based on uncorrected catch and/or effort (B and C). The 95% CI of F_0 for all scenarios ranged from close to 0 to more than 0.044, indicating no significant differences between scenarios.

5.8.1.3 Current status

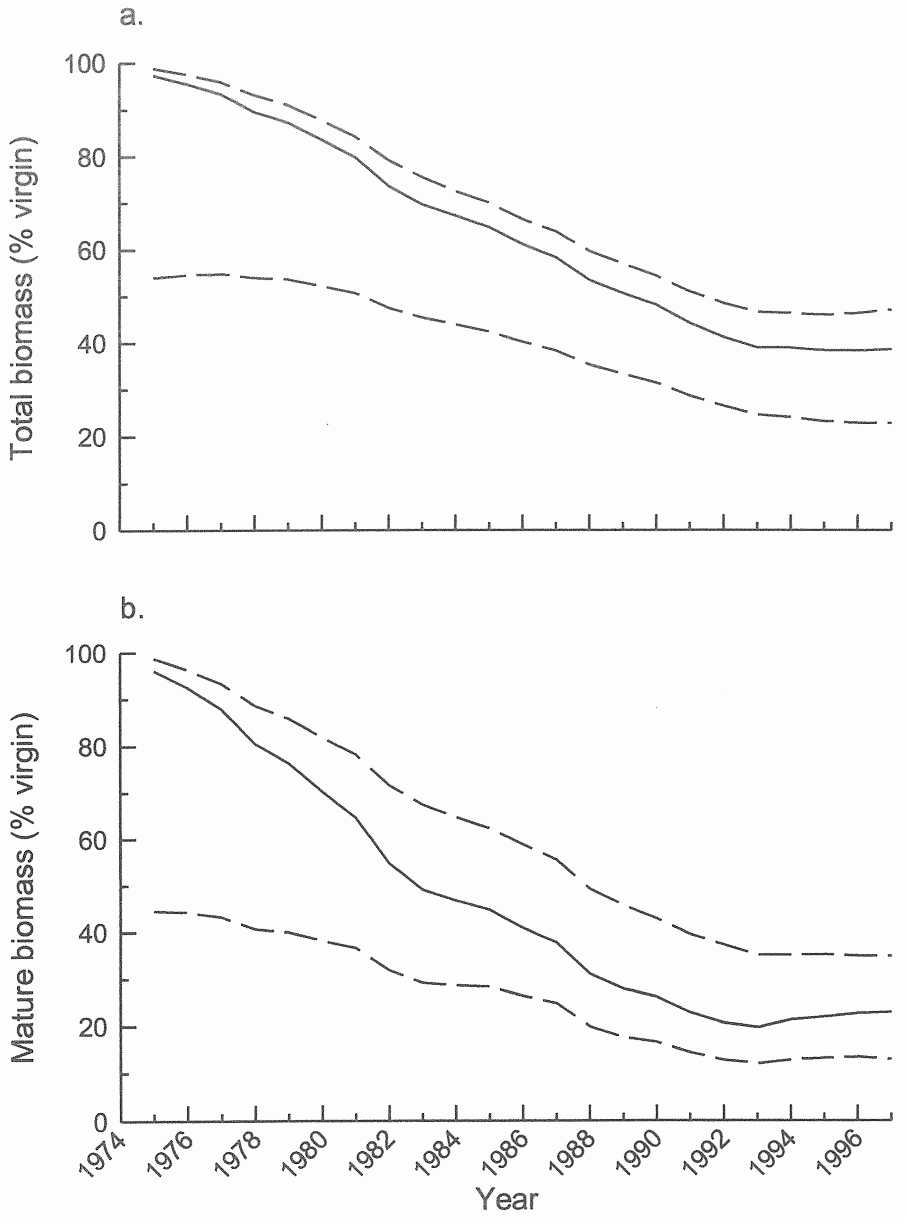
The estimate of the 1997 total biomass from the base case (scenario A) was 38.8% of virgin (CI 22.7% - 47.2%), and for mature female biomass was 23.0% (CI 13.4% - 36.4%) (Table 5.31). The lowest estimates of 1997 biomass were for scenario B (uncorrected catch and effort) with 7.8% total (CI 4.3% - 98.2%) and 5.3% mature female (CI 3.2% - 97.1%). The highest estimate of biomass was in scenario D (no efficiency increase) where total biomass was 50.5% (CI 22.8% - 61.7%) and mature female biomass 35.1% (CI 16.5% - 50.9%). For the remaining scenarios the best estimates of total biomass were between 32.0% and 40.1%, and for mature female biomass between 21.2% and 30.3% (Table 5.31). The 95% CI's for biomass estimates indicated that there was no significant differences between the 1997 levels of total or mature female biomass for all scenarios.

