STOCK ASSESSMENT OF LARGE COASTAL AND DEMERSAL SHARKS.

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FISHERIES DEPARTMENT
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DEVELOPMENT
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93/067 Stock assessment of large coastal and demersal sharks.

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OBJECTIVES:

1. Improve the quality of the catch and effort information collected from fishers in the shark fishery of southern half as Western Australia.
2. Undertake tagging of *Carcharhinus obscurus, C. plumbeus* and *Furgaleus macki* to determine their exploitation rates, growth and movements.
3. Investigate the biology, especially the reproductive biology, of the important commercial shark species.
4. Determine the gillnet mesh selectivity characteristics of the main commercial shark species.
5. Develop population models to assess the status of the stocks and evaluate future management options for the fishery.

NON TECHNICAL SUMMARY:

The principal purpose of this project was to improve the stock assessment advice available to the managers of the shark fishery in southern half of Western Australia. This fishery is currently worth approximately $7 million per year. Decreasing catch rates during the 1980s and 1990s raised concerns for the status of the main commercial shark species - the dusky whaler, thickskin, gummy and whiskery sharks. To enable the managers of the fishery to make informed decisions on the future of the fishery improved stock assessment, and the ability to evaluate future management strategies, was required.

Computer simulation models of the key shark populations in southern Western Australia were developed as part of this project to provide information on the current status of the stocks and provide a framework for harvest strategy evaluation. The models utilise information on the biology, characteristics of the fishing gear, and time series of catch and effort from the fishery. Much of the research undertaken as part of this FRDC project was to provide data for use in the models for dusky and whiskery sharks.

A tagging program was used to provide information on the movements, growth and level of exploitation, of key shark species. A total of 3026 sharks were tagged, including 2199 juvenile dusky whalers, 343 juvenile thickskin sharks and 282 whiskery sharks. At the time of reporting 339 dusky whalers, 17 whiskery and 14 thickskin sharks had been recaptured. Recapture information showed that juvenile dusky whalers move throughout the southern half of Western Australia, with some moving as far as central South Australia. Whiskery sharks, although mostly moving only short distances, were found to be capable of moving many hundreds of kilometres. Juvenile thickskin sharks were found to often move long distances along the coast with some suggestion of a seasonal migration from the west coast to the south coast. The growth of juvenile dusky whalers was estimated on the basis of tagging data to be approximately 9.5cm fork length a year.

It was estimated that between 16 and 22% of the young born in autumn in the south-west of Western Australia are caught in the following 12 months.

Investigations on the biology of dusky whaler, whiskery and thickskin sharks were based on sharks caught by commercial gillnet fishers. Dusky whaler and thickskin sharks were caught mostly as juveniles in the fishery, while whiskery sharks were caught mostly as subadults or adults. Whiskery sharks mature at sizes just over a metre in fork length and produce litters of approximately 19 young every second year. Thickskin sharks mature at approximately 1.3 metres fork length, with females producing litters of between 6 and 10 young. The reproductive biology of dusky whalers could not be determined as no adults were obtained in samples.

The characteristics of the fishing gear, in particular the size range of sharks caught by commercial gillnets, was estimated by use of an experimental net made up of six different sized meshes. The experimental net was set on 102 occasions throughout southern Western Australia. The resulting data were analysed to provide a mathematical relationship between the mesh size and the size of sharks (of a particular species) caught.

Techniques were developed to analyse the raw monthly catch and effort data that fishers supply. Data quality was improved, and a set of standardised catch and effort figures produced for use in the models. It was hoped that further improvements in the catch and effort data would be achieved from analysis of daily logbook information provided on a voluntary basis by fishers. However, very low cooperation with the project in recent years meant that there were insufficient data to provide meaningful information. Efforts are continuing to improve levels of cooperation with the logbook programme so that it may provide useful data in the future.

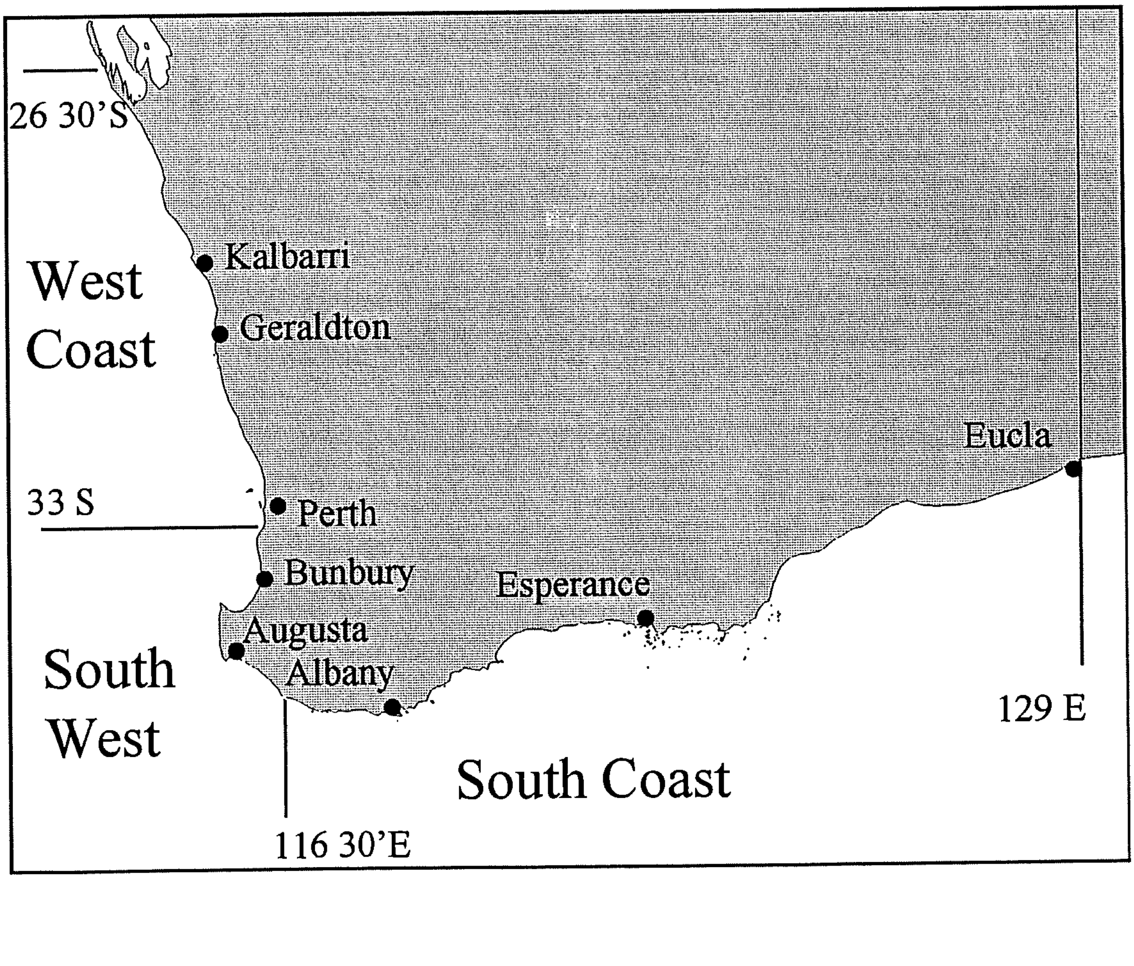
The results from the population models for whiskery and gummy sharks indicate that levels of catch are currently higher than required to meet targets set for the stock size by the management committee for the fishery. The biological characteristics of the dusky whaler meant that the model for this species was not able to provide a meaningful result as to the levels of future catch required to meet target stock sizes.

All of the data collected in this project are stored in validated databases and will be extensively used to provide ongoing advice to industry and the wider community on the shark populations of southern Western Australia. Collection of data from tag returns is ongoing, with many years of information still to be collected. Additionally, the data will form the basis of scientific and popular publications on the biology and fishery of shark populations.

1 BACKGROUND

The shark fishery in southern Western Australia exploits a number of shark species and in 1993/94 was valued at approximately $7 million. The main shark species exploited by the fishery are *Carcharhinus obscurus* (dusky whaler), *C. plumbeus* (thickskin shark), *Mustelus antarcticus* (gummy shark) and *Furgaleus macki* (whiskery shark). The fishery began in the 1940s in the Bunbury area, mostly as a dropline and demersal longline fishery. The introduction of monofilament netting during the late 1960s and early 1970s resulted in the majority of fishers moving to demersal gillnets. Concerns about the levels of mercury in the flesh of sharks during the early 1970s resulted in a drop in production. However, with the introduction of a maximum size limit designed to limit the mercury content of sharks sold, the fishery quickly rebounded. Catches and effort increased steadily through the late 1970s and early 1980s. In the 1980s concerns over the ability of the shark stocks to sustain fishing pressure were raised. As a result the Fisheries Department of Western Australia formed a working group to examine management options for the fishery. This resulted in the introduction of a limited entry fishery south and east of Cape Bouvard (33°S) under a Joint Authority with the Commonwealth. This limited entry fishery has two management zones, one in the south-west of the state, and the second along the south coast (Figure 1). Management arrangements for the area north of Cape Bouvard remain to be finalised.

Figure 1: Management zones for the shark fishery in the southern half of Western Australia. Locations discussed in the report are indicated.



2 NEED

The concerns about the status of the shark stocks in the southern half of Western Australia resulted in the need to:

- understand the dynamics of the fishery, and
- undertake assessment of the status of the stocks.

Considerable information was already available on the biology and status of *Mustelus antarcticus* (eg. Kirkwood and Walker 1986; Lenanton *et al.* 1990; Moulton *et al.* 1992; Walker 1992; Williams and Schaap 1992). As a result the most pressing need was for information on the remaining major commercial species: *Carcharhinus obscurus, C. plumbeus* and *Furgaleus macki*.

3 OBJECTIVES

To address the need for information on the dynamics and status of the stocks, the project had the following objectives:

1. Improve the quality of the catch and effort information collected from fishers.
2. Undertake tagging of *C. obscurus, C. plumbeus* and *F. macki* to determine their exploitation rates, growth and movements.
3. Investigate the biology, especially the reproductive biology, of the important commercial shark species.
4. Determine the gillnet mesh selectivity characteristics of the main commercial shark species.
5. Develop population models to assess the status of the stocks and evaluate future management options for the fishery.

All of the objectives of the project were met.

4 METHODS

4.1 IMPROVE THE QUALITY OF CATCH AND EFFORT DATA

Commercial fishers in Western Australia are required to provide monthly catch and effort data to the Fisheries Department. These data form the basis of stock assessment for most fish stocks, including the major commercial shark species. The quality of the data provided by commercial fishers is variable. Robust stock assessments require that the quality of the data is as high as possible. A number of approaches were taken to improving the quality of the catch and effort data for the purposes of assessing the shark stocks:

- Improving the accuracy of data provided on monthly fishing returns by working closely with industry and providing feed back and assistance in the provision of information.

- Developing techniques to analyse the monthly catch and effort data provided by commercial fishers to improve its quality. Specifically the identification of species composition for catches where no detailed data was provided, comparison of reported and actual effort on the basis of "At Sea" monitoring, correction for missing returns and estimation of effective effort values to incorporate effort standardisation and efficiency increases.
- Investigation of "At Sea" monitoring as a tool to check reported levels of catch.
- Collection of "set-by-set" catch and effort data from a voluntary logbook programme.

The methods associated with each of these initiatives is outlined below.

4.1.1 Analysis of monthly catch and effort data

4.1.1.1 Identification of "other" shark catches

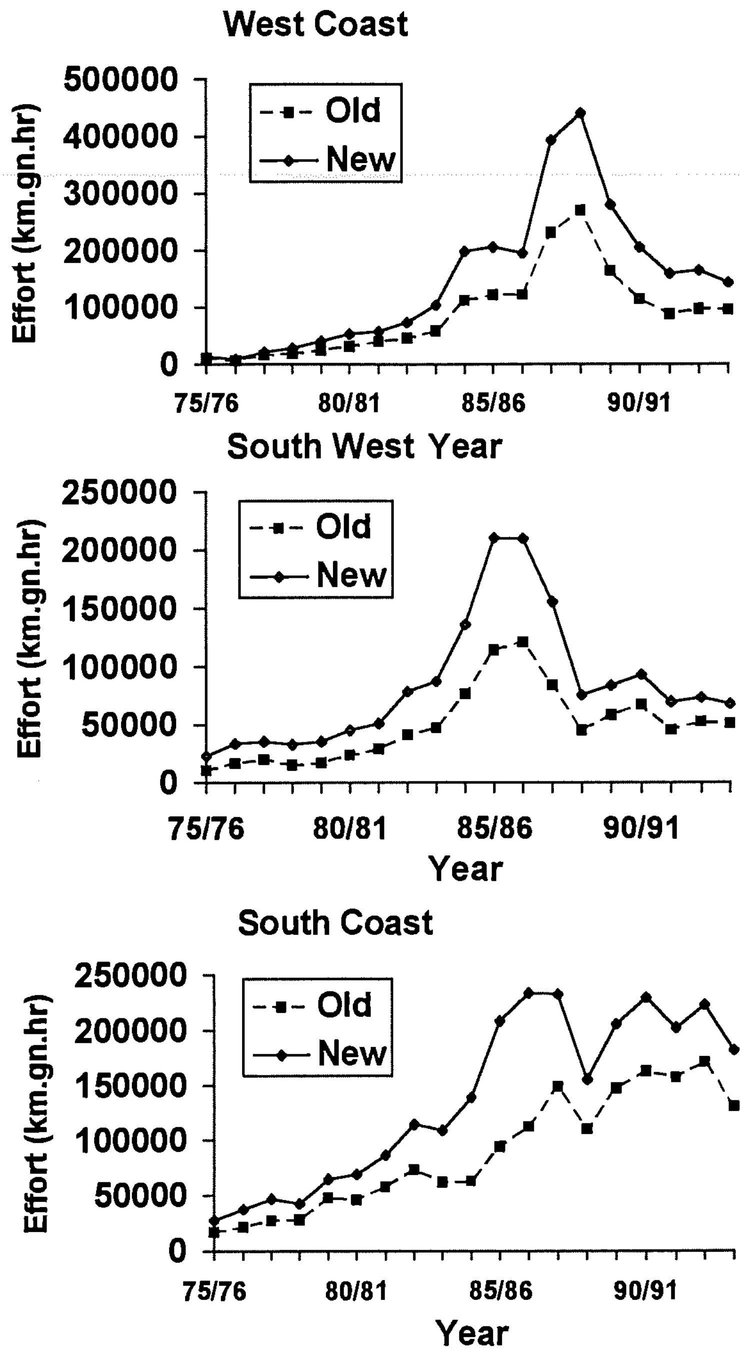
One problem with the catch and effort data is that some fishers have not provided an accurate breakdown of the species composition of their catch. In particular some fishers, especially in the past, have simply reported "shark" on their monthly fishing returns. To overcome this problem the following was undertaken:

1. The proportion of each species landed is calculated for those boats that have been judged to have accurately recorded their catch by species. An algorithm referred to as "good split" incorporates the criteria used to assess the accuracy of the data for each vessel in each month. Catch rates are then calculated for each species for these vessels.
2. The species composition for the other boats is then obtained by partitioning their total catch weight using the proportion of each species recorded by the boats that were judged to have accurate records.

4.1.1.2 Determination of actual nominal effort

Interviews with fishers, and analysis of information on the monthly fishing returns, revealed that many were not supplying accurate information on the amount of time the gear was fishing. Instead many fishers had interpreted the request for information on time fishing as the number of hours that they spent fishing during a trip, not the number of hours the gear was deployed. To correct for this mistake, the mean amount of time that commercial fishing gear was in the water fishing while Fisheries Department staff were onboard in a monitoring capacity was calculated for each of the three management zones. In all three zones the mean time in the water for the gear each day was 19 hours. Discussion with fishers who had operated in the industry since the 1970s suggested that this mistake in the supply of data had occurred consistently over this period. Thus the figure of 19 hours was used to correct all of the nominal effort data since 1975 to provide more accurate effort data. The difference between the previously used effort series and the corrected effort series for each of the three management zones is shown in Figure 2.

Figure 2: Corrected and uncorrected nominal effort data for the three management zones of the commercial shark fishery in southern Western Australia.



4.1.1.3 Correction for missing returns

Catch and effort data were corrected for missing monthly fishing returns. The amount of adjustment for each year was calculated from an assessment of missing returns. The outcome of these adjustments led to catch and effort being increased by 20% in 1986, 35% in 1987, and by 5% in all other years up to 1989/90. Since 1989/90 the compliance with the submission of monthly returns has been enforced and no adjustments have been needed.

4.1.1.4 Effective effort calculations

To more accurately represent the effort targeted at the main species in the commercial shark fishery in southern Western Australia "effective effort" was calculated. Average annual catch rates were calculated for the three major shark species only in the regions in which the catch commonly occurs. The ranges for these species are:

- *Furgaleus macki* 28°S to 129°E
- *Mustelus antarcticus* 116°E to 129°E
- *Carcharhinus obscurus* 28°S to 120°E

The annual catch rate for each of these species within each of the blocks in these ranges was calculated by dividing the catch by nominal effort. The average annual catch rates were then calculated by averaging the catch rates by block and incorporating adjustments for the fishable area within each block, and areas within the range of the stock where there was no fishing. Effective effort was then calculated by dividing the total catch of a species by the average annual catch rate for that species.

4.1.2 "At Sea" monitoring of the commercial shark catch

The species and size composition of the commercial shark catch was recorded during "At Sea" monitoring trips from July 1994 to June 1996. These trips were combined with trips used to tag sharks for another part of this project. As a result more fishing activities were monitored in the areas and times where and when most of the shark tagging operations were carried out. The spatial distribution of the fishing effort monitored over the two year period in the southern part of Western Australia is shown in Figure 3. The highest amounts of fishing effort monitored were in the region from Perth to Augusta (Figure 3). However, fishing effort from all areas south of 28°S was undertaken. The temporal distribution of fishing effort sampled by month during the period is shown in Figure 4. Greatest amounts of effort were monitoring during autumn of each year (Figure 4) as this was the period when most of the tagging was carried out. No monitoring was carried out during only two months (November 1994 and January 1996), with more than 1000 km.gn.hr's of effort monitored in most months (Figure 4).

Where possible all sharks brought onboard a vessel were counted and measured. However, when large catches were taken it was not possible to measure all sharks and a representative subsample was measured. When a subsample was taken specimens were selected to reflect the composition of the catch. Information on the catch rates (number per kilometre gillnet hour) were calculated and the mean values determined for each of the management zones. The catch rates were combined with effort data reported by commercial fishers for each of the regions to estimate the catch in numbers. To estimate the catch in weight the mean length of each species by region was calculated from the size composition data and length-weight relationships used to calculate mean weight by region for the major species. Total regional catches were compared to those reported by commercial fishers to the Fisheries Department of Western Australia on monthly fishing returns.

Figure 3: Spatial distribution of nominal fishing effort sampled by "At Sea" monitoring programme for one degree statistical blocks. Numbers in each block are the total effort (km.gillnet.hours) sampled between July 1994 and June 1996.