Table 5.31: Estimates of the 1997/98 level of total and mature biomass for the *Furgaleus macki* population off south-western Australia from 13 different scenarios (see text for description of scenarios). Values indicated are the best estimate and 95% confidence interval calculated from the solutions of 500 bootstrapped data sets (in parentheses).

Scenario	B_t (% virgin)	B_m (% virgin)
A	38.8 (22.7 - 47.2)	23.0 (13.4 - 36.4)
B	7.8 (4.3 - 98.2)	5.3 (3.2 - 97.1)
C	32.0 (4.0 - 64.8)	26.8 (3.8 - 59.6)
D	50.5 (22.8 - 61.7)	35.1 (16.5 - 50.9)
E	38.7 (28.9 - 49.8)	22.3 (14.1 - 36.4)
F	38.2 (6.2 - 47.0)	29.6 (5.0 - 38.7)
G	38.3 (14.4 - 46.8)	24.9 (10.0 - 38.0)
H	38.7 (13.9 - 50.1)	23.3 (5.8 - 35.9)
I	36.8 (7.0 - 46.6)	30.3 (6.4 - 41.1)
J	39.4 (20.4 - 49.5)	21.2 (10.2 - 35.5)
K	40.1 (18.9 - 50.1)	28.0 (11.8 - 37.0)
N	39.5 (24.8 - 48.9)	23.5 (14.2 - 35.3)
O	39.1 (22.6 - 49.0)	23.4 (13.6 - 37.5)

To illustrate the trend in biomass levels through time the annual estimates of total and mature female biomass (and 95% CI's) for the base case (scenario A) are illustrated in Figure 5.35. Total biomass declined consistently between 1975 and 1993, but since has been much more stable. Mature female biomass declined more rapidly than total biomass between 1975 and 1981, continued to decline between 1982 and 1992, and since 1993 has been slowly increasing. The best fit to the data indicates that total and mature female biomass were close to 100% of virgin level in 1975. However, some bootstrap results that had higher levels of F_0 indicated lower levels of biomass in 1975, resulting in the large 95% CI.

Figure 5.35: Trends in (a) total biomass, and (b) mature female biomass (solid lines), between 1975 and 1997 with 95% confidence intervals (dashed lines). Confidence intervals are based on the results of refitting the model to 500 bootstrapped catch and effort data sets (see text for details).



5.8.1.4 Risk assessment

The probability curves for achieving 40% total biomass by the 2010/11 season, and increasing biomass from 1996/97 to 2010/11, are similar (Figure 5.36). The probability of meeting these targets decreases slowly at annual catches less than 100 tonnes, and then falls more rapidly. A 50% chance of achieving the target of 40% total biomass by 2010/11 occurs at an annual catch of approximately 190 tonnes; the 50% chance of achieving the increased biomass target by 2010/11 occurs at an annual catch of approximately 195 tonnes. The probability of a crash in the fishery (defined as the predicted catch exceeding the exploitable biomass) was insignificant at annual catches below 150 tonnes, but increased to a 50% chance at annual catches of approximately 280 tonnes (Figure 5.37). The impact of different CVs of recruitment on the results of the risk assessment were only slight, with the probability curves for CV's of 0.1, 0.2 and 0.3 being almost identical (Figure 5.37).

Figure 5.36: Results of risk analysis for *Furgaleus macki* in south-western Australia. The probability of achieving three different biological reference points was tested: total biomass is greater than 40% in the 2010/11 season (circles), total biomass in the 2010/11 season is greater than, or equal to, that in 1996 (squares), and catch greater than exploitable biomass (triangles). Actual annual catches were randomly selected from a range within 10% of indicated annual catches (see text for details). Probability levels are the average of all probabilities across the eleven scenarios, with each scenario assumed to be equally likely.

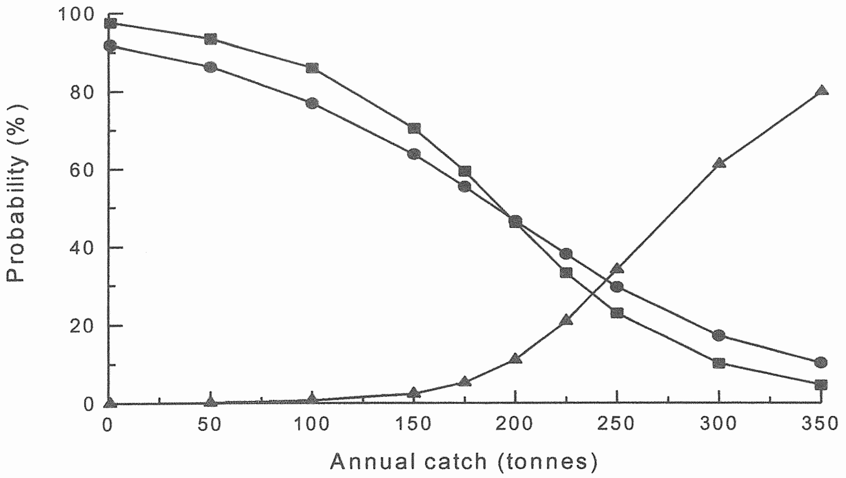
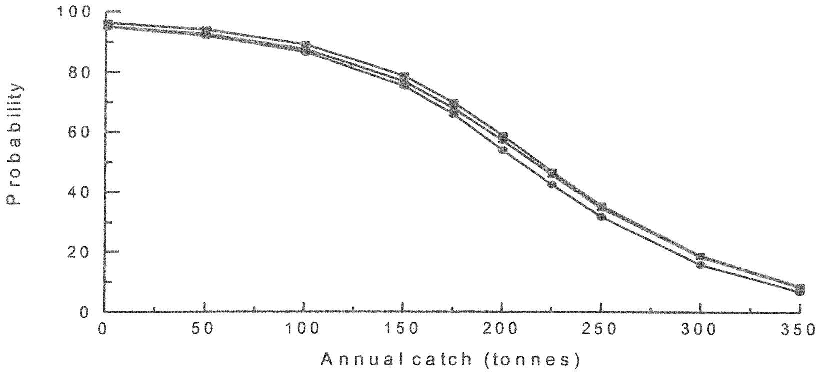


Figure 5.37: Comparison of the results of risk analysis for the total biomass being at least 40% of virgin by the 2010/11 season with three different levels of coefficient of variation (CV) of recruitment. Squares, CV = 0.1, triangles, CV = 0.2, and circles, CV = 0.3.



5.8.2 Dusky whalers

5.8.2.1 Age-specific exploitation rates

A total of 517 double tagged *C. obscurus* were released during the tagging experiment. Seventy nine of these were recovered with one or two tags intact. The annual rate of tag shedding estimated from these data for Jumbo Rototags was 0.0358 year^{-1} (standard error 0.0359), and for Hallprint metal-headed dart tags was 0.346 year^{-1} (standard error 0.1046).

Estimates of non-reporting rate varied considerably between regions and months (Table 5.32). The mean non-reporting rate over the study period was lowest in region 2 (0.071) and highest in region 3 (0.315). The mean non-reporting rate over all months and regions was 0.201. Numbers of tag returns reported, and the estimated number captured, varied considerably between months (Table 5.33). The estimates of the number of tags recaptured indicated that in the first year after release between two and 12 tags were not reported each month.

Table 5.32: **Estimated monthly non-reporting rates for the commercial gillnet fishery in south-western Australia by region (denoted by *i*). Rates were calculated from compulsory monthly catch and effort returns supplied by all commercial fishers.**

Month	Non-reporting rate		
	i=1	i=2	i=3
Mar 94	0.096	0.118	0.000
Apr 94	0.238	0.100	0.000
May 94	0.163	0.086	0.049
Jun 94	0.000	0.000	0.000
Jul 94	0.377	0.000	0.383
Aug 94	0.288	0.063	0.208
Sep 94	0.423	0.059	0.291
Oct 94	0.319	0.042	0.319
Nov 94	0.202	0.000	0.383
Dec 94	0.000	0.000	0.388
Jan 95	0.152	0.147	0.494
Feb 95	0.000	0.056	0.307
Mar 95	0.083	0.124	0.541
Apr 95	0.187	0.049	0.358
May 95	0.182	0.041	0.247
Jun 95	0.823	0.172	0.000
Jul 95	0.000	0.043	0.326
Aug 95	0.150	0.080	0.319
Sep 95	0.441	0.069	0.342
Oct 95	0.105	0.089	0.380
Nov 95	0.174	0.073	0.472
Dec 95	0.487	0.000	0.242
Jan 96	0.453	0.096	0.555
Feb 96	0.378	0.111	0.284
Mar 96	0.099	0.077	0.515
Apr 96	0.119	0.111	0.530
May 96	0.124	0.107	0.527
Jun 96	0.000	0.076	0.370

Table 5.33: Numbers of tag returns reported by region (denoted by *i*), and estimated number of tag recaptures ($\hat{R}_{a,t}$), by month.