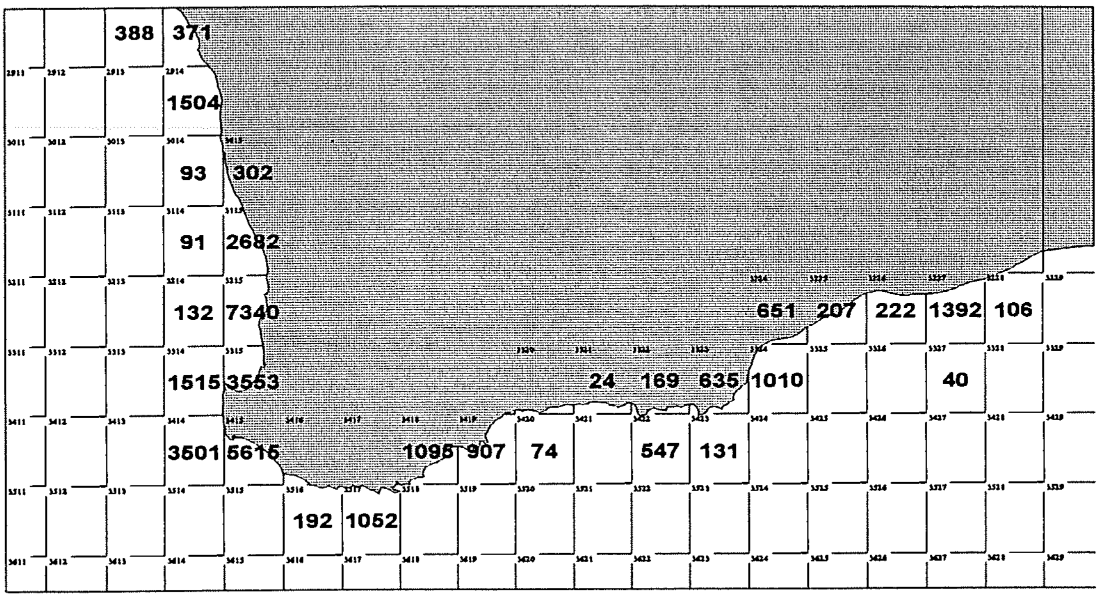
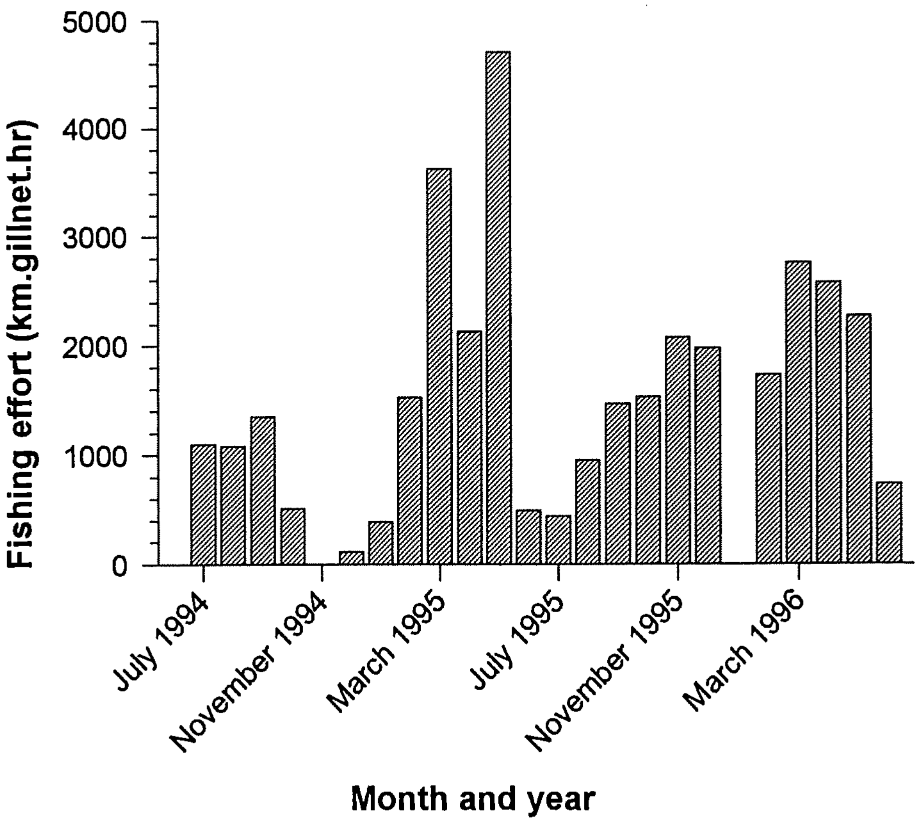


Figure 4: Monthly levels of nominal fishing effort sampled by "At Sea" monitoring between July 1994 and June 1996. Effort expressed in km.gillnet.hours.



4.1.3 Voluntary logbook programme

A voluntary logbook programme has been running in the commercial shark fishery in southern Western Australia since 1973 with varying amounts of success. The most successful period of this programme was during the period when management for the fishery was being discussed. However, since the implementation of management within some zones of the fishery, the numbers of fishers cooperating with the programme has decreased. The implementation of management changes (specifically reductions in gear entitlements) has also resulted in a decrease in cooperation with the logbook programme. As a result less than 5% of the fleet are currently supplying useful logbook information. No vessels in the south-west or west coast regions are currently supplying logbook information. On the basis of the lack of current data it was decided that the analysis of these data was not warranted and that other approaches to improving the catch and effort data should be pursued. Fishers not currently participating with the logbook programme, however, are still being encouraged to supply logbook data.

4.2 TAGGING STUDIES

4.2.1 Data collection

The initial project proposal was to charter commercial shark vessels during the peak pupping season of dusky whalers (autumn) to provide specimens for tagging. Discussions with commercial fishers, and detailed analysis of past catch rates indicated that the anticipated number of animals that could have been tagged during this period would be insufficient to provide the data required to satisfy Objective 2. Instead, Fisheries Department of Western Australia research staff accompanied commercial fishers on their regular fishing trips throughout the year in order to tag live sharks that came aboard.

Sharks were measured (fork length), sexed, and the presence or absence of an umbilical scar noted. All individuals were tagged with a Jumbo Rototag inserted through the first dorsal fin. A proportion of animals were also double tagged (to estimate tag shedding rates) and/or injected with tetracycline (to assist in age validation work). A rotational system was applied such that every second animal was injected and every third double tagged. Animals were double tagged using metal headed dart tags inserted into the musculature near the first dorsal fin. Double tagged animals were used to estimate tag shedding rates for both the Jumbo Rototag and metal headed dart tag. Sharks injected with tetracycline received an intramuscular injection of 25mg/kg body weight. The condition of individuals on release was assessed qualitatively based on their response when returned to the water (Table 1). Information on location, date, weather and sea conditions at release were also recorded.

Table 1: Release condition index for tagged sharks.

Condition index	Response on release
1	swam away strongly from the boat
2	swam away slowly from the boat
3	not observed to swim when released

Tagging trips on board commercial shark fishing vessels were undertaken between Kalbarri on the mid-west coast and the WA/SA border. With the main target of the project being juvenile dusky whalers, greatest tagging effort was concentrated in waters off the south-west of Western Australia where catch rates indicate abundance is highest (Figure 5) pupping occurs mostly during autumn. The spatial and temporal distribution of tagging effort (number of sets for which staff were available to tag sharks) are shown in Figure 6 and 7, respectively.

Figure 5: Distribution of catch rates of *Carcharhinus obscurus* along the coast of Western Australia by one degree of latitude/longitude in the 1994/95 financial year. Location of fishery management zones are indicated. Insufficient data were available for 30°S to provide accurate estimate of catch rate.

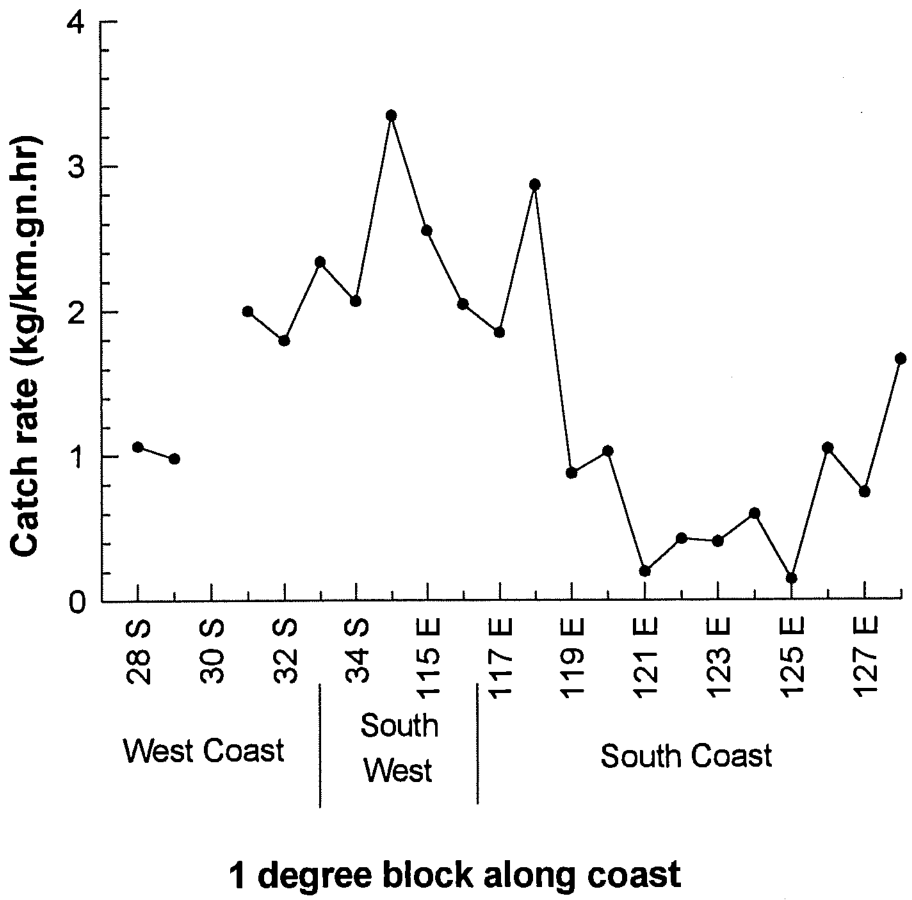


Figure 6: Distribution of tagging effort (number of gillnets sets for which staff were on board to tag sharks) by one degree statistical block.

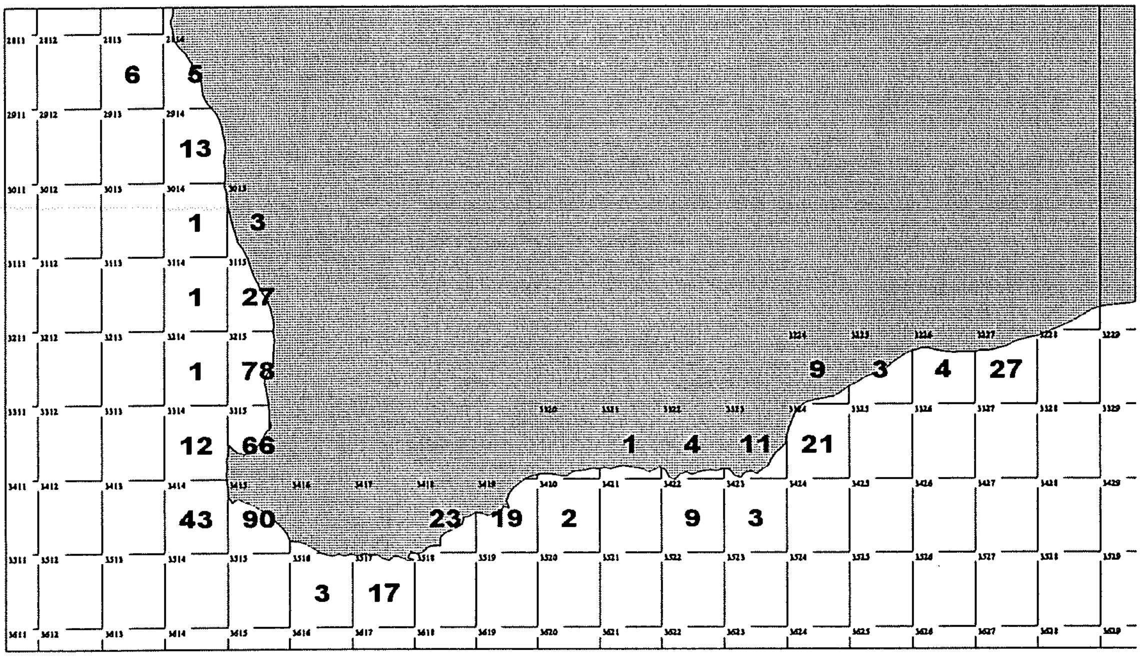
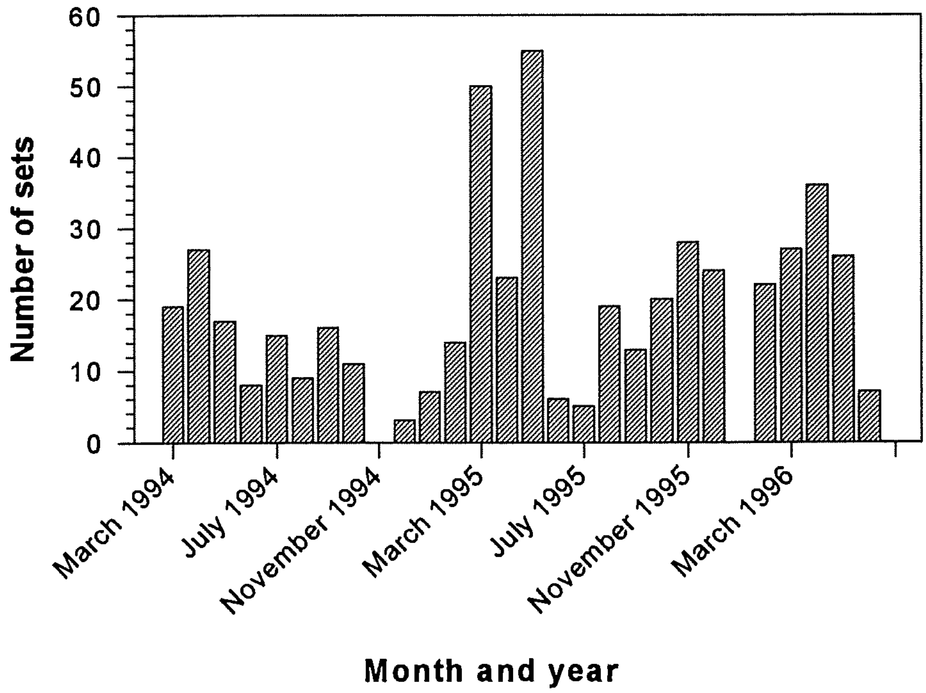


Figure 7: Distribution of tagging effort (number of gillnet sets for which staff were on board to tag sharks) by year and month.



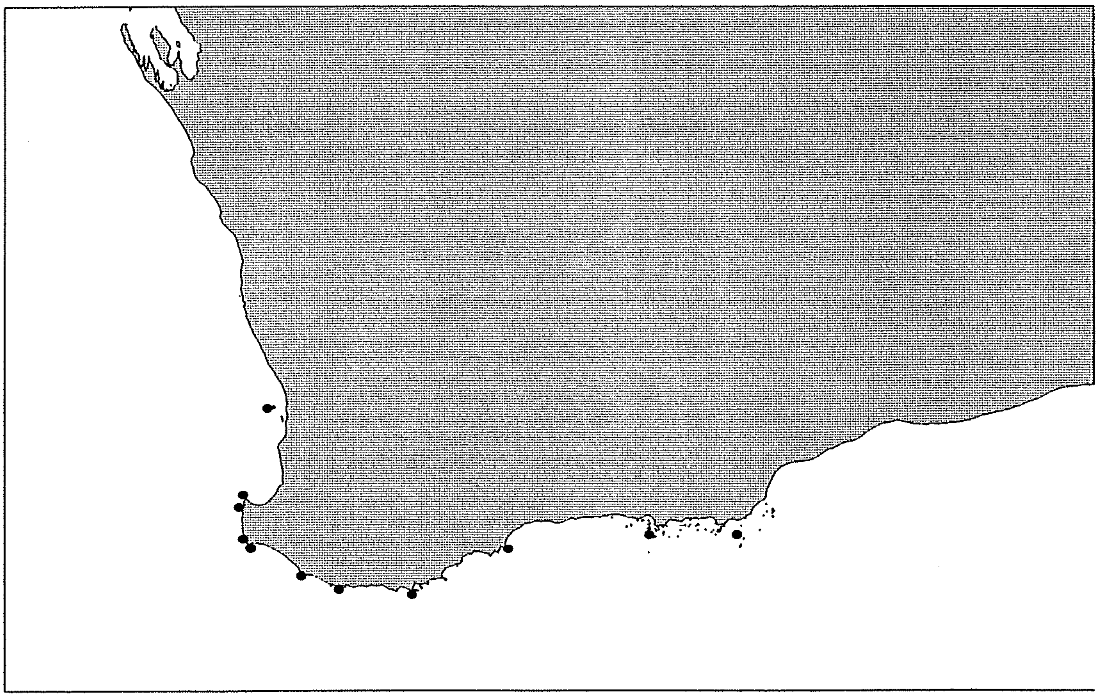
Tag returns were received from both commercial and recreational fishers. Recapture information requested included the date and location of capture, length, tag number(s), species, sex, and condition of shark and tag. Where possible a sample of vertebrae was also collected. In order to assist in providing accurate recapture information commercial shark fishers were given tag reporting forms, and instructions on how to measure sharks and remove vertebrae.

4.2.2 Analysis

4.2.2.1 Distance moved

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 (Figure 8). The locations of the turning points were determined such that a shark would not move over land as it travelled along the coast. 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 the two turning points mentioned above. The result is an estimate of the minimum "at-sea" distance moved, rather than that given by a straight line that passed over land.

Figure 8: Turning points (●) used for the calculation of distances moved by tagged sharks in southern Western Australia.



4.2.2.2 Growth parameters

Growth increments were calculated from lengths at release and recapture. Growth parameters were estimated using the technique of Francis (1988). This technique fits growth increment data to a reparameterised version of the von Bertalanffy growth equation using a maximum likelihood function. Growth increment data from animals at liberty greater than 60 days were used to fit the model. The Francis method also allows for the estimation of growth variability, measurement error (mean and standard deviation) and the probability that any point is erroneous (contamination probability).

4.2.2.3 Tag shedding

Rates of tag shedding were estimated from recaptured double tagged individuals using the technique of Xiao (1996). This technique uses information from the loss of tags from double tagged individuals and the period at liberty to estimate annual rates of tag loss. The method assumes that the probability of loss of one tag is independent of the loss of the other tag. Estimates of tag shedding rates were made for both Jumbo Rototags and metal headed dart tags.

4.2.2.4 Non-reporting of tag returns

The rate at which the non-reporting of tag returns occurred for the demersal gillnet fleet was estimated using a technique that apportioned the fishing effort between boats that reported and did not report tag returns. Vessels in the fishery were designated as "good reporters" or "bad reporters". There was a clear distinction between "good" and "bad" reporters, with "bad" reporters rarely, if ever providing data on tag returns. The monthly nominal fishing effort of each vessel is available from the monthly fishing returns. Monthly effort was apportioned into "good" and "bad" reporting effort based on each vessel's reporting status. From the known reporting rate of the "good" vessels within an area, the non-reporting rate of the "bad" vessels could be estimated on a monthly basis. The estimation of non-reporting rate was undertaken on a regional basis to account for different regional catchabilities and availabilities of tagged sharks.

4.2.2.5 Exploitation rate

It was possible to identify newly pupped *C. obscurus* by the presence of an umbilical scar between the pectoral fins. The scar lasts only for several weeks. With most of the juvenile *C. obscurus* tagged being born during autumn it was possible to identify individual cohorts and calculate the exploitation rate of each cohort based on tag returns.