Month	1994 cohort				1995 cohort			
	i=1	i=2	i=3	$\hat{R}_{a,t}$	i=1	i=2	i=3	$\hat{R}_{a,t}$
Mar 94	3	0	0	3.44	-	-	-	-
Apr 94	11	0	0	14.96	-	-	-	-
May 94	13	0	0	16.09	-	-	-	-
Jun 94	1	0	4	5.18	-	-	-	-
Jul 94	12	0	4	26.69	-	-	-	-
Aug 94	8	0	8	22.11	-	-	-	-
Sep 94	1	0	4	7.65	-	-	-	-
Oct 94	6	0	2	13.21	-	-	-	-
Nov 94	1	0	3	6.34	-	-	-	-
Dec 94	5	0	0	5.18	-	-	-	-
Jan 95	5	0	2	11.24	-	-	-	-
Feb 95	3	0	0	3.11	-	-	-	-
Mar 95	3	0	2	7.91	4	0	0	4.52
Apr 95	4	0	2	8.33	2	0	1	3.59
May 95	2	0	0	2.53	1	0	1	2.30
Jun 95	0	0	0	0.00	1	0	3	8.97
Jul 95	0	0	0	0.00	0	1	0	1.08
Aug 95	0	0	0	1.04	0	1	0	1.13
Sep 95	1	0	0	1.85	8	0	2	19.01
Oct 95	2	0	1	5.02	8	2	1	13.21
Nov 95	2	0	1	4.47	3	0	0	3.76
Dec 95	0	0	0	0.00	2	1	0	5.08
Jan 96	0	2	1	4.62	1	1	0	3.04
Feb 96	1	0	0	1.67	5	1	1	10.95
Mar 96	1	0	0	1.15	3	0	0	3.45
Apr 96	1	0	0	1.18	1	0	0	1.18
May 96	3	0	0	3.55	0	1	0	1.16
Jun 96	0	0	1	1.64	0	0	0	0.00

Age-specific exploitation rates were highest in the first year after birth (Table 5.34). In the second year after release the exploitation rate had decreased sharply. Subsequently, the age-specific exploitation rates were assumed to continue decreasing until they reached 0.01 for the sixth year after release, and were zero thereafter.

Table 5.34: Estimated age-specific exploitation rates of released *Carcharhinus obscurus*. Astrices indicate years for which age-specific exploitation rates were assumed (see text for details).

Year after release	1994 cohort (releases = 442)		1995 cohort (releases = 324)	
	$\sum \hat{R}_{a,t}$	Exp. rate	$\sum \hat{R}_{a,t}$	Exp. rate
1st	114.3	0.284	63.0	0.207
2nd	26.2	0.083	-	0.083^*
3rd	-	0.05^*	-	0.05^*
4th	-	0.03^*	-	0.03^*
5th	-	0.02^*	-	0.02^*
6th	-	0.01^*	-	0.01^*

5.8.2.2 Demographic analysis

A total of 17 life tables were constructed to examine the demography of *C. obscurus* in south-western Australian waters. These comprised one "base case" representing the most likely life history parameters, and 16 scenarios exploring the sensitivity of the results to variations in the life history parameters and exploitation rate from the "base case" values (Table 5.35). For each scenario the reproductive rate per generation, intrinsic rate of population increase, population doubling time and the proportion of recruits surviving to maturity were calculated for three levels of fishing: no fishing (Table 5.36), and those levels indicated by the exploitation rates of the 1994 and 1995 cohorts (Table 5.37). The generation time and F_{MSY} are independent of the level of fishing and were calculated once for each set of life history parameters (Table 5.36).

Table 5.35: Life history parameter, and exploitation rate, specifications for the 17 life tables (scenarios A - Q) used in this study. *LS*, average litter size; *M*, natural mortality; *Px*, exploitation rate; *r*, intrinsic rate of population increase; *RP*, reproductive periodicity; t_{mat}, age at maturity; and t_{max}, maximum age. Astrices denotes scenarios where natural mortality was doubled for the first age class.

Scenario	Increase *Px* (%)	Life history parameters t_{mat} (years)	*RP* (years)	*LS*	t_{max} (years)	*M* (year^{-1})
"Base case"						
A	0	20	3	10	50	0.083
Mortality						
B	0	20	3	10	50	0.05
C	0	20	3	10	50	0.11
D*	0	20	3	10	50	0.083
E*	0	20	3	10	50	0.05
Reproduction						
F	0	14	3	10	50	0.083
G	0	24	3	10	50	0.083
H	0	20	2	10	50	0.083
I	0	20	4	10	50	0.083
J	0	20	3	8	50	0.083
K	0	20	3	12	50	0.083
Longevity						
L	0	20	3	10	40	0.083
M	0	20	3	10	60	0.083
Extremes						
N	0	14	2	12	60	0.05
O	0	24	4	8	40	0.11
Exploitation rates						
P	10	20	3	10	50	0.083
Q	20	20	3	10	50	0.083

Table 5.36: **Results of demographic analyses for the 15 scenarios for *Carcharhinus obscurus* from south-western Australia assuming that there was no fishing. Results of scenarios P and Q are not presented as these relate to fished populations only. F_{MSY}, theoretical value of fishing mortality that gives the maximum sustainable yield; *G*, generation time; *PM*, proportion of the population reaching maturity; *r*, intrinsic rate of population increase; and *Ro*, reproductive rate.**

Scenario	Demographic results - No fishing					
	Ro	*G*	*r*	t_{x2}	*PM*	F_{MSY}
"Base case"						
A	3.36	29.8	0.042	16.5	0.175	0.021
Mortality						
B	9.29	31.9	0.075	9.23	0.350	0.038
C	1.53	28.5	0.015	45.8	0.099	0.008
D	3.09	29.8	0.039	17.7	0.161	0.014
E	8.83	31.9	0.073	9.45	0.333	0.036
Reproduction						
F	5.72	24.6	0.078	8.89	0.288	0.039
G	2.32	33.2	0.026	26.8	0.126	0.013
H	5.04	29.8	0.057	12.2	0.175	0.028
I	2.52	29.8	0.032	21.8	0.175	0.016
J	2.69	29.8	0.034	20.3	0.175	0.017
K	4.03	29.8	0.049	14.2	0.175	0.024
Longevity						
L	2.97	27.9	0.040	17.4	0.175	0.020
M	3.53	31.1	0.043	16.2	0.175	0.022
Extremes						
N	26.1	29.4	0.140	4.95	0.472	0.070
O	0.508	30.3	-0.022	-	0.099	-

Table 5.37: Results of life tables for *Carcharhinus obscurus* from south-western Australia incorporating the exploitation rates experienced by the 1994 and 1995 cohorts. Explanation of demographic symbols given in Table 4.6.

Scenario	Exp. rates from 1994 cohort				Exp. rate from 1995 cohort			
	Ro	*r*	t_{x2}	*PM*	*Ro*	*r*	t_{x2}	*PM*
"Base case"								
A	1.97	0.023	29.8	0.103	2.18	0.027	25.9	0.114
Mortality								
B	5.45	0.056	12.3	0.205	6.04	0.060	11.6	0.227
C	0.90	-0.004	-	0.058	0.99	-0.0002	-	0.065
D*	1.81	0.020	34.1	0.095	2.01	0.024	29.0	0.105
E*	5.19	0.054	12.7	0.195	5.75	0.058	11.9	0.216
Reproduction								
F	3.36	0.053	13.2	0.169	3.72	0.057	12.1	0.187
G	1.36	0.009	73.6	0.074	1.51	0.013	55.2	0.082
H	2.96	0.038	18.5	0.103	3.27	0.041	16.8	0.114
I	1.48	0.013	52.3	0.103	1.64	0.017	41.3	0.114
J	1.58	0.015	44.8	0.103	1.75	0.019	36.5	0.114
K	2.37	0.030	23.4	0.103	2.62	0.033	20.9	0.114
Longevity								
L	1.74	0.020	34.5	0.103	1.93	0.024	29.1	0.114
M	2.07	0.024	28.7	0.103	2.29	0.028	25.0	0.114
Extremes								
N	15.3	0.114	6.10	0.277	17.0	0.119	5.84	0.307
O	0.30	-0.039	-	0.058	0.33	-0.036	-	0.065
Exploitation rate								
P	1.85	0.021	32.9	0.097	2.08	0.025	27.6	0.109
Q	1.74	0.019	36.6	0.091	1.99	0.023	29.5	0.103

The reproductive rate per generation of the "base case" (scenario A) without fishing was 3.36, and the generation time 29.8 years (Table 5.36). The intrinsic rate of population increase was 0.042 year^{-1} giving a doubling time of 16.5 years and an F_{MSY} of 0.021. The life table indicates that 17.5% of recruits reach maturity when there is no fishing. Inclusion of the exploitation rates experienced by the 1994 and 1995 cohorts into the life table reduced the intrinsic rate of population increase to 0.023 and 0.027, increased population doubling times to 29.8 years and 25.9 years, and reduced the proportion reaching maturity to 0.103 and 0.114, respectively (Table 5.37).