The exploitation rate (ER, the proportion of tagged individuals recaptured in a specified time period) was calculated for a juvenile *C. obscurus* of cohort a at time t using the equation:

$$ER_{a,t} = \frac{N_{a,t}.e^{-TS.t}\sum_{i=1}^{r} R_{a,i,t}/(1-NR_{a,i,t})}{N_{a,t}.e^{-TS.t}} \quad (1)$$

where $N_{a,t}$ is the number of tagged animals of cohort a available for capture during time period t,

$R_{a,i,t}$ is the number of reported recaptures of animals from cohort a in region i during time period t,

r is the number of regions,

TS is the annual tag shedding rate, and
$NR_{a,i,t}$ is the non-reporting rate for region i during time period t.

Exploitation rates were calculated for the periods from July to June (financial years) for each of the cohorts released. This allowed the tagged sharks a minimum period at liberty of one month (and up to 4 months) to mix with the population before being included in the exploitation rate calculations. The calculation of exploitation rates by financial year also matched catch and effort data that was collected in this fashion.

4.3 MESH SELECTION CHARACTERISTICS

Mesh selection characteristics were examined using an experimental demersal gillnet. The net contained 7 panels, each with different mesh sizes and/or mesh drops. Details of the mesh size, mesh drop and line size of each panel are given in Table 2. The hanging ratio of all panels of net was 0.6, and each panel was approximately 270m in length. The net was constructed by a commercial shark fisher so that the net was as similar as possible to nets used by the fishing industry. Mesh sizes are given in inches as the fishing industry still uses imperial units for these measurements.

Table 2: Net characteristics for each panel of the experimental net.

Panel number	Mesh size (inches)	Mesh drop (7 inch equivalent)	Line size
1	5	20	30
2	6	20	30
3	6.5	20	35
4	7	20	35
5	7	15	35
6	8	20	35
7	8.5	20	35

The net was deployed from commercial shark fishing vessels throughout the southern half of Western Australia. The seven panels of net were randomly ordered when placed on each new vessel. Details of the periods of fishing with the experimental net are given in Table 3.

Table 3: Fishing periods with the experimental net in southern Western Australia.

Trip number	Region	Date	Number of panels	Number of Shots
1	Bunbury	March/April 1994	7	15
2	Augusta	May/June 1994	7	7
3	Mandurah	August/ September 1994	7	15
4	Augusta	October 1994	7	11
5	Augusta	January 1995	7	7
6	Esperance	March 1995	7	23
7	Esperance	December 1995	4	8
8	Esperance	April 1996	4	2
9	Two Rocks	May/June 1996	7	14

Information from all of the sharks and scalefish caught in the experimental net were recorded, including mesh size, species, fork length or total length, sex and whether it was meshed, tangled or rolled in the net.

Catch rates of the main shark species were calculated for each mesh size for each set of the experimental net. Catch rates were expressed as both the number caught per unit of fishing effort and weight per unit of fishing effort. Weights of individual sharks were calculated from lengths using the length-weight relationships given in Table 4. The measure of fishing effort (kilometre hours) was calculated by multiplying the length of net by the period that the net was in the water. Catch rates were compared between mesh sizes using a single factor ANOVA on log transformed data.

Mesh selectivity relationships for the two main commercial shark species caught in the south-west of Western Australia (*C. obscurus* and *F. macki*) were estimated using the method of Kirkwood and Walker (1986). This technique fits a gamma distribution to the size distribution data for each mesh size using a maximum likelihood function. The mesh selection parameters estimated - θ_1 and θ_2 - can be used to calculate relative mesh selectivities for any size mesh.

Table 4: Length weight relationships for *Carcharhinus obscurus* and *Furgaleus macki*. Data from historical Fisheries Department of Western Australia records. *w*, total weight; *l*, total length.

Species	Relationship	r^2
Carcharhinus obscurus	$w = 1.2334 \times 10^{-5}.l^{2.855}$	0.967
Furgaleus macki	$w = 1.63 \times 10^{-5}.l^{2.733}$	0.769

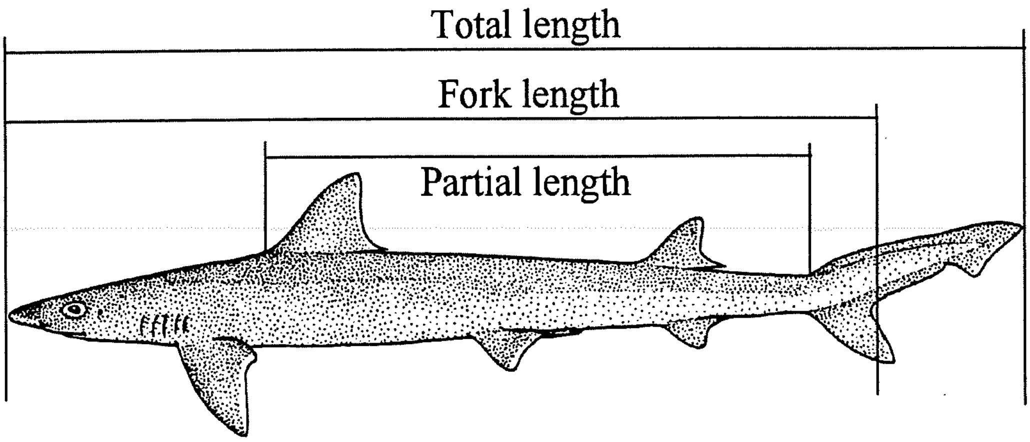
4.4 BIOLOGICAL STUDIES

4.4.1 Data collection

Biological data for shark species caught by the commercial shark fishers in southern Western Australia were collected during "At Sea" monitoring. These sampling trips were combined with tagging trips. Biological data was collected from vessels operating of the southern half of Western Australia.

Information on the location, date, sea conditions, depth, bottom type, etc., were recorded for all gillnet sets from which biological information was collected. Attempts were made to record the species, sex, presence of umbilical scar and length of all individual sharks that came aboard. However, at times the large number of sharks caught made it impossible to achieve this task. In this situation the numbers of each species captured were recorded, with sex and size data collected from a sub-sample of the catch. One or more of total, fork and partial length were measured on each shark (Figure 9). A subsample of specimens were dissected to provide data on the reproduction and feeding.

Figure 9: Length measurements taken from sharks sampled during "At Sea" sampling.



Males were considered mature when the claspers were elongate and fully calcified. Clasper length of males was measured as the distance from the tip of the clasper to its junction with the pelvic fin. Females were considered mature if they possessed enlarged yolky ovarian follicles (yolky ova), or embryos in the uteri. The number of yolky ova were counted and the diameter of the largest measured to the nearest millimetre (MOD - maximum ova diameter). The size at sexual maturity was estimated based on the size at which approximately 50% of males or females were mature.

The condition of the uterus was divided into six stages on the basis of those used by Lenanton *et al.* (1990) (Table 5). The number of embryos in the uteri of pregnant and post-ovulatory females were counted and the total length of up to four measured to the nearest millimetre.

Table 5: Uterus stage index used for 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

4.5 MODELLING

An age structured population model was developed for each of the three main species of sharks caught in the shark fishery of southern Western Australia. The model structure was the same for each of the species. The structure of this model for a single species is described below.

4.5.1 Dynamics

Dynamics of the stock are assumed to be described by:

$$N_{a,t+1} = \begin{cases} N_{0,t+1} & a = 0 \\ N_{a-1,t}.e^{-(M+F_t.S_{a-1})} & 1 \le a < x \\ N_{a-1,t}.e^{-(M+F_t.S_{a-1})} + N_{a,t}.e^{-(M+F_t.S_a)} & a = x \end{cases} \quad (2)$$

where $N_{a,t}$ is the number of fish at age a at the start of year t,
M is the instantaneous rate of natural mortality,
F is the instantaneous rate of fishing mortality for sharks that are fully selected,
S_a is the selectivity of the gear of age a fish, and
x is the maximum age of fish.

4.5.2 Recruitment

Recruitment to the fishery is assumed to follow a Beverton and Holt style stock-recruitment relationship. The number of animals entering the 0+ age class at time t is given by:

$$N_{0,t} = \frac{\sum_{a=m}^{x} N_{a,t}.P'_a.P''_a.P'''_a}{\left(SRRa + (SRRb.\sum_{a=m}^{x} N_{a,t}.P'_a.P''_a.P'''_a)\right)} \quad (3)$$

where P'_a is the number of pups per pregnant female at age a,
P''_a is the proportion of females pregnant at age a, and
P'''_a is the sex ratio at age a, and
m is the age at maturity.

The two stock-recruitment parameters (*SRRa* and *SRRb*) are calculated from the known reproductive characteristics of the species and the parameters of the Beverton-Holt relationship (z and R^*) (Hilborn *et al.* 1994):

$$SRRa = \frac{\sum_{a=m}^{x} N^*_a.P'_a.P''_a.P'''_a.\left(1 - \frac{(z-0.2)}{(0.8z)}\right)}{R^*} \quad (4)$$

where N^*_a is the number of sharks of age a in the unexploited population,

z is the steepness of the Beverton Holt stock recruitment relationship near the origin, and

R^* is the number of recruits in the unexploited population.

And,

$$SRRb = \frac{z-0.2}{0.8\,z\,R^*} \tag{5}$$

4.5.3 Gear selectivity

The use of gillnets in the fishery necessitated the inclusion of a selectivity term in the model. Details of the calculation of gear selectivity for *Carcharhinus obscurus* and *Furgaleus macki* are given in another section of this document. Selectivity was expressed as a gamma function following the method of Kirkwood and walker (1986):

$$S_a = \left(\frac{L_a}{\alpha\beta}\right)^{\alpha} . e^{\alpha - \frac{L_a}{\beta}} \tag{11}$$

where,

$$\alpha\beta = \theta_1 . ms \tag{12}$$

and,

$$\beta = -\tfrac{1}{2}\left((\theta_1 . ms) - \left(\theta_1^2 . ms^2 + 4\theta_2\right)^{\frac{1}{2}}\right) \tag{13}$$

and,

$$\alpha = \frac{\alpha\beta}{\beta} \tag{14}$$

where L_a is the mean size at age a,
ms is the mesh size, and
θ_1 and θ_2 are the mesh selectivity parameters.

4.5.4 Catches

The predicted catch (in weight) for time period t is calculated using the equation:

$$\hat{C}_{a,t} = \frac{N_{a,t} . F_t . S_a . (1 - e^{-(M + F_t . S_a)})}{(M + F_t . S_a)} . w_a \tag{6}$$

where,

$$F_t = q.E_t \qquad (7)$$

And,

$$w_a = lwa.L_a^{lwb} \qquad (8)$$

where *lwa* and *lwb* are constants determined from length-weight regression.

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

$$L_a = L_\infty.(1 - e^{-(K(a+0.5-t_0))}) \qquad (9)$$

where *K*, l_∞ and t_0 are known parameters of the von Bertalanffy growth equation.

Total catch for time period *t* is given by:

$$\hat{C}_t = \sum_{a=1}^{x} \hat{C}_{a,t} \qquad (10)$$

4.5.5 Biomass

Total biomass at time *t* was calculated by:

$$B_t = \sum_{a=1}^{x} N_{a,t}.w_a \qquad (15)$$

4.5.6 Pre-exploitation condition

The population is assumed to be in pre-exploitation equilibrium prior to 1975. Numbers of individuals at age *a* at equilibrium were assumed to be:

$$N_a^* = \begin{cases} R^* & a = 0 \\ N_{a-1}^*.e^{-M} & 1 \le a < x \\ \dfrac{N_{a-1}^*.e^{-M}}{1-e^{-M}} & a = x \end{cases} \qquad (16)$$

4.5.7 Fitting the model

The model was fitted on catch to provide estimates of *z*, R^* and q using a least squares method:

$$SS = \sum_{t=1975}^{1994} (C_t - \hat{C}_t)^2 \tag{17}$$

where C_t is the observed catch for time *t*, and
$\hat{C}_t$ is the predicted catch at time *t* from the model.

4.5.8 Uncertainty

To provide a measure of the uncertainty associated with the fitting of the model a Bayesian approach was taken. Three scenarios are presented - most likely (the best fit of the model), conservative (approximately the lower 95% confidence interval) and optimistic (approximately the upper 95% confidence interval). The area between the optimistic and conservative scenarios represents the range of solutions over which it is 95% certain that the "real" solution occurs if the model structure is correct.

4.5.9 Future harvest strategies

The age-structured models were used to assess the impact of future harvest strategies on the stock in relation to reference points used in managing the fishery. The current target reference point for the stocks of *C. obscurus*, *F. macki* and *M. antarcticus* are 40% of 1975 level of total biomass. It was assumed that the 1975 level of biomass was a reasonable approximation to virgin biomass. The management committee for the fishery has set the year 2010 as the target date for achieving the biomass targets for *F. macki* and *M. antarcticus,* and 2040 for *C. obscurus.* The model was used to calculate the annual catches required until the target year to achieve a biomass level equal to the target reference point.

5 DETAILED RESULTS

5.1 IMPROVE THE QUALITY OF CATCH AND EFFORT DATA

5.1.1 Analysis of monthly catch and effort data

The improvements to the monthly catch and effort data provided by fishers enabled the calculation of standardised sets of catch (Table 6) and effective effort (Table 7) data for each of the major commercial species. These data series were used in the age-structured population models developed as part of this project.

Table 6: Corrected annual catch data for *Furgaleus macki*, *Mustelus antarcticus* and *Carcharhinus obscurus* for the commercial shark fishery in southern Western Australia from 1975.

Year	Catch (tonnes)		
	F. macki	*M. antarcticus*	*C. obscurus*
75/76	162	64	128
76/77	214	74	130
77/78	346	101	202
78/79	273	110	245
79/80	388	149	280
80/81	413	188	269
81/82	611	223	332
82/83	493	165	354
83/84	389	160	478
84/85	399	201	677
85/86	481	150	701
86/87	441	203	638
87/88	583	320	697
88/89	447	260	683
89/90	409	396	652
90/91	494	415	534
91/92	433	538	480
92/93	372	498	579
93/94	227	263	561
94/95	261	304	517

Table 7: Effective effort data for *Furgaleus macki*, *Mustelus antarcticus* and *Carcharhinus obscurus* for the commercial shark fishery in southern Western Australia from 1975.

Year	Effective effort (km.gn.hr)		
	F. macki	*M. antarcticus*	*C. obscurus*
75/76	66156	17783	43552
76/77	78589	26455	57785
77/78	125622	50202	102896
78/79	102663	77712	80052
79/80	174760	99959	137469
80/81	216383	85040	155356
81/82	342034	136367	176156
82/83	396881	135970	251678
83/84	409256	159319	290834
84/85	414193	116657	404320
85/86	703125	194669	652976
86/87	792184	253362	625928
87/88	963167	348978	720081
88/89	652651	259285	592214
89/90	758267	343250	496407
90/91	678862	345715	528162
91/92	612821	331115	459117
92/93	709783	386423	416557
93/94	605912	290816	399166
94/95	588418	202819	438425

5.1.2 "At Sea" monitoring of the commercial shark catch

The "At Sea" monitoring of commercial shark catches was only able to cover a small proportion of all of the fishing effort in the fishery. During the 1994/95 financial year the coverage of the south-west management area was over 11%, but in the other areas was less than 5% (Table 8). The limited coverage of the "At Sea" monitoring will restrict the accuracy of the final figures.

Table 8: Coverage of the "At Sea" monitoring of commercial shark catches. Reported levels of effort in the fishery are based on monthly figures provided by fishers.

Management area	1994/95			1995/96
	Reported effort (km.gn.hr)	"At Sea" monitoring effort (km.gn.hr)	Percent coverage of "At Sea" monitoring	At Sea" monitoring effort (km.gn.hr)
south-west	62000	7384	11.9	7219
south coast	127000	2958	2.33	5263
west coast	161000	6895	4.28	6008

The species composition (in numbers) of the catch from each of the three management zones, as observed during "At Sea" monitoring, is shown in Table 9.

Table 9: Catch composition (% of total number of fish caught) of the three management regions as observed during "At Sea" monitoring of commercial catches.

Species	Management zone		
	south west	south coast	west coast
Shark			
Carcharhinus obscurus	55.25	11.83	35.32
Mustelus antarcticus	1.99	37.51	0.59
Furgaleus macki	7.66	6.89	7.28
Carcharhinus plumbeus	3.70	4.69	15.59
Galeorhinus galeus	0	12.37	0
Sphyrna zygaena	3.00	4.92	4.37
Orectolobus spp.	1.35	0.41	2.97
Myliobatus australis	1.71	6.35	2.83
Carcharhinus brevipinna	0.36	0.06	8.70
Other shark	1.66	4.34	3.26
Scalefish			
Nemadactylus valenciennesi	7.53	4.82	5.05
Glaucosoma hebraicum	4.09	0.07	4.80
Pentacerotidae (all spp.)	2.44	2.10	0.57
Acherodus gouldii	2.37	1.69	0.96
Pagrus auratus	1.23	0.25	2.25
Nelusetta ayraudi	2.12	0.04	0.61
Other scalefish	3.53	1.63	4.83

The size composition of the seven most commonly caught shark species are shown in Figure 10. The limited size distributions for each species reflects the size selective nature of the gillnets used in the fishery. Size selectivity would appear to be similar within families. The dusky whaler, thickskin and longnose grey (all from the family Carcharhinidae) all have similar size distributions, while the whiskery, gummy and eastern school (all from the family Triakidae) also have similar size distributions.

Catch rate and total catch (in number of animals) figures for the main shark species caught are given in Table 10, and the total catch in weight of each species are given in Table 11. The results for *Furgaleus macki* were the closest to those reported by fishers for each of the management areas. However, for other species the results were quite variable, with estimates normally greater than those observed. It is impossible to determine if these differences are the result of the relatively low coverage of the "At Sea" monitoring, or of miss-reporting of effort or catch by fishers. To improve the quality of the predictions from the "At Sea" monitoring, greater coverage throughout the year would need to be achieved. Such a task would require considerably more resources than were available to the present study.

Figure 10: Size frequency distributions of the seven most commonly caught species of shark as observed during "At Sea" monitoring of the commercial fishery. Data from all management regions combined.