Four scenarios explored the variation in the demographic parameters with changes to the level of natural mortality (scenarios B, C, D and E). Changes in the natural mortality rate resulted in significant changes to the population increase rate due to changes in the proportion of the population reaching maturity (Table 5.36). Decreasing natural mortality to 0.05 year^{-1} (scenario B) increased the intrinsic rate of population increase to 7.8% year^{-1} without fishing (Table 5.36), and 5.0% year^{-1} and 5.5% year^{-1} with the level of fishing experienced by the 1994 and 1995 cohorts (Table 5.37). The Pauly (1980) estimate of natural mortality (0.11 year^{-1}, scenario C) resulted in a population increase rate of 1.5% year^{-1} with no fishing, and population decline (-1.6% year^{-1} and -1.0% year^{-1}, respectively) at the level of fishing experienced by the 1994 and 1995 cohorts. Doubling of natural mortality for the first age class (scenarios D and E) produced only small changes to the results for a given level of natural mortality (Tables 5.36 and 5.37).

The impact of different reproductive parameters on the demography of *C. obscurus* was tested with six scenarios that varied age at maturity (scenarios F and G), reproductive periodicity of females (scenarios H and I) and mean litter size (scenarios J and K). Variations in the reproductive parameters did not change the proportion of the population reaching maturity. Changes in the age at maturity produced the largest changes in demography from the "base case", while changes to the reproductive periodicity and litter size resulted in small changes (Table 5.36). All of the scenarios testing sensitivity to reproductive parameters gave positive rates of population increase, even at the level of fishing experienced by the 1994 cohort (Table 5.36).

Changes to the longevity of *C. obscurus* by ten years (scenarios L and M) produced only small changes in demographic parameters from the "base case" at all levels of fishing (Tables 5.36 and 5.37). The final two scenarios (N and O) combined a range of changes to the life history parameters (natural mortality, reproduction and longevity) from the "base case". These scenarios represent optimistic or pessimistic extremes where the effects of different life history parameters are compounded. Not surprisingly these scenarios produce the highest and lowest values of population increase. The optimistic scenario (N) resulted in a population increase rate of 14.0% year^{-1} without fishing (Table 5.36), and 10.4% year^{-1} and 11.1% year^{-1} with the level of fishing experienced by the 1994 and 1995 cohorts, respectively (Table 5.36). The pessimistic scenario (O) had negative values of population increase rate at all levels of fishing tested, including no fishing (Tables 5.36 and 5.37).

Increasing the exploitation rates experienced by the 1994 and 1995 cohorts (scenarios P and Q) resulted in more pessimistic outcomes (Table 5.37). The resulting changes in the annual rate of population increase were approximately proportional to the changes in exploitation rate. For example, increasing the exploitation rate by 20% above that estimated from the tag recapture data reduced the percentage of annual population increase from 2.3% to 1.9% for the 1994 cohort.

The F_{MSY} values estimated for the 15 scenarios were all low (Table 5.36). The highest value was 0.070 for the extremely optimistic scenario (N). All other values were less than 0.04, and most were less than 0.03.

6. CONCLUSIONS

This FRDC funded project, the second to focus on the assessment of the Western Australian temperate shark fishery, has provided a range of useful information to assist in the improvement of management for the fishery. The major conclusions of this project include:

- Nursery areas for *Furgaleus macki* are unlikely to occur in waters where the main part of the shark fishery occurs. Limited data on juveniles was collected, suggesting that either deep water, or unfishable areas for gillnet vessels (e.g. heavy coastal reefs), may function as nursery areas. Further research will be required to clearly identify the nursery areas.

- Accumulation patterns of elements in the jaw cartilage of gummy, dusky and whiskery sharks were shown to be attributable to the location of capture. However, the accumulation pattern only persists for periods of one to two years suggesting changing environmental conditions and/or available food organisms. The elemental differences in the diet of these sharks suggest that some elements that accumulate in the jaw cartilage may reflect the available food organisms consumed. This location specific accumulation pattern is in good agreement with tag-recapture data obtained for dusky and whiskery sharks that were mainly recaptured within 100 km of their release sites.

- The research provided a broad range of biological and life history data on adult *Carcharhinus obscurus*. Teleost fish are the most common prey, with cephalopods and elasmobranchs also important. Size at maturity for females is approximately 250 cm FL, and for males 240 cm FL. The occurrence of full-term litters and females with fresh placental scars present in the uterus, indicated that parturition occurs between February and June in areas south of the Abrolhos Islands. The presence of stored sperm in males indicates that mating may occur in winter in the waters of the North West Shelf. Vertebral ageing yielded von Bertalanffy growth parameters of $L_\infty = 386.8$ cm FL, $K = 0.036$ year^{-1} and $t_0 = -6.08$ years, indicating the average age at maturity is 22 years in males and 24 years in females.

- Analysis of catch rate data for neonate *Carcharhinus obscurus* showed that there were differences between years, regions and moon phases. However, over five years there was no significant trend in the catch rates, suggesting that recruitment was not decreasing. These results concur with the results of the demographic analysis based on tag recapture information. Highest catch rates were achieved around the time of the full moon in the Augusta region, either side of the full moon in the Albany region, and showed no clear trend in the Bunbury region. There was no significant influence of sea surface temperature or Leeuwin Current strength on catch rates. This is unlike many other fisheries in Western Australia.

- The research provided a range of biological and life history data for *Furgaleus macki*. The diet is composed almost entirely of cephalopods, with a very small component of crabs and teleost fishes. Age and growth was examined using vertebral ageing and tag-recapture data. Both methods produced similar results, indicating that growth was initially rapid, but that around the time of maturity growth slowed considerably. The age at maturity was estimated to be 4.5 years in males and 6.5 years in females. Maximum age was estimated to be around 15 years. These growth characteristics are similar to other triakid sharks, especially the gummy shark, *Mustelus antarcticus*. Movements of *F. macki* are mostly less than 50 km, although a small percentage will move between the south and west coasts of Western Australia.

- *Carcharhinus obscurus* tagged as part of the previous FRDC funded project continued to be recaptured over the course of the current study. The data from these animals was combined with the previous data and re-analysed. The maximum time at liberty was 1706 days, but most were recaptured after only 400 days. Maximum distance between release and recapture was 2205 km, but most were recaptured within 100 km of their release site. The recaptures indicate that there is a single stock of *C. obscurus* in southern Western Australia. Detailed analysis of the growth of tagged *C. obscurus* was undertaken. A variety of techniques was used to analyse the data. Some methods did not provide useable results, but those that did all indicated that growth of juvenile *C. obscurus* is linear, with annual growth increments averaging approximately 9 cm. There were no differences between males or females.

- Data from catch and effort supplied by commercial fishers, photographic surveys, and observers, provided information on the impact of non-gillnet fisheries on shark populations. Several fisheries were identified as having a significant impact, all of them in the northern half of the state. The data also demonstrated that current identification of sharks caught in northern fisheries is poor, and that Fisheries WA's catch and effort database is currently not capable of handling the diversity of elasmobranchs caught.
- A sex and age structured population model for *F. macki* indicates that the total biomass has been reduced to 39% of virgin, and the mature biomass has been reduced to 23% of virgin. Risk assessment indicates that to have a greater than 50% chance of achieving the biomass target set by the Management Advisory Committee future catches will have to be less than 195 tonnes, while the stock has a high probability of crashing with sustained annual catches above 280 tonnes.
- Demographic assessment of the *C. obscurus* population using fishing mortalities estimated from tag-recapture information, indicate that the gillnet fishery is currently taking sustainable levels of catch. However, if unreported claims of catches of larger individuals are substantiated, this may result in population depletion. The models indicate that at fishing mortality levels above 0.04 for animals older than 10 years would results in population depletion.

7. BENEFITS

The beneficiaries of this research are the fishers and managers of the shark fishery in southern Western Australia because of improved stock assessment and harvest strategy evaluation for key shark species enabling more effective decision making processes for the management of the stocks. These benefits and beneficiaries are the same as those in the original application. There will also be benefits to the community as a whole because of the ability to more appropriately manage the shark stocks of Western Australia.

8. INTELLECTUAL PROPERTY

No saleable intellectual property is expected from this project.

9. FURTHER DEVELOPMENT

No further development recommended beyond that already undertaken.

10. STAFF

Staff employed by this project:

Dr Colin Simpfendorfer
Mr Rory McAuley
Mr Justin Chidlow
Mr Adrian Kitchingman

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13. APPENDICES:

Appendix A: Notation used in the *Furgaleus macki* population model.