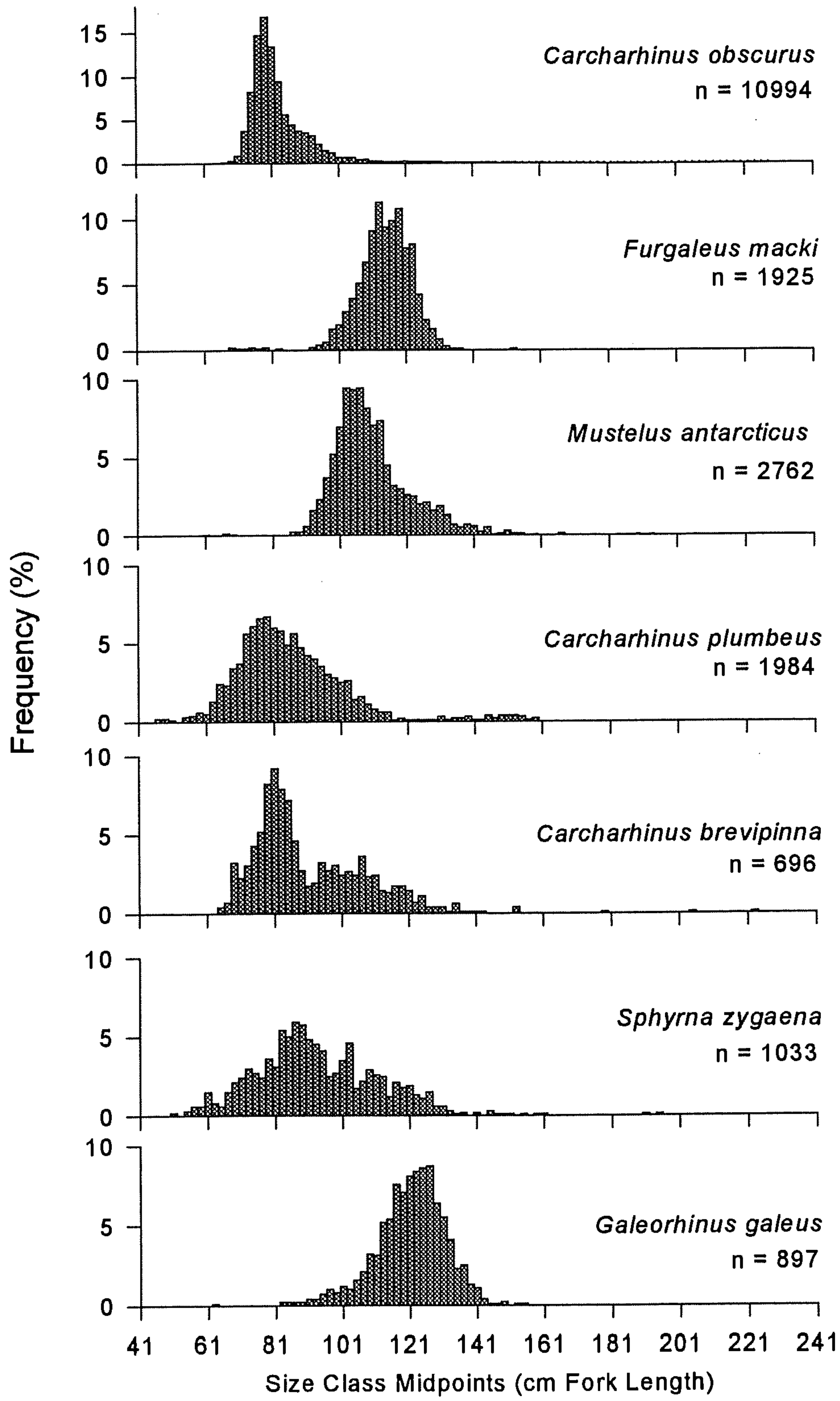


Table 10: Catch rates of the main commercial shark species reported from each of the three management areas as determined from "At Sea" monitoring for the 1994/95 financial year. The predicted catch (in numbers) for each management area was determined by multiplying catch rate by the reported level of effort.

Species	Catch rate (number/km.gn.hr)			Predicted catch (number)		
	south-west	south coast	west coast	south-west	south coast	west coast
Carcharhinus obscurus	0.3032	0.1972	0.2451	18798.4	25044.4	39461.1
Galeorhinus galeus	0	0.0003	0	0	38.1	0
Mustelus antarcticus	0.0186	0.3945	0.0032	1153.2	50101.5	515.2
Sphyrna zygaena	0.021	0.0492	0.032	1302	6248.4	5152
Carcharhinus brevipinna	0.0036	0.0008	0.082	223.2	101.6	13202
Hypogaleus hyugaensis	0.0059	0.0281	0.0005	365.8	3568.7	80.5
Carcharhinus plumbeus	0.0068	0.0048	0.0801	421.6	609.6	12896.1
Furgaleus macki	0.138	0.0729	0.048	8556	9258.3	7728

Table 11: Predicted catch (in live weight) from the "At Sea" monitoring of commercial catches and the proportion of the reported catch from the fishery.

Species	Predicted catch (kg)				Proportion of reported catch			
	south-west	south coast	west coast	Total	south-west	south coast	west coast	Total
Carcharhinus obscurus	107195	198040	275013	580249	0.767	2.067	1.527	1.395
Galeorhinus galeus	0	567	0	567	0	0.012	0	0.012
Mustelus antarcticus	13140	446897	5466	465503	1.739	1.785	1.003	1.768
Sphyrna zygaena	10932	41404	41126	93463	4.021	1.636	1.834	1.853
Carcharhinus brevipinna	3008	1519	102599	107126	3.331	3.806	2.947	2.966
Hypogaleus hyugaensis	2000	19197	426	21622	8.732	4.940	0.395	4.164
Carcharhinus plumbeus	2115	3375	99383	104873	1.622	1.175	1.359	1.357
Furgaleus macki	73335	84966	67777	226078	1.087	0.999	1.111	1.059

5.2 TAGGING STUDIES

5.2.1 Release details

A total of 3026 sharks, from 17 species, were tagged between March 1994 and June 1996 (Table 12). The majority of sharks tagged were *Carcharhinus obscurus*, *C.*

plumbeus, and *Furgaleus macki*. In addition, 83 school and 533 gummy sharks were also tagged to assist with FRDC project 93/066 (Southern Shark Tagging Project).

Table 12: Numbers of tagged sharks released in the waters of southern Western Australia between March 1994 and June 1996.

Species	Number tagged
Carcharhinus obscurus	2199
Carcharhinus plumbeus	343
Furgaleus macki	282
Carcharhinus brevipinna	70
Carcharhinus brachyurus	48
Orectolobus spp.	33
Hypogaleus hyugaensis	13
Sphyrna zygaena	11
Mustelus sp.	6
Carcharias taurus	6
Galeocerdo cuvier	4
Carcharodon carcharias	2
Aptychotrema vincentianna	2
Isurus oxyrinchus	2
Notorhynchus cepedianus	1
Squalus megalops	1
Rhynchobatus djiddensis	1

5.2.1.1 *Carcharhinus obscurus*

A total of 2199 *Carcharhinus obscurus* (1062 female, 1100 male and 37 of unknown sex) were tagged during the project. They ranged in size from 64 cm FL to 108 cm FL, with the majority between 70 cm FL and 80 cm FL (Figure 11). 78.7% had umbilical scars indicating that they had recently been born. 517 *C. obscurus* were double tagged, 879 injected with tetracycline and 230 were double tagged and injected. The condition on release was recorded for 2092 *C. obscurus* (Table 13).

Releases of *C. obscurus* were concentrated in the south-west of the State in the region from Perth to Augusta (Figure 12). Most animals were released during Autumn of 1994, 1995 and 1996 (Figure 13). However, there were releases over the full tagging area from Kalbarri to Eucla and throughout the year. The distribution of the releases reflects the utilisation of the south-west as a nursery area for this species, with the majority of pups born during the months of March to May.

Figure 11: Size frequency distribution of male (open bars) and female (hatched bars) *Carcharhinus obscurus* tagged in the southern half of Western Australia.

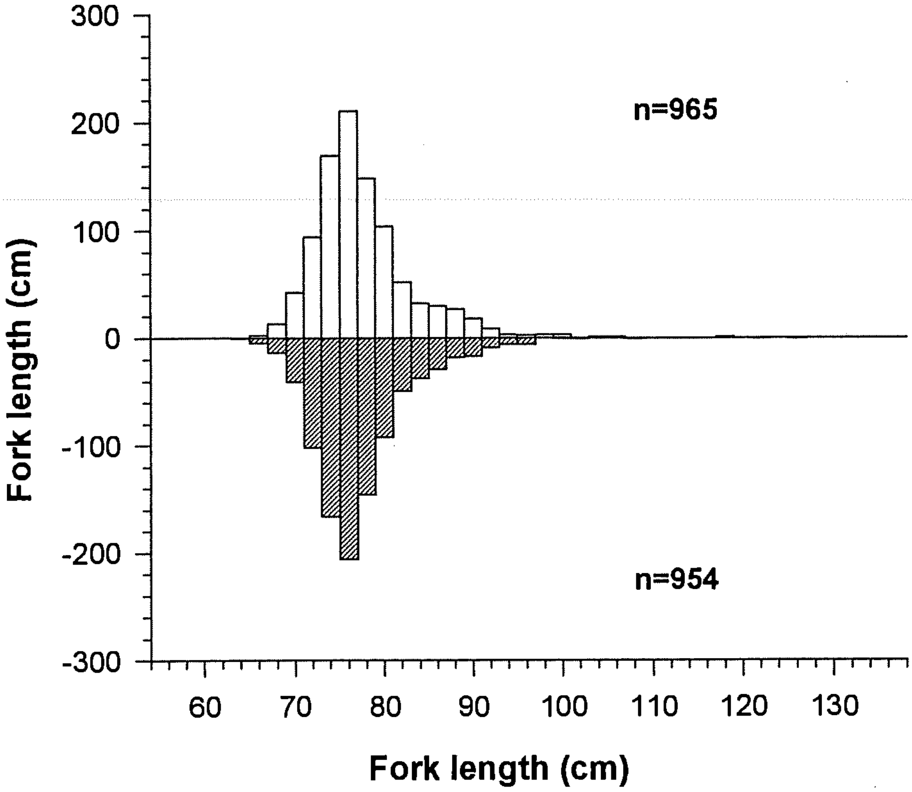


Table 13: Condition of *Carcharhinus obscurus* on release after tagging. See Table for description of the release index.

Release condition index	Number
1	1651
2	369
3	72
not recorded	107

Figure 12: Numbers of tagged *Carcharhinus obscurus* released by one degree statistical block.

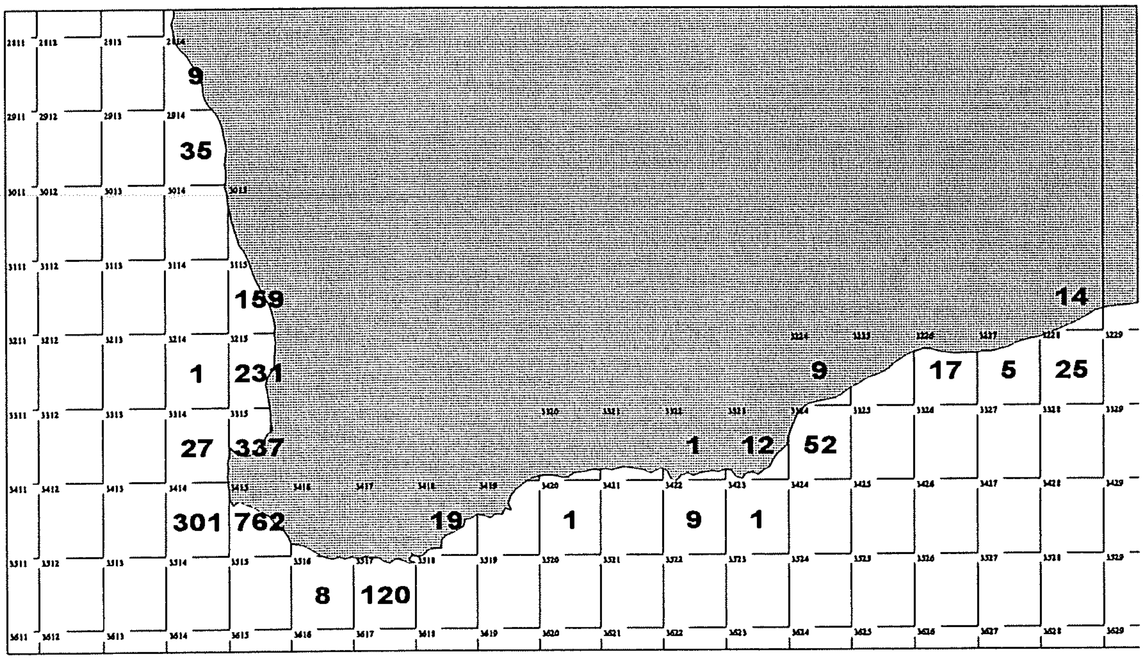
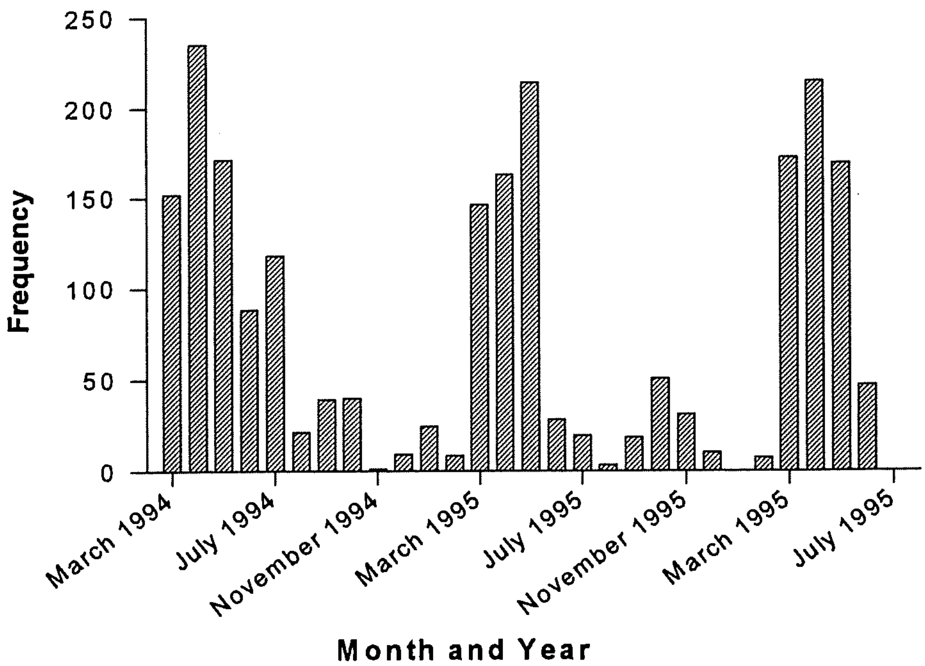


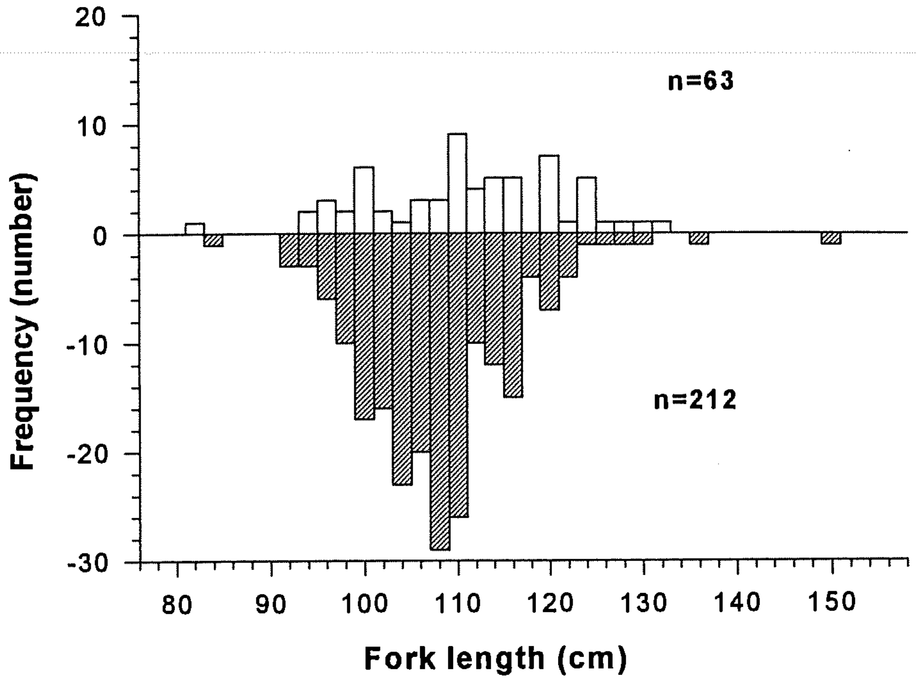
Figure 13: Numbers of tagged *Carcharhinus obscurus* released by year and month.



5.2.1.2 Furgaleus macki

A total of 278 *Furgaleus macki* were tagged during the project. The sex ratio of released *F. macki* was biased towards females (77% female). The sex ratio of the commercial catch is approximately 61% female, suggesting that female *F. macki* may survive better in the nets. Sizes ranged from 80 cm FL to 140 cm FL, with most in the range from 96 to 124 cm FL (Figure 14). 42 were double tagged, 105 were injected with tetracycline and 21 were double tagged and injected.

Figure 14: Size frequency distribution of male (open bars) and female (hatched bars) *Furgaleus macki* released in southern Western Australia.



Releases occurred throughout the tagging area, with the majority in the region from Bunbury to Augusta (Figure 15). Typically only small numbers of *F. macki* were tagged each month, with larger numbers released in September and October 1994, May 1995 and August 1995 (Figure 16). The overall low number of tag releases reflects the fact that commercial fishers rarely target whiskery sharks, and that this species appears not to survive netting as well as species such as *C. obscurus*.

Figure 15: Numbers of tagged *Furgaleus macki* released by one degree statistical block in southern Western Australia.