Symbol	Definition
a	age
A_j	block effect for block *j*
b	a parameter of the Beverton-Holt stock recruitment curve
B_t	the biomass at time *t*
B_t^e	exploitable biomass at time *t*
B_t^m	mature female biomass at time *t*
B_v	virgin biomass
B_v^m	virgin mature female biomass
c	a parameter of the Beverton-Holt stock recruitment curve
$\hat{C}_{a,g,t}$	catch in numbers of *F. macki* of age *a* and sex *g* at time *t*
$C_{i,j,t}^G$	catch of *F. macki* by "good reporting" fisher *I* in block *j* at time *t*
C_r	catch of all sharks in region *r*
C_r^G	catch of all sharks in region *r* by "good reporting" fishers
C_r^{GN}	catch of total shark in region *r* by "good reporting" fishers using gillnets
$\hat{C}_s$	corrected total catch of species *s*
$C_{s,r}^G$	catch of species *s* in region *r* by "good reporting" fishers
$\hat{C}_{s,r}$	corrected total catch of species *s* in region *r*
C_t	observed catch of time period *t*
$\hat{C}_t$	estimated catch in time *t*
$CPUE_r^{GN}$	catch per unit effort of total shark in region *r* by "good reporting" fishers using gillnets
e	error
$\hat{E}$	total gillnet equivalent effort over all regions
$E_{i,j,t}^G$	fishing effort of "good reporting" fisher *i* in block *j* at time *t*
$\hat{E}_r$	total gillnet equivalent effort in region *r*
E_r^{GN}	nominal effort in region *r* by "good reporting" fishers using gillnets
E_t^E	effective effort in time *t*
F_0	pre-1975 fishing mortality
F_t	instantaneous rate of fishing mortality
g	sex
K_g	parameter of the von Bertalanffy function for sex *g*

$L_{a,g}$	the length of a fish of age *a* and sex *g*
LL	log likelihood
lwa	parameter of the length-weight relationship
lwb	parameter of the length-weight relationship
$L_{\infty,g}$	parameter of the von Bertalanffy function for sex *g*
m	age at maturity
M	instantaneous rate of natural mortality
ms	mesh size
$N_{a,g,t}$	number of fish of sex *g* and age *a* at the start of time *t*
$N^*_{a,g,0}$	pre-1975 number per recruit
$N_{a,g,v}$	number of animals of age *a* and sex *g* in the virgin population
P_a'	number of pups per pregnant female at age *a*
P_a''	proportion of females pregnant at age *a*
P_g'''	proportion of embryos of sex *g*
q_t	catchability at time *t*
R^*	the recruitment at virgin biomass
R_0	pre-1975 recruitment
S_t	egg production at time *t*
S^*	unexploited egg production
SSQ	sum of squares
$t_{0,g}$	parameter of the von Bertalanffy function for sex *g*
u	overall mean catch rate of *F. macki*
$U_{j,t}$	catch rate of *F. macki* in block *j* at time *t*
$\hat{U}_t$	predicted catch rate at time *t*
$v_{a,g}$	vulnerability of a fish of age *a* and sex *g* to the fishing gear
$w_{a,g}$	weight of a fish of age *a* and sex *g*
x_g	maximum age of sex *g*
X_0	pre-1975 eggs per recruit
y_t	Average annual catch rate for time *t*
Y_t	catch in weight at time *t*
z	the proportion of R^* obtained at 20% of the fecundity of virgin biomass
α	gamma function gear selectivity parameter
β	gamma function gear selectivity parameter
σ	variance of residuals
θ_1	constant proportionality between $\alpha\beta$ and *ms*
θ_2	variance of length of sharks captured (constant across all mesh sizes)

Appendix B: Derivation of the upper bound of z in *Furgaleus macki* population model.

The Beverton-Holt stock recruitment relationship is represented by:

$$R_t = \frac{S_t}{a + bS_t}, \tag{34}$$

where,

$$b = \frac{S^*.\left(1 - \frac{(z-0.2)}{(0.8z)}\right)}{R^*}, \tag{35}$$

and,

$$c = \frac{z - 0.2}{0.8\ z\ R^*}. \tag{36}$$

This equation can be rewritten for the number of recruits resulting from each egg:

$$\frac{R_t}{S_t} = \frac{1}{b + cS_t}. \tag{37}$$

This equation approaches a maximum of $1/b$ when egg production approaches zero, and asymptotes towards zero as egg production approaches infinity. For the fish stock, the minimum value is reached when it is in its virgin state (i.e. at S^*), when recruits-per-egg is R^*/S^*. That is recruits-per-egg ranges from R^*/S^* when the fish stock is unexploited to a maximum,

$$\frac{R^*}{S^*}\left(\frac{4z}{1-z}\right), \tag{38}$$

when egg production approaches zero. For the Beverton-Holt for of the stock recruitment relationship, the factor,

$$\left(\frac{4z}{1-z}\right), \tag{39}$$

represents the maximum level of compensation by the fish stock for the increased mortality of fishing.

If both recruitment and egg production are measured in the same units, then the ratio of R_t/S_t may not exceed one. In this case, this imposes the condition on z that, when the ratio R_t/S_t is a maximum,

$$\frac{R^*}{S^*}\left(\frac{4z}{1-z}\right) \le 1. \tag{40}$$

This can be rearranged to give:

$$z \le \frac{S^*}{4R^* + S^*} \tag{41}$$