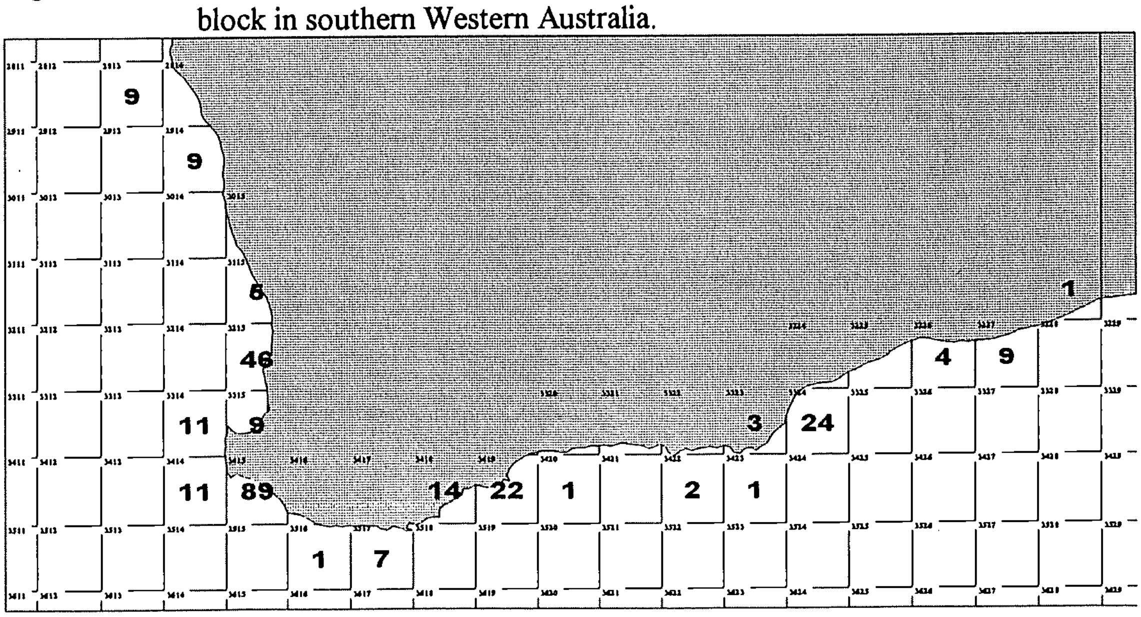
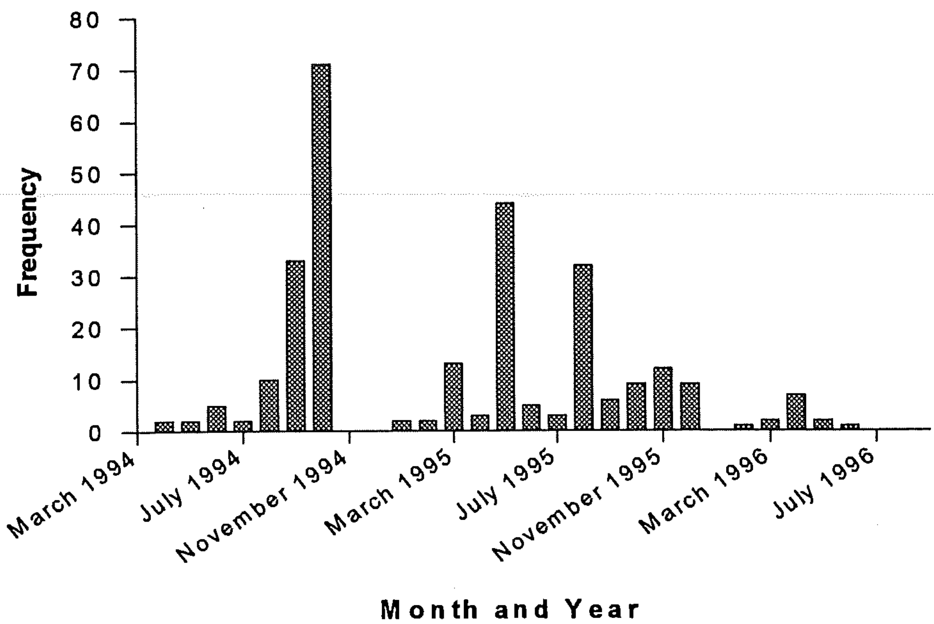


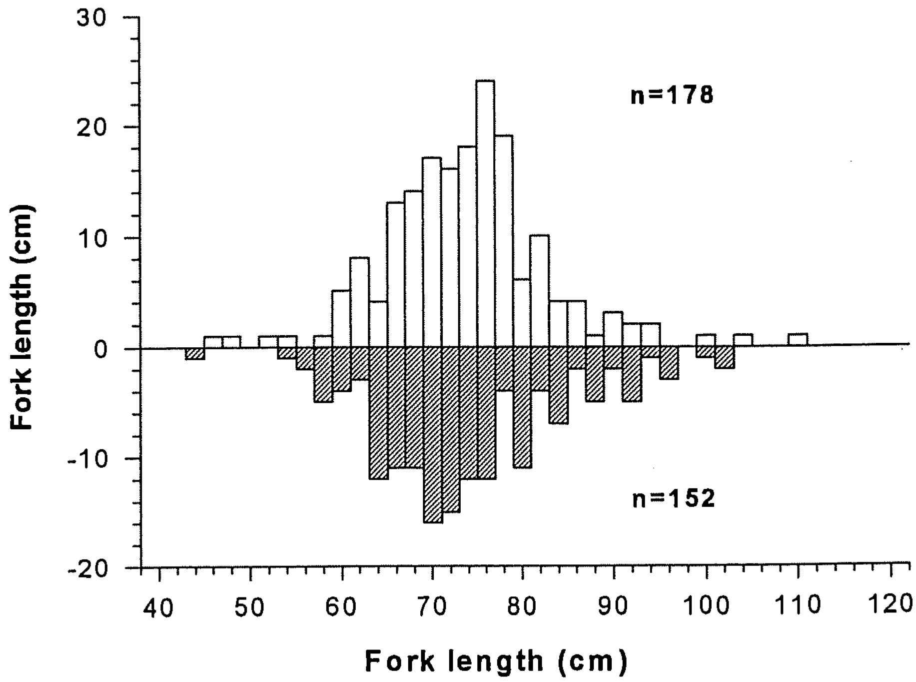
Figure 16: Numbers of tagged *Furgaleus macki* released by year and month in southern Western Australia.



5.2.1.3 *Carcharhinus plumbeus*

A total of 342 *Carcharhinus plumbeus* (153 females, 178 males and 10 of unknown sex) were tagged during the project. Sizes ranged from 44 to 110 cm FL with the majority between 58 and 84 cm FL (Figure 17). 74 individuals were double tagged, 147 injected with tetracycline and 10 double tagged and injected.

Figure 17: Size frequency distribution of male (open bars) and female (hatched bars) *Carcharhinus plumbeus* released in southern Western Australia.



Releases occurred between Geraldton and Bremmer Bay, with a relatively even spread throughout this region (Figure 18). Releases were patchy through the tagging period with significant numbers released in Autumn of 1996 (Figure 19) reflecting the fact that *C. plumbeus* is rarely targeted by commercial net fishers in the south-west of Western Australia or have a low abundance in the study area.

Figure 18: Numbers of tagged *Carcharhinus plumbeus* released by one degree statistical block in southern Western Australia.

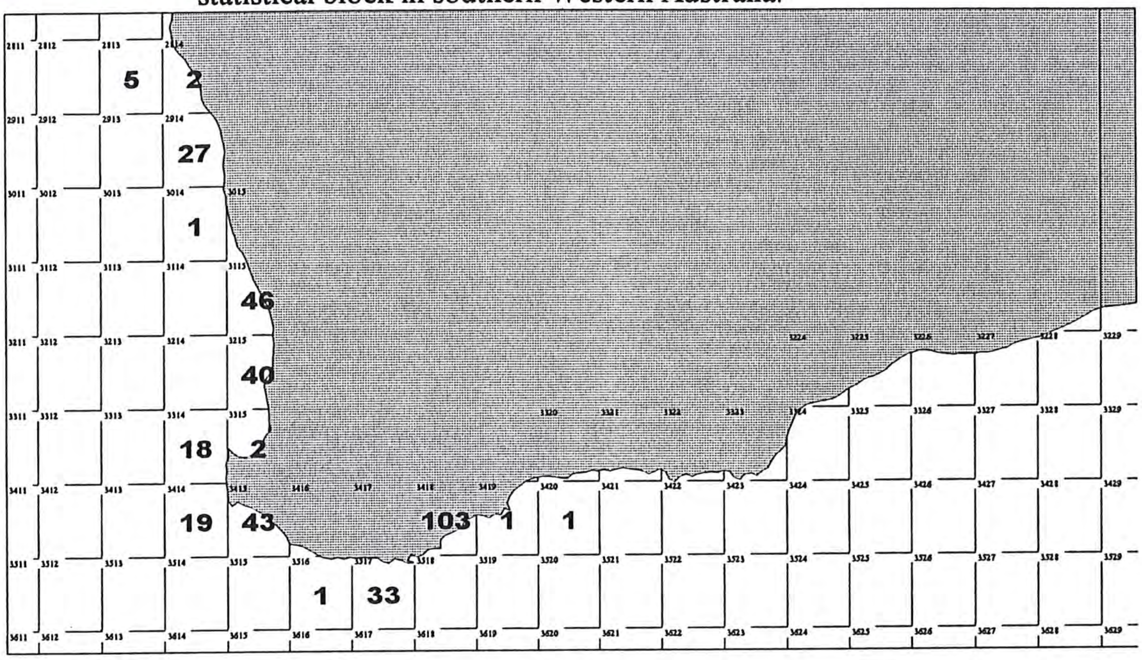
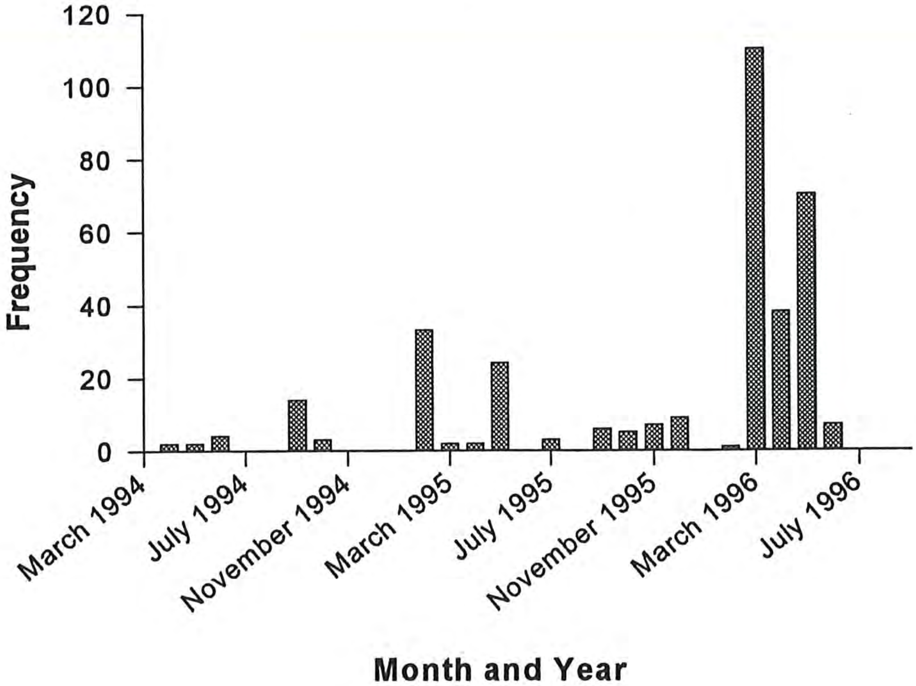


Figure 19: Numbers of tagged *Carcharhinus plumbeus* released by year and month in southern Western Australia.



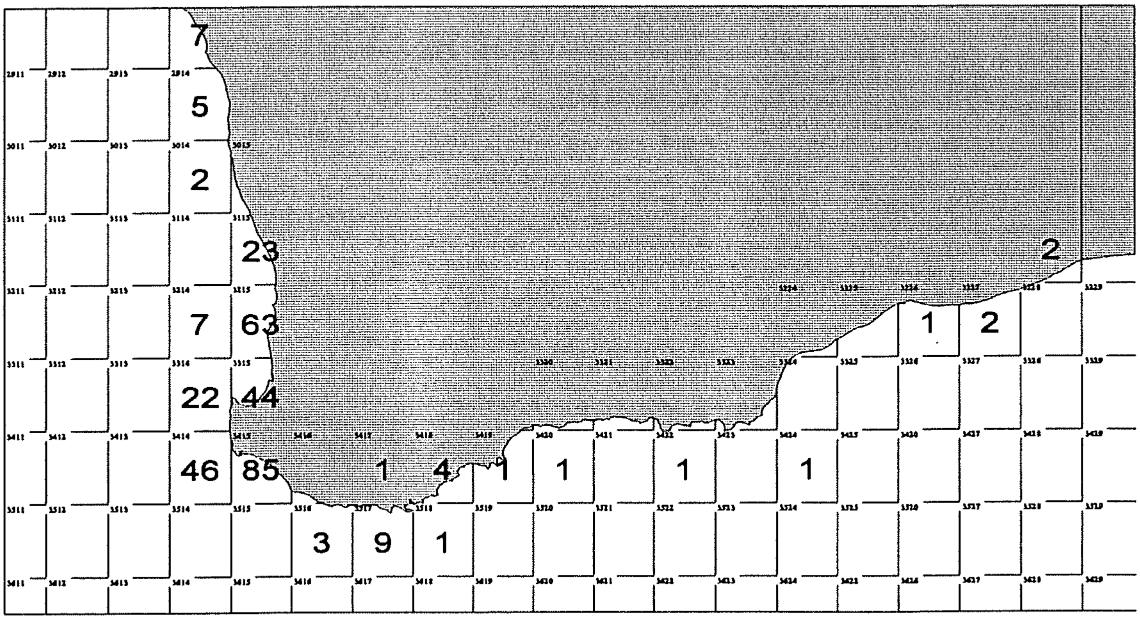
5.2.2 Recaptures

The analysis of the tag recapture data is based on the recaptures reported prior to July 1st 1996. It is expected that recaptures will continue to be made for many years to come and that the analysis presented here is only preliminary.

5.2.2.1 *Carcharhinus obscurus*

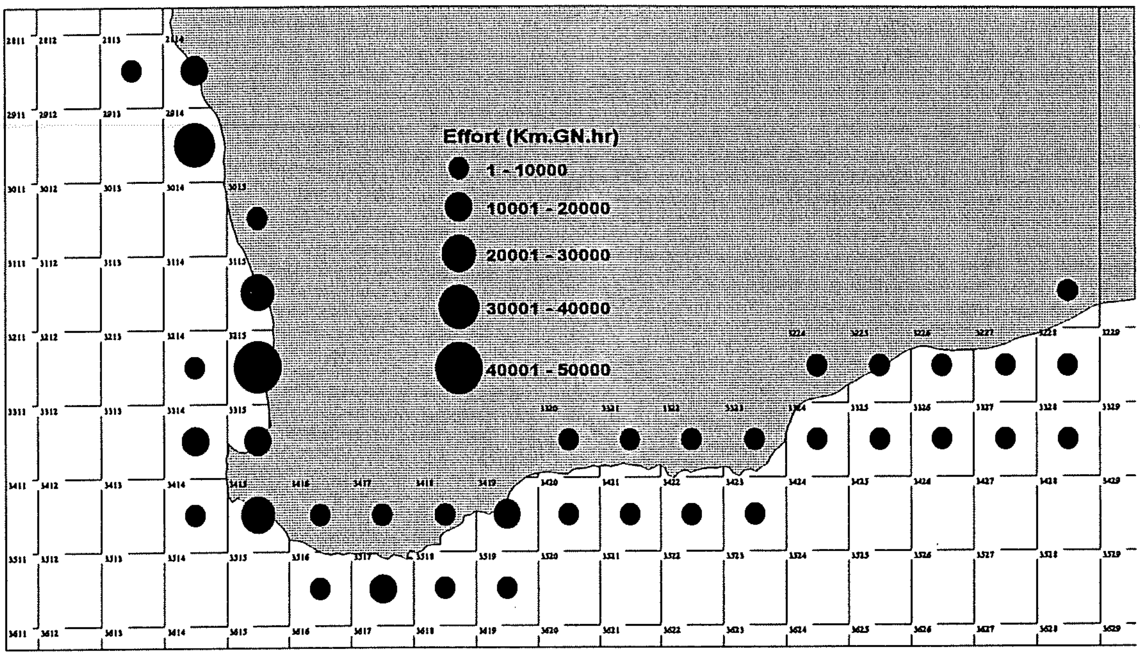
A total of 339 recaptures of *Carcharhinus obscurus* had been reported at July 1st 1996. Commercial gillnet fishers reported a total of 324 recaptures, other commercial fishers 5 and amateur fishers 10. The distribution of these recaptures by one degree statistical block is shown in Figure 20. To help interpret these data the distribution of fishing effort for 1994/95 is shown in Figure 21. The recaptures were concentrated in the main *C. obscurus* nursery area between Augusta and Perth where fishers target this species. The small number of recaptures on the south coast may reflect the fact that fishers do not target *C. obscurus*, instead targeting *M. antarcticus* and *Galeorhinus galeus*, or that their abundance is low in this area.

Figure 20: Numbers of tagged *Carcharhinus obscurus* recaptured by one degree statistical block in southern Western Australia.



A total of 324 individuals with release condition information had been recaptured at the time of writing of this report. There was no significant difference between the proportions of individuals of each release condition between release and recapture (Chi square test, df=2, p>0.05) indicating that the recapture rate of *C. obscurus* was independent of release condition.

Figure 21: Distribution of demersal gillnet effort (in kilometre gillnet hours) by one degree statistical blocks in southern Western Australia during 1994/95. Data from the Fisheries Department of Western Australia's Catch and Effort System.



5.2.2.2 *Furgaleus macki*

A total of 17 *Furgaleus macki* have been reported up to the end of June 1996. All recaptures have been made by commercial gillnet fishers. All tag recaptures were made within the area in which releases were made.

5.2.2.3 *Carcharhinus plumbeus*

A total of 14 *Carcharhinus plumbeus* had been recaptured to the end of June 1996. One recapture was made by a recreational fisher, the remainder being taken by commercial gillnet fishers. All recaptures have been confined to the area where tagged *C. plumbeus* were released.

5.2.3 Movement patterns

The analysis of movement pattern data is based on recaptures reported prior to July 1st 1996. Continued recaptures will add to the data and the present analysis should be viewed as preliminary.

5.2.3.1 *Carcharhinus obscurus*

Juvenile *Carcharhinus obscurus* showed considerable variations in their movement patterns. The majority were captured within 100km of the point of release, even after periods up to 800 days at liberty (Figure 22). However, a considerable proportion of the recaptures occurred at distances greater than 100km from the point of release (Figure 22), with the maximum distance being 1936km after 498 days at liberty. The movement tracks for each of the recaptures indicates that there is a large amount of movement within region from Perth to Augusta (Figure 23) where the majority of juvenile *C. obscurus* are born (and were tagged). However there is also a substantial number of movements from within this area to areas both to the east and the north. Several returns have been made by fishers in South Australia. The lack of tag returns from the region between 30°S and 31°S is most likely to be due to the relatively low level of fishing effort in this area (Figure 21). The small number of recaptures reported from the south coast of the State (Figure 23) may indicate that *C. obscurus* is less abundant in this region, but may also be a result of commercial shark fishers preferentially targeting *Mustelus antarcticus* and *Galeorhinus galeus*.

Figure 22: Period at liberty - distance moved plot for *Carcharhinus obscurus* released in southern Western Australia.

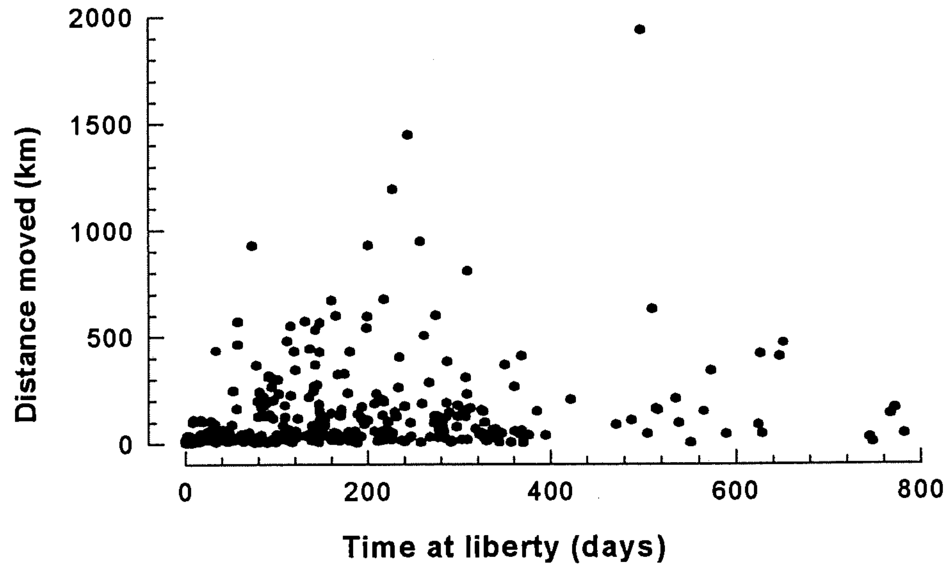
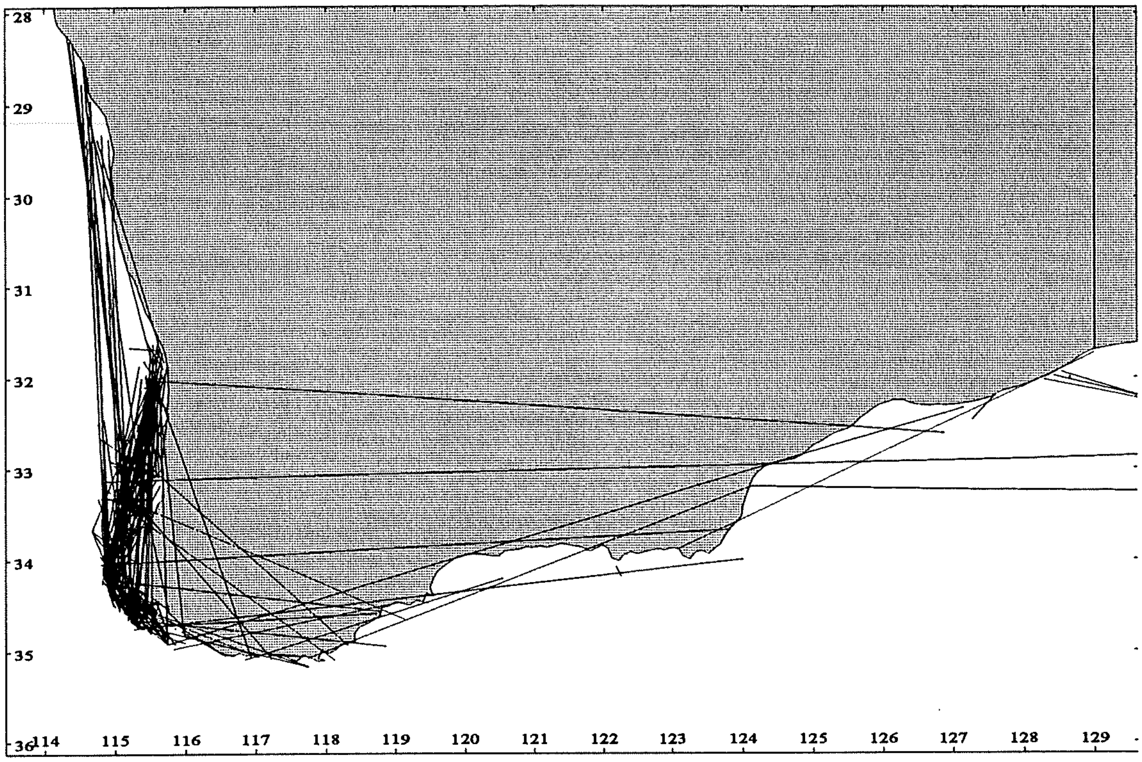
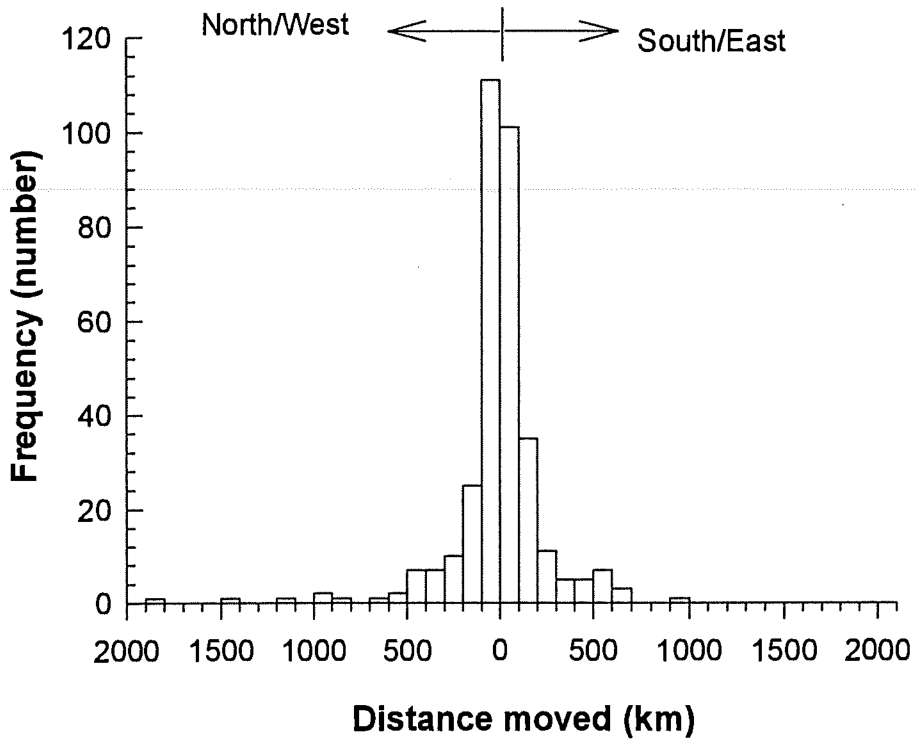


Figure 23: Point to point movements by tagged *Carcharhinus obscurus* in southern Western Australia. Although figure shows point to point distance, all estimates of distance moved are based on movement algorithm described in the methods section.



Juvenile *C. obscurus* after release move in both directions along the coast (north/west and south/east, depending upon the location). In the waters off South Africa juvenile male *C. obscurus* were observed to be more likely to move south, while females were more likely to move north (Bass *et al.* 1975). In the current study there was no significant difference in the numbers of males and females that were recaptured in either direction along the coast (Chi square homogeneity test, $p>0.05$). There also appeared to be very similar distributions of distances moved in either of these directions from the point of release (Figure 24). There were no significant differences in the mean distance moved between male and female *C. obscurus* (ANOVA, $F=2.43$, $p=0.1203$). There were also no significant differences in distance moved between the main tagging areas (ANOVA, $F=0.32$, $p=0.8903$) and condition on release (ANOVA, $F=0.54$, $p=0.5858$).

Figure 24: Distances and directions moved by tagged *Carcharhinus obscurus* in southern Western Australia.



5.2.3.2 *Furgaleus macki*

Most recaptures (13) of *Furgaleus macki* were made within 50km of the point of release, even after long periods at liberty (Figure 25, 26). Three individuals were recaptured greater than 100km from the point of release. The maximum distance between release and recapture was 384km over a period of 256 days at liberty. There are insufficient recaptures to date on which to make conclusions about the movement patterns of *F. macki*. However, it would appear that although this species normally moves relatively short distances it is capable of moving over longer distances.

Figure 25: Period at liberty - distance moved plot for *Furgaleus macki* released in southern Western Australia.

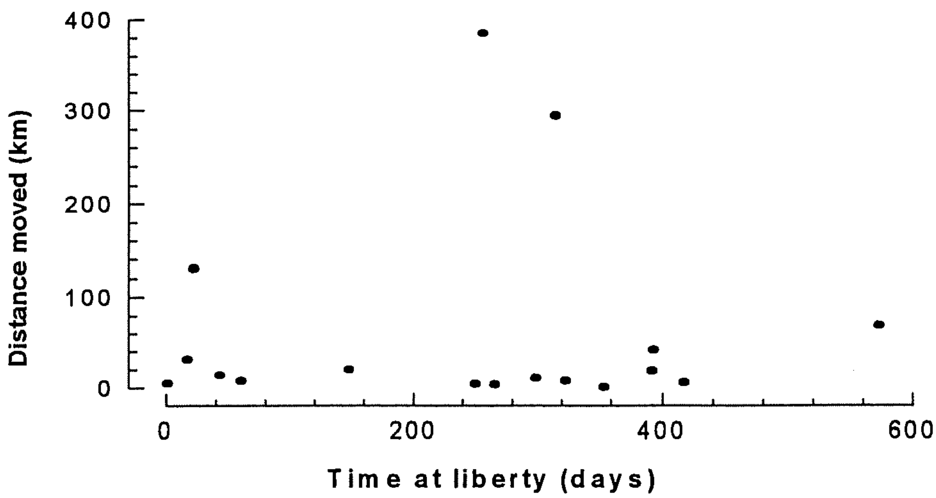
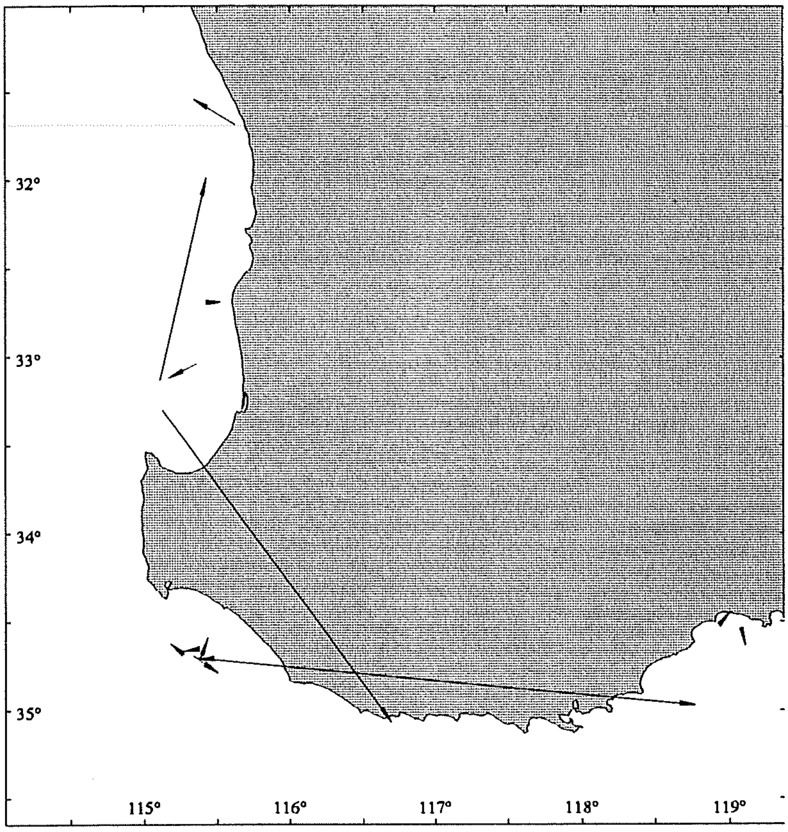


Figure 26: Point to point movements by tagged *Furgaleus macki* in southern Western Australia. Although figure shows point to point distance, all estimates of distance moved are based on movement algorithm described in the methods section.



5.2.3.3 *Carcharhinus plumbeus*

Carcharhinus plumbeus at liberty less than 400 days were recaptured within 100km of the point of release (Figure 27, 28). Individuals at liberty greater than 400 days had all moved distances greater than 100km, with the maximum distance being 643km over a period of 538 days. The data are too limited to provide a clear picture of movements within the south-west of Western Australia. However, it would appear that some juvenile *C. plumbeus* move long distances along the coast. Commercial fishers have reported that particularly along the western section of the south coast this species occurs in significant numbers only during Autumn, suggesting there may be a seasonal migration to this area.

Figure 27: Period at liberty - distance moved plot for *Carcharhinus plumbeus* released in southern Western Australia.

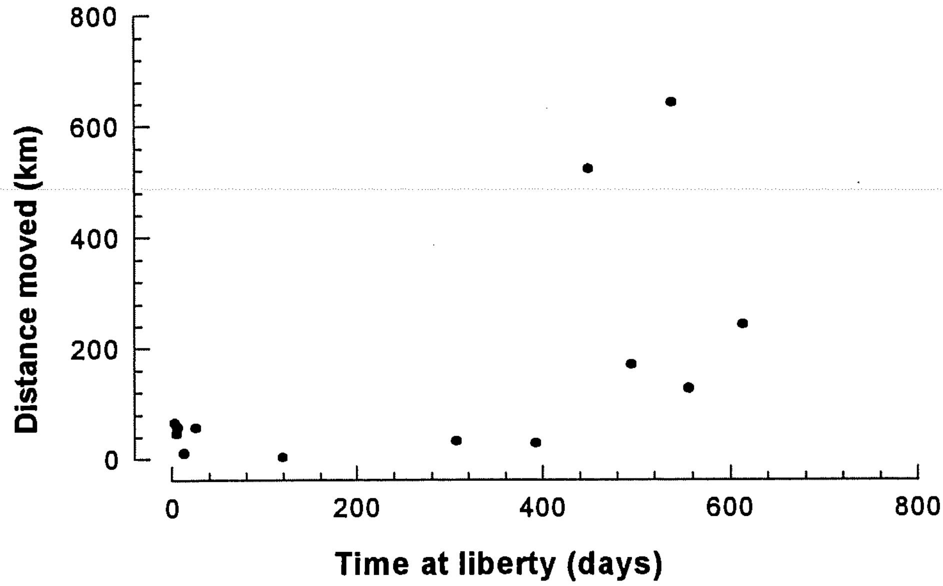
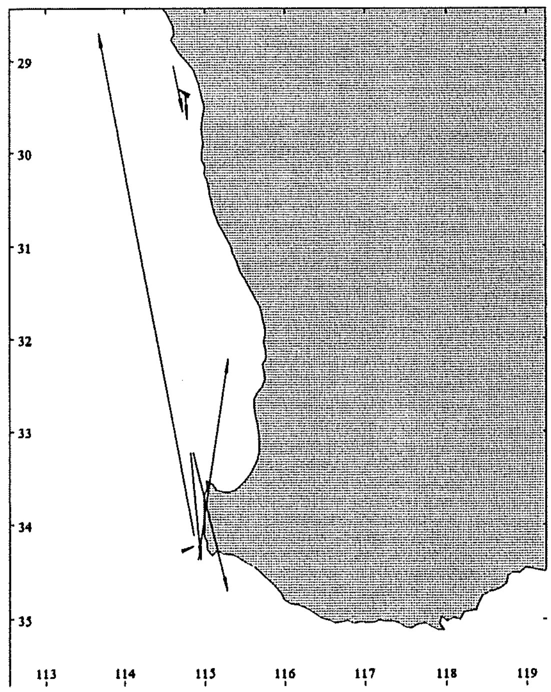


Figure 28: Point to point movements by tagged *Carcharhinus plumbeus* in southern Western Australia. Although figure shows point to point distance, all estimates of distance moved are based on movement algorithm described in the methods section.



5.2.4 Growth

Analysis of recapture data to provide information on growth was undertaken for *C. obscurus*. There were insufficient recaptures of other species to provide meaningful data.

5.2.4.1 Carcharhinus obscurus

Growth increment data were available from 188 *C. obscurus*. Three combinations of parameters for the Francis model were fitted to the data. Model A was a three parameter model that included growth rates (g_α and g_β, the growth rates at lengths α and β) and the growth variability (ν, standard deviation of a normal distribution representing growth variability), Model B was a five parameter model that included the parameters from Model A and the mean (*m)* and standard deviation (*s*)of the measurement error, and Model C was the full six parameter model including the parameters from Model B and the contamination probability (*p*) (Table 14).

Each of the models specified indicated that growth rates for juveniles up to 100cm FL were essentially linear. The models with greater numbers of parameters gave lower values of growth rates and lower growth variability. The difference in log(likelihood) value between model A and model B was small (Table 14), indicating that simply adding the measurement error parameters did not greatly improve the fit to the data. However, the difference in log(likelihood) between model B and model C was much larger (Table 14), indicating that adding the contamination probability and measurement error led to a significant improvement in the fit to the data.

The size range for which the data were gathered was small relative to the overall size range for the species, and the periods at liberty are short relative to the maximum age. As a result the conclusion of linear growth is not unexpected. The conclusion of linear growth in *C. obscurus* from southern Western Australia concurs with the observation of Pratt and Casey (1990) that growth of *C. obscurus* in the Western North Atlantic was best represented by a linear function.

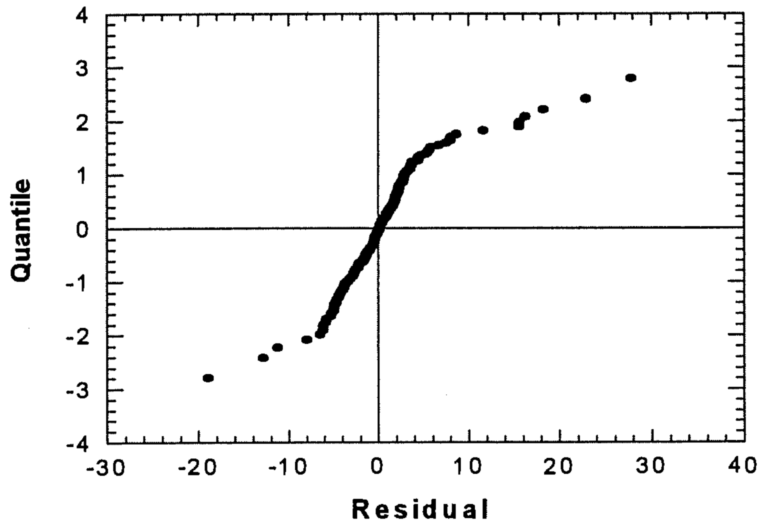
Table 14: Results of fitting the Francis growth model to tag recapture data from juvenile *Carcharhinus obscurus*. Values of α and β used in fitting the model were 75 and 100 cm FL (ie g_α is the growth rate at 75 cm FL).

	Model		
Parameter	**A**	**B**	**C**
g_α (cm FL/year)	11.380	10.001	9.423
g_β (cm FL/year)	11.369	9.991	9.414
ν	0.602	0.624	0.454
s (cm)	-	1.053	1.600
m (cm)	-	0.608	0.624
p	-	-	0.035
log(likelihood)	-470.22	-467.60	-454.34

A quantile plot of the residuals for the six parameter growth model (Figure 29) indicated that the assumption of normality could not be attained. This problem was caused by a small number of observations with large positive and negative values. These observations were the result of reported tag returns that had been at liberty very short periods and the reported recapture length indicated that the growth increment was very large, or the opposite situation where the period at liberty was large, but that the size increment was small.

To examine the effect of these few observations on the results of the model they were removed from the data and the model re-fitted. The model returned very similar parameter values to model C, except for the contamination probability which was zero. This results suggests that the model was accounting for these suspect points, when they were included, by treating them as contaminated.

Figure 29: Quantile plot for the six parameter Francis growth model fitted to data from *Carcharhinus obscurus* recaptures in southern Western Australia.



5.2.5 Tag-shedding

Tag shedding rates were only calculated for *Carcharhinus obscurus* as there were insufficient returns of double tagged individuals of other species.

5.2.5.1 *Carcharhinus obscurus*

Data from 79 recaptured *C. obscurus* that had been double tagged were used to estimate tag shedding rates. The estimate of the annual rate of tag shedding for the Jumbo Rototags was 0.0358 year^{-1} (standard error 0.0359), and for the metal headed dart tags 0.346 year^{-1} (standard error 0.1046). These tag shedding rates indicate that fin tag retention is much greater than for the metal headed dart tags.

5.2.6 Non-reporting of tag returns

Estimates of non-reporting rate were only available for the 1994/95 fishing year (Table 15) as finalised effort figures for 1995/96 were not available. All fishers operating in the west coast management area were classed as good reporters using the classification system and so non-reporting was assumed to be zero. The non-reporting proportion in the other two management areas varied considerably from month to month (Table 15).

Table 15: Non-reporting proportions calculated for each of the management zones of the southern Western Australian shark fishery.

Month	Non-reporting rate		
	south-west	south coast	west coast
July 1994	0.377	0.000	0.000
August 1994	0.288	0.063	0.000
September 1994	0.423	0.059	0.000
October 1994	0.319	0.042	0.000
November 1994	0.202	0.000	0.000
December 1994	0.000	0.000	0.000
January 1995	0.152	0.147	0.000
February 1995	0.000	0.056	0.000
March 1995	0.083	0.124	0.000
April 1995	0.187	0.048	0.000
May 1995	0.182	0.041	0.000
June 1995	0.823	0.172	0.000

5.2.7 Exploitation rate

Exploitation rates were only available for the 1994 cohort of juvenile *C. obscurus* during 1994/95 (Table 16) due to the requirements of waiting for tag returns to be made (over a year from the release of a cohort) and finalised fishing effort figures for the previous financial year to be available. However, preliminary estimates of the exploitation rate of the 1995 cohort during 1995/96 and the 1994 cohort during 1995/96, were made based on the non-reporting proportions from 1994/95 (Table 15).

Table 16: Exploitation rates (% per year)for cohorts of juvenile *Carcharhinus obscurus*. * indicates estimates adjusted for the previous years non-reporting proportion data.

Year	Cohort		
	1994	1995	1996
1994/95	23.8	-	-
1995/96	6.5*	18.2*	-

5.3 MESH SELECTION CHARACTERISTICS

A total of 3119 elasmobranchs and 939 teleosts were captured in the 102 sets of the experimental net. The most commonly caught sharks were *Heterodontus portusjacksoni* (936), *Carcharhinus obscurus* (916), *Furgaleus macki* (349), *Mustelus antarcticus*

(245), *Sphyrna zygaena* (126) and *Carcharhinus plumbeus* (100). The most commonly caught teleost species were *Kyphosus sydneyanus* (122), *Glaucosoma hebraicum* (109), and *Nemadactylus valenciennesi* (109). Sufficient data were available to calculate mesh selection parameters for *C. obscurus* and *F. macki*.

5.3.1 *Carcharhinus obscurus*

A total of 916 *Carcharhinus obscurus* were captured in the experimental net. The catch rates in terms of the number and weight for each of the mesh sizes are shown in Figure 30. There were significant differences in the catch rates between mesh sizes for number of individuals per unit effort (ANOVA, F=4.54, p=0.0002) and weight per unit effort (ANOVA, F=2.35, p=0.0298). The numbers of *C. obscurus* caught per unit of effort were lowest for the 8.5 inch net and highest for the 6 inch net, with all other mesh sizes producing similar catch rates (Figure 30). The larger size of individuals caught in the 8.5 inch net resulted in a more even distribution of weight per unit of effort, with highest catch rates in the 6 and 8 inch nets (Figure 30).

The data for calculation of mesh selection parameters by the method of Kirkwood and Walker (1986) are given in Table 17. These data include all individuals caught in the net, irrespective of whether they were meshed, rolled or tangled. The values of θ_1 and θ_2 estimated by the model were 127.65 and 27307.16, respectively. The selectivity plots for the mesh sizes used in the experimental net as calculated from the estimated parameters are shown in Figure 31a. The model was refitted to data that included only meshed individuals. This produced parameter estimates of θ_1 = 124.72 and θ_2 = 18595.17. The selectivity plots for these parameters are shown in Figure 31b. The removal of the non-meshed sharks resulted in little change to the value of θ_1, but resulted in a large drop in θ_2 (variance).

Table 17: Size frequency data by mesh size for *Carcharhinus obscurus* caught in the experimental net.

Length class (mm)		Mesh size (inches)						Total
mid point	range	5	6	6.5	7	8	8.5	
675	651-700	9	9	1	3	0	0	22
725	701-750	41	55	45	51	1	2	195
775	751-800	40	85	44	72	14	3	258
825	801-850	17	23	18	48	13	3	122
875	851-900	10	18	13	33	16	7	97
925	901-950	3	7	7	20	12	8	57
975	951-1000	5	3	2	9	9	4	32
1025	1001-1050	0	2	2	5	5	3	17
1075	1051-1100	0	0	0	3	4	11	18
1125	1101-1150	0	0	4	2	6	6	18
1175	1151-1200	0	2	1	3	4	5	15
1225	1201-1250	1	2	2	3	4	5	17
1275	1251-1300	0	1	0	2	7	1	11
1325	1301-1350	0	4	0	4	1	1	10
1375	1351-1400	0	1	0	0	3	3	7
1425	1401-1450	0	0	0	0	0	2	2
Total		126	212	139	258	99	64	898

Figure 30: Catch rates of *Carcharhinus obscurus* by mesh size in the experimental net (a) by numbers of individuals, and (b) by weight.

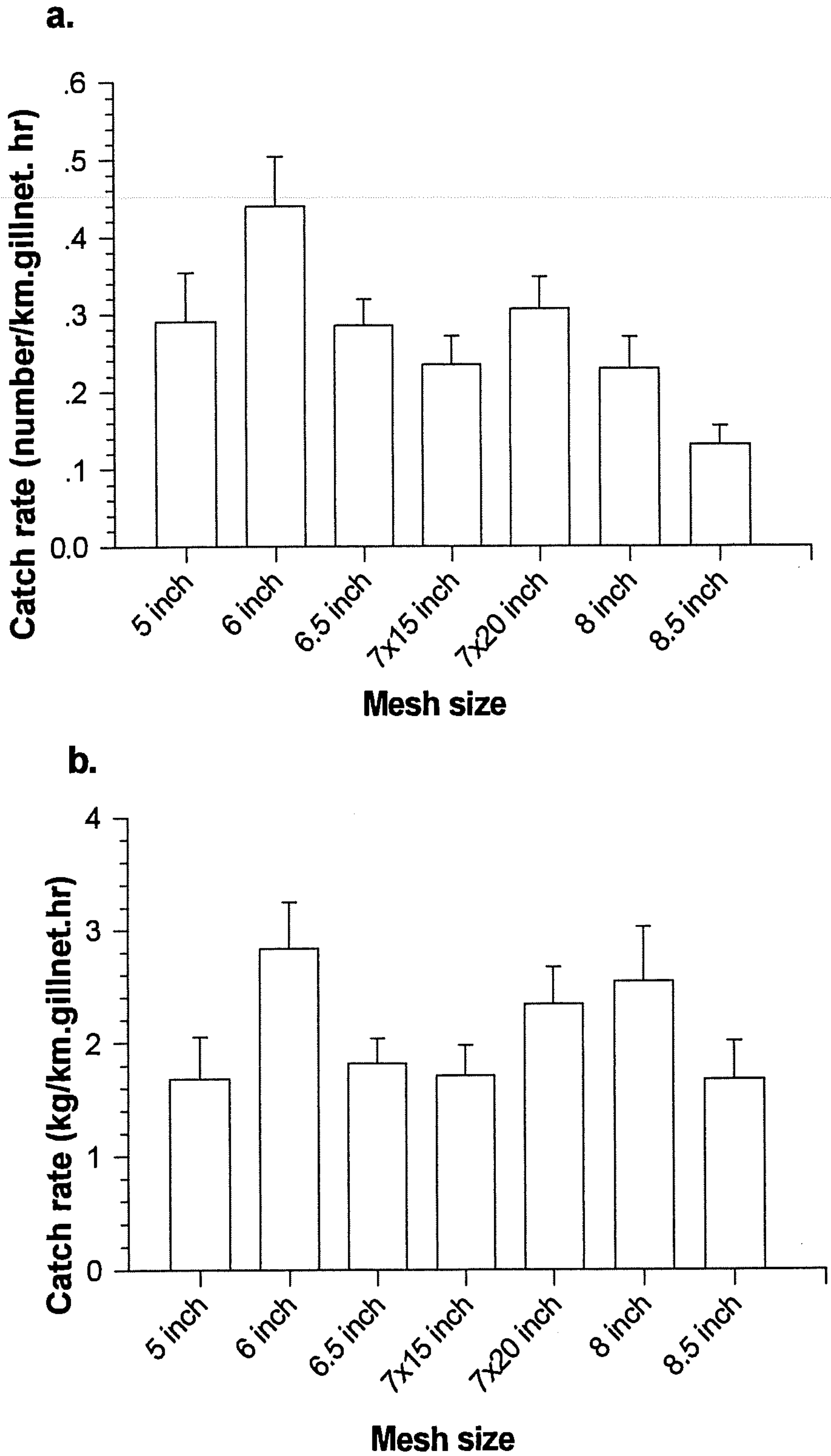
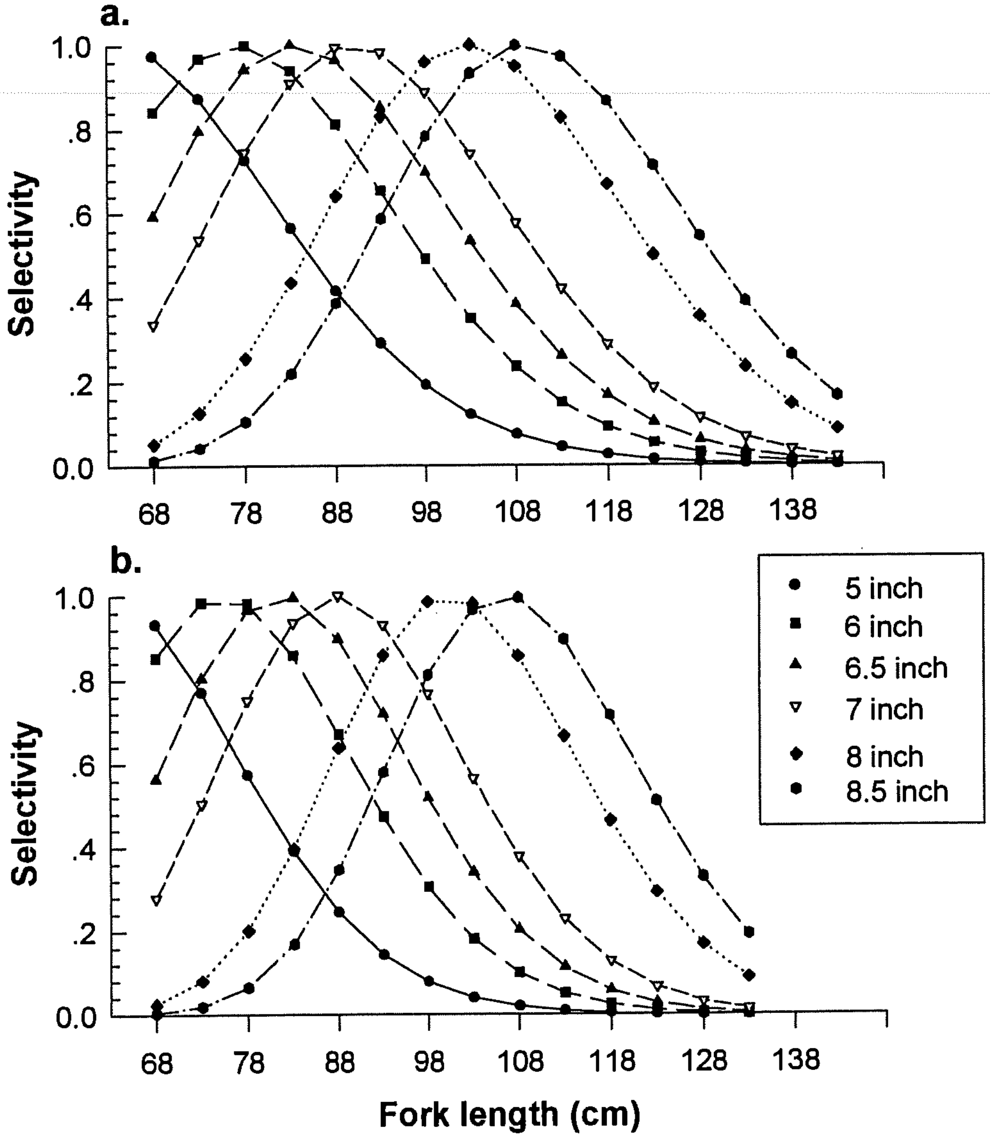


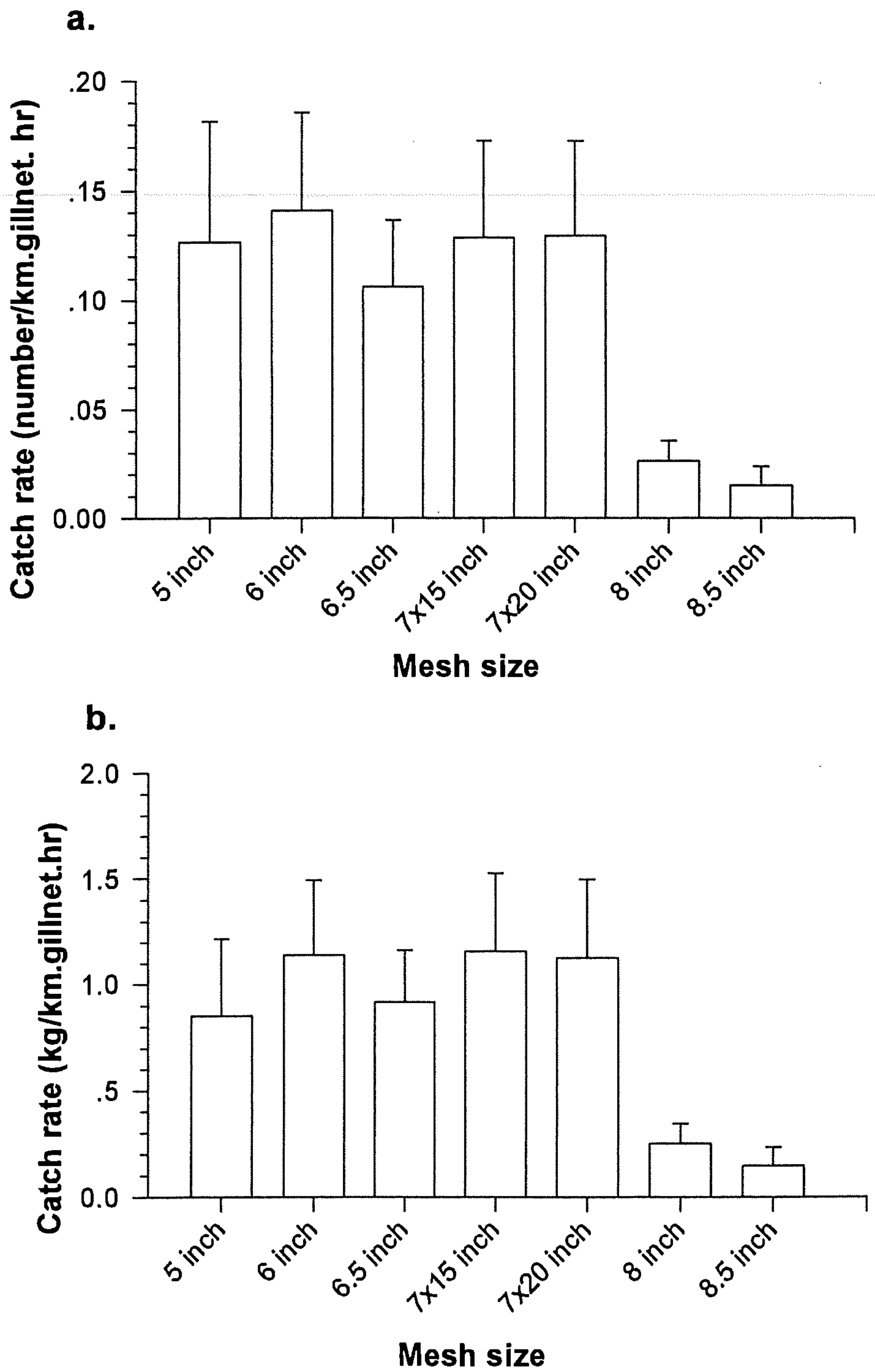
Figure 31: *Carcharhinus obscurus* gillnet selectivity curves for mesh sizes used in the experimental net: (a) all individuals caught, and (b) only individuals that were gilled.



5.3.2 *Furgaleus macki*

A total of 346 *Furgaleus macki* were caught in the experimental net. There were significant differences in catch rates between net for *F. macki*, both in terms of numbers (ANOVA, F=2.54, p=0.0191) and weight (ANOVA, F=2.93, p=0.0078). Catch rates of the two largest mesh sizes (8 and 8.5 inches) were low, while for the remainder they were relatively even (Figure 32).

Figure 32: Catch rates of *Furgaleus macki* by mesh size in the experimental net (a) by numbers of individuals, and (b) by weight.

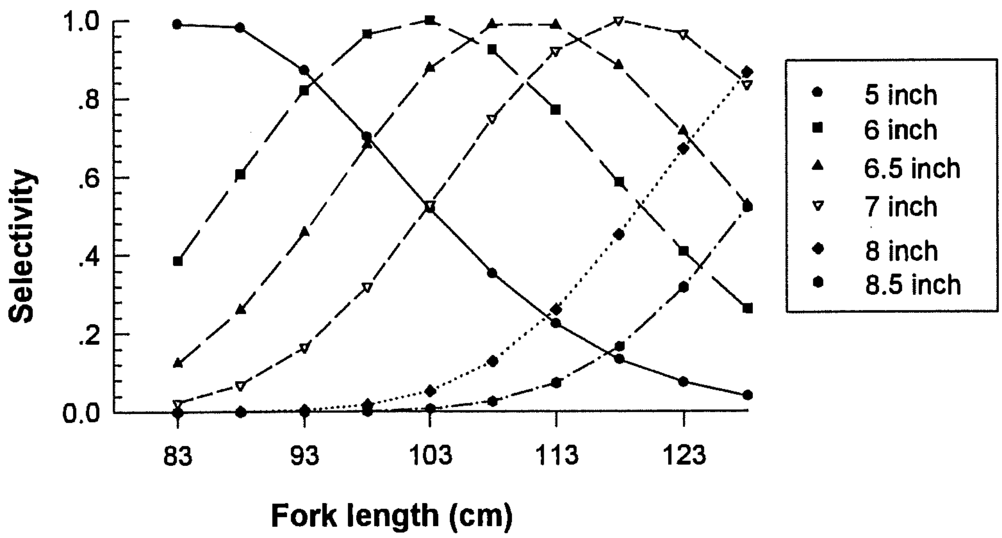


The data used for the fitting of the Kirkwood and Walker model are given in Table 18. The mesh selection parameters estimated by the model were of θ_1 = 169.13 and θ_2 = 22059.10. The selectivity curves based on these parameter estimates for the mesh sizes used in the experimental net are shown in Figure 33. The selectivity curves indicate that the peak selectivities of the 8 and 8.5 inch nets are above normal size observed for *F. macki* accounting for the low catch rates in these mesh sizes.

Table 18: Size frequency data by mesh size for *Furgaleus macki* caught in the experimental net.

Length class (mm) mid point	range	Mesh size (inches) 5	6	6.5	7	8	8.5	Total
825	801-850	4	0	0	0	0	0	4
875	851-900	2	1	0	0	0	0	3
925	901-950	10	2	2	2	0	0	16
975	951-1000	20	8	9	4	0	0	41
1025	1001-1050	14	12	4	20	0	0	50
1075	1051-1100	13	24	14	47	2	1	101
1125	1101-1150	3	15	16	37	4	0	75
1175	1151-1200	3	5	5	16	4	4	37
1225	1201-1250	0	1	1	7	3	0	12
1275	1251-1300	0	1	1	1	0	0	3
Total		69	69	52	134	13	5	342

Figure 33: *Furgaleus macki* gillnet selectivity curves for mesh sizes used in the experimental net.



5.4 BIOLOGICAL STUDIES

5.4.1 *Furgaleus macki*

A total of 1933 *Furgaleus macki* were measured and sexed on commercial shark fishing boats during this project. 61% of specimens examined were female.

The smallest male *F. macki* with elongate and calcified claspers was 96cm FL and the largest immature male was 119cm FL (Figure 34). The size at which 50% of males are mature is approximately 105cm FL. Female *F. macki* mature at approximately 114cm

FL (Figure 35). The smallest pregnant female recorded was 105cm FL and the largest immature female 125cm FL.

Figure 34: Relationship of clasper length (as a percentage of fork length) to fork length of male *Furgaleus macki* with uncalcified (squares) and calcified (triangles) claspers caught in southern Western Australia.

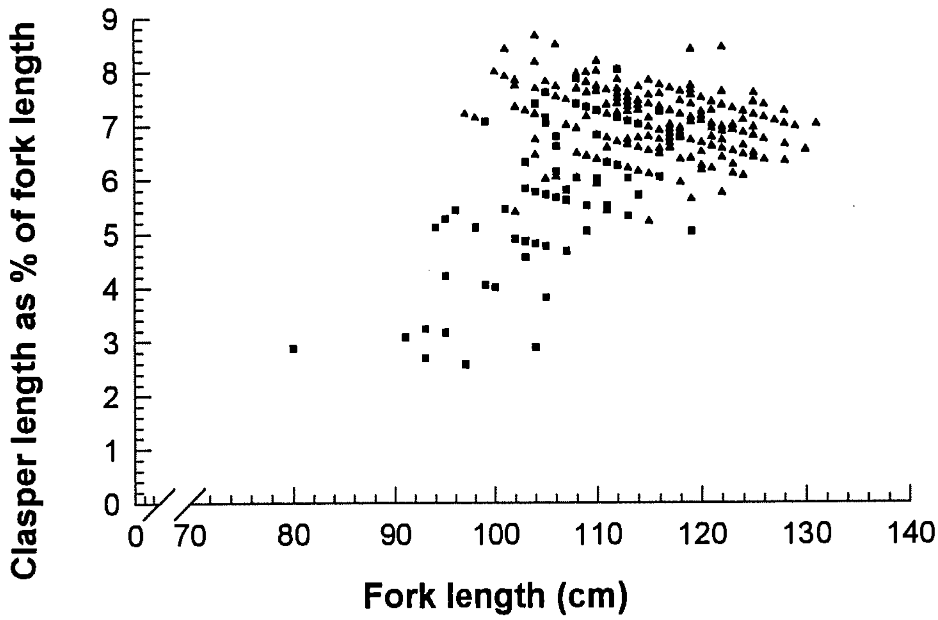
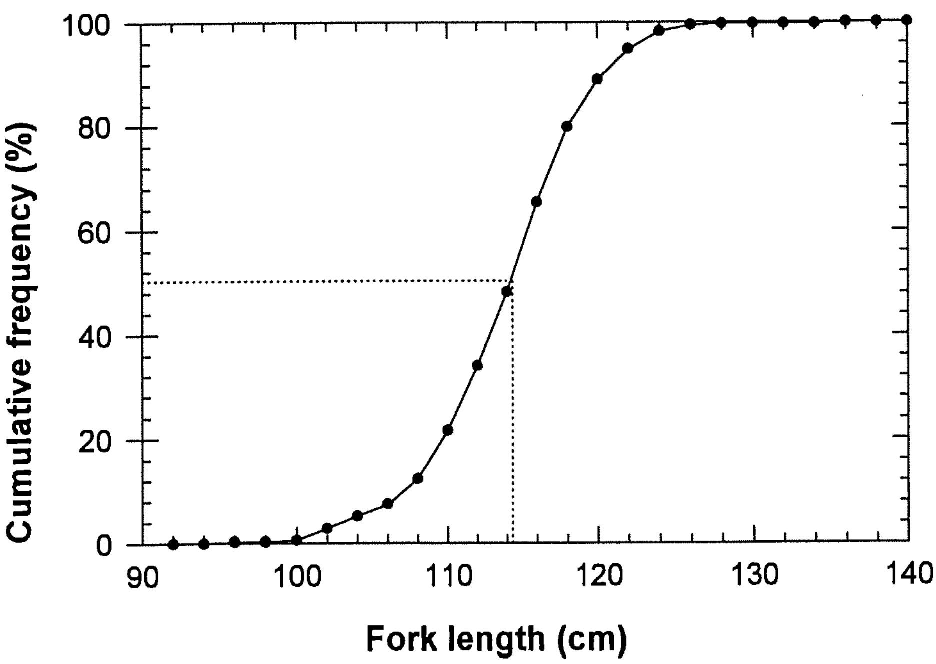
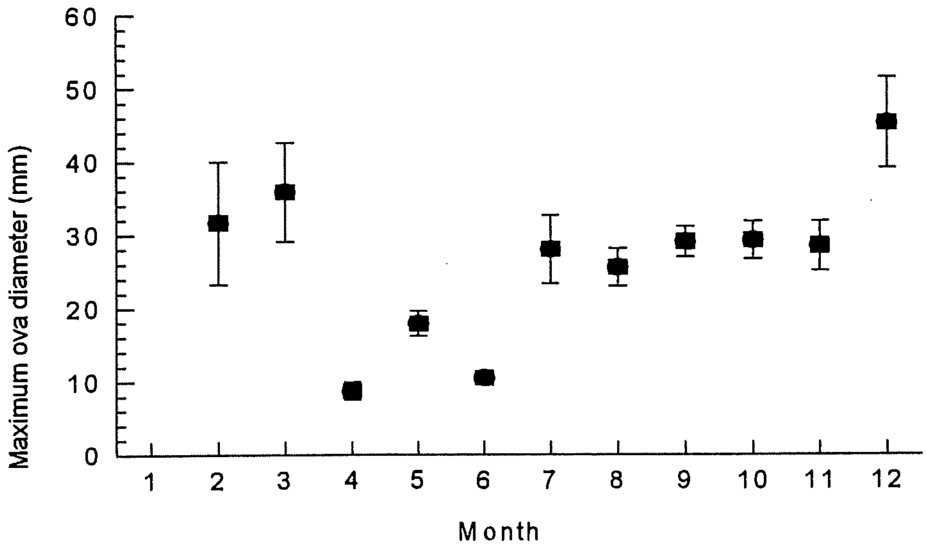


Figure 35: Percentages of female *Furgaleus macki* by maturity state in 2cm size classes. Dotted lines represent the size at 50% maturity.



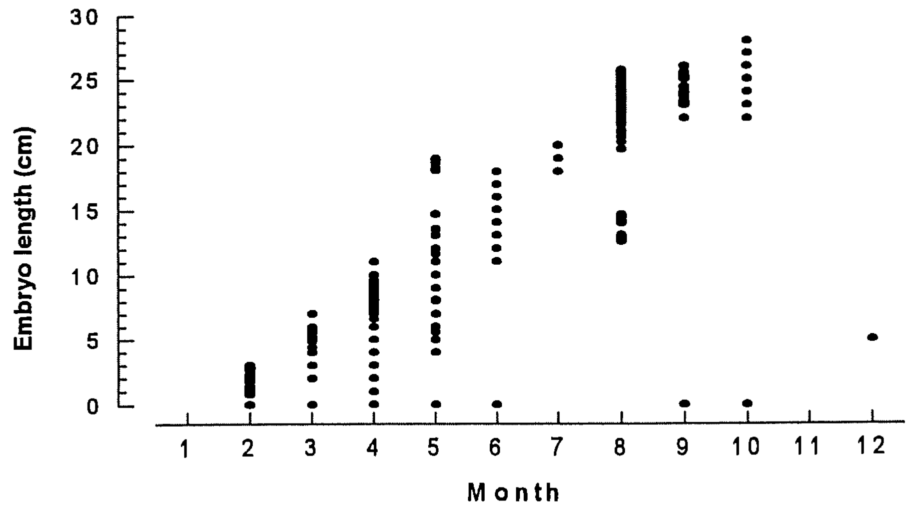
F. macki has a seasonal reproductive cycle. Mean monthly maximum ova diameter (MOD) was lowest in March and April and increased through the year to a maximum in the following February (Figure 36). Ovulation was observed to occur during January and February. Mature females did not breed each year, with two groups being easily identifiable: those pregnant without developing yolky ova, and those not pregnant and with developing yolky ova. The proportion of mature females in each of these groups suggests that females probably breed every second year. Litter sizes ranged from 4 to 28, with a mean of 19.

Figure 36: Mean monthly values of maximum ova diameter (MOD) for mature female *Furgaleus macki* from southern Western Australia.



The smallest *F. macki* embryos were 1.5cm TL from a specimen caught in February. Embryo size increased through the year until late winter and spring (Figure 37). Full term embryos ranged in size from 22 to 28cm TL. No free-swimming neonates were observed. On the basis of the embryo development the gestation period is approximately 7 to 9 months.

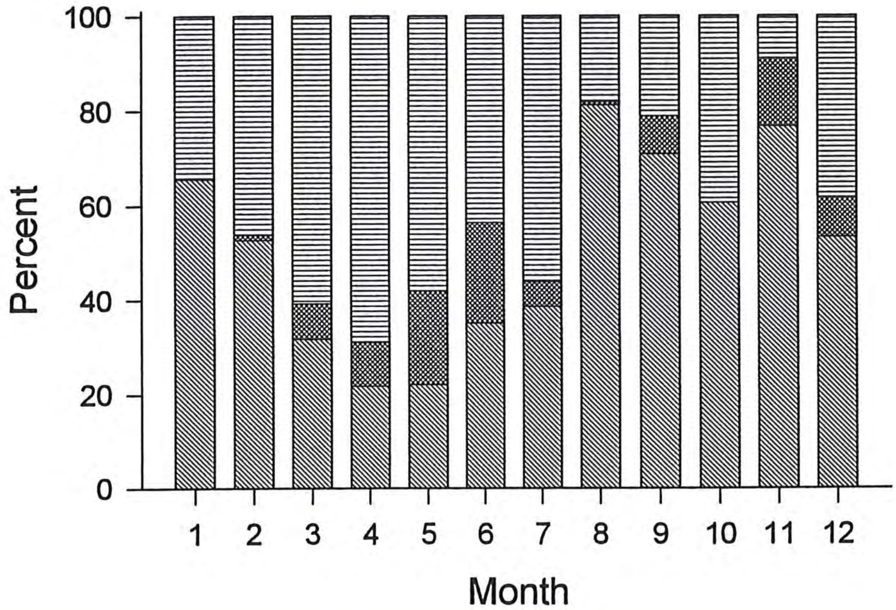
Figure 37: Distribution of embryo sizes by month for *Furgaleus macki* caught in southern Western Australia.



5.4.2 *Carcharhinus obscurus*

All of the *C. obscurus* specimens examined as part of the "At Sea" monitoring of the fishery were immature. As a result no reproductive information was available for this species. A large proportion of the specimens examined had umbilical scars, indicating that they had been recently born. The proportion of *C. obscurus* with umbilical scars (full or partial) was highest in autumn and winter, but were observed year round (Figure 38). This suggests that *C. obscurus* are born year round, but with the majority born in autumn. On the basis of specimens with fresh umbilical scars the size at birth of *C. obscurus* is 64 to 90cm FL.

Figure 38: Proportion of *Carcharhinus obscurus* specimens examined during the "At Sea" monitoring programme with open (horizontal lines), partially closed (cross hatched) and without (single hatch), umbilical scars.

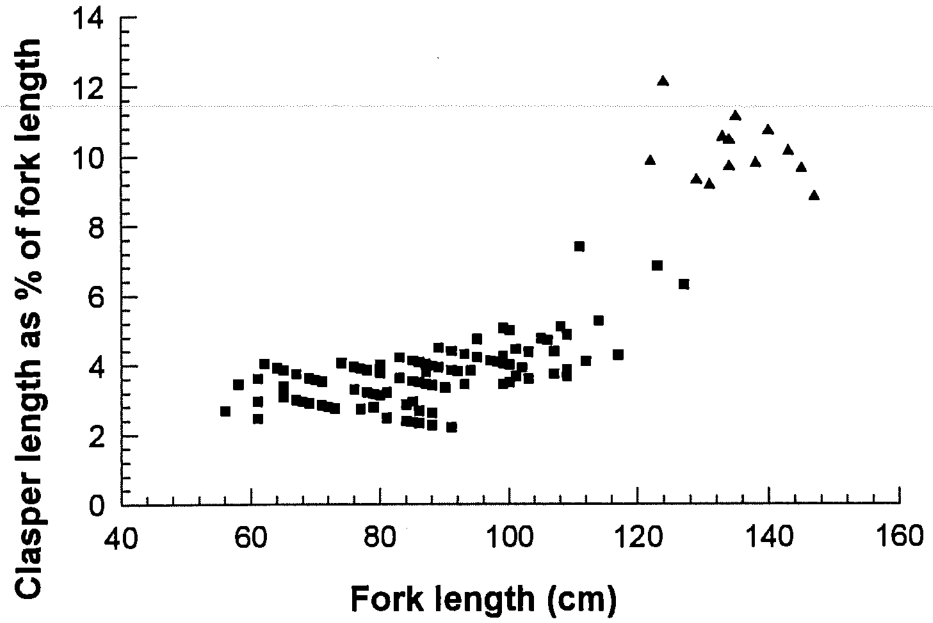


5.4.3 *Carcharhinus plumbeus*

The majority of *C. plumbeus* specimens caught in the commercial fishery were juveniles less than 110cm FL. However, some adults were caught to enable an understanding of reproductive biology.

The size at maturity for males is approximately 124cm FL. The smallest male with elongate and calcified claspers was 121cm FL and the largest with immature claspers was 127cm FL (Figure 39). The smallest mature female was 135cm FL, and the largest immature specimen was 125cm FL. Few female sharks were caught in this size range and it is difficult to determine the size at maturity with a great deal of accuracy. However, it would appear that the maturity of females occurs at approximately 130cm FL.

Figure 39: Relationship of clasper length (as a percentage of fork length) to fork length of male *Carcharhinus plumbeus* with uncalcified (squares) and calcified (triangles) claspers caught in southern Western Australia.



Insufficient mature females were collected to determine the timing of the reproductive cycle (mating and parturition periods). Litter sizes ranged from 6 to 10, with a mean of 7.9 (n=12).

5.5 POPULATION MODELLING

The other sections of this research project provided most of the data used in the model. The improved catch and effort, mesh selectivity and biological studies all provided important data for the models. Where data was not available from the research project values were obtained from the literature for the same, or similar species. The results of the age-structured models are outlined below for each of the main commercial species.

In the original grant proposal it was suggested that a model be developed for *Carcharhinus plumbeus*. This was suggested as it was anticipated at the time that this species would continue to increase in importance in the catch. However, catches of this species have stabilised at levels much lower than anticipated. As a result a model was not developed. However, as both *C. obscurus* and *C. plumbeus* have similar biological characteristics the *C. obscurus* model could be easily adapted for use as the *C. plumbeus* model.

5.5.1 Furgaleus macki

Parameter specifications for the whiskery shark model are given in Table 19. The results of the model indicate that the current level of biomass is 22-23% of the 1975 level (Figure 40). This level of biomass is currently below the target reference point set for the stock. The evaluation of future harvest strategies indicates that an annual catch of 170-220 tonnes (best estimate 205 tonnes) between the present and 2010/11 would result in the stock reaching the target reference point of 40% of the 1975 level by 2010 (Figure 41). The 1994/95 catch of *F. macki* was 261 tonnes (Table 6). This indicates that a reduction in catch over current levels is needed to achieve the level of biomass required in 2010.

Table 19: Parameter values used in the *Furgaleus macki* age-structured population model.

Parameter	Value	Source
M, natural mortality	0.2	Estimate for gummy, similar biology
P_a', number of pups per litter	19	Current study
P_a'', proportion females pregnant	0.5	Current study
P_a''', sex ratio	0.5	Current study
m, age at maturity	5	Estimate from similar species
x, maximum age	20	Estimate from similar species
lwa, length-weight parameter	0.0000163	Previous study, WA Fisheries
lwb, length-weight parameter	2.733	Previous study, WA Fisheries
l_∞, von Bertalanffy parameter	1500mm	Preliminary data
K, von Bertalanffy parameter	0.4	Preliminary data
t_0, von Bertalanffy parameter	-0.2	Preliminary data
θ_1, mesh selection parameter	169.13	Current study
θ_2, mesh selection parameter	22059.1	Current study

Figure 40: Biomass of the *Furgaleus macki* stock in southern Western Australia relative to the 1975 level. Solid line, best estimate; dashed line, lower 95% confidence interval; dotted line, upper 95% confidence interval.

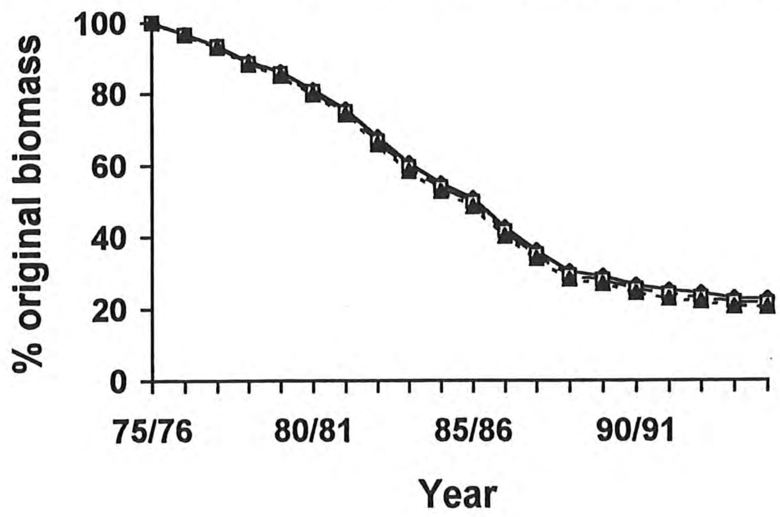
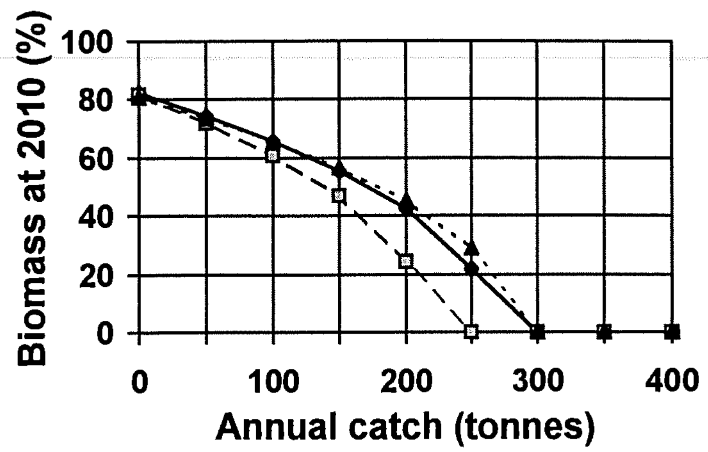


Figure 41: Evaluation of the effect of future catch levels on the level of biomass of *Furgaleus macki* at the year 2010/11. Annual catches are assumed to be constant from the present to 2010/11. Solid line, best estimate; dashed line, lower 95% confidence interval; dotted line, upper 95% confidence interval.



5.5.2 Mustelus antarcticus

Parameter specifications for the *Mustelus antarcticus* model are given in Table 20. The results of the model indicate that the current level of biomass is 25-95% (best estimate 45%) of the 1975 level (Figure 43). The present best estimate of biomass level is currently just above the target reference point set for the stock. The high level of uncertainty about the outcomes of the model reflect a lack of information in the catch and effort data series for this species. However, it is reasonable to assume that the optimistic scenario is biologically impossible and should be regarded as a mathematical possibility only. Given the uncertainty of the model outcomes the evaluation of future harvest strategies is difficult. However, on the basis of the best estimate scenario future catch levels around 230 tonnes between the present and 2010/11 should maintain the stock at around the target reference point (Figure 43).

Figure 42: Biomass of the *Mustelus antarcticus* stock in southern Western Australia relative to the 1975 level. Solid line, best estimate; dashed line, lower 95% confidence interval; dotted line, upper 95% confidence interval.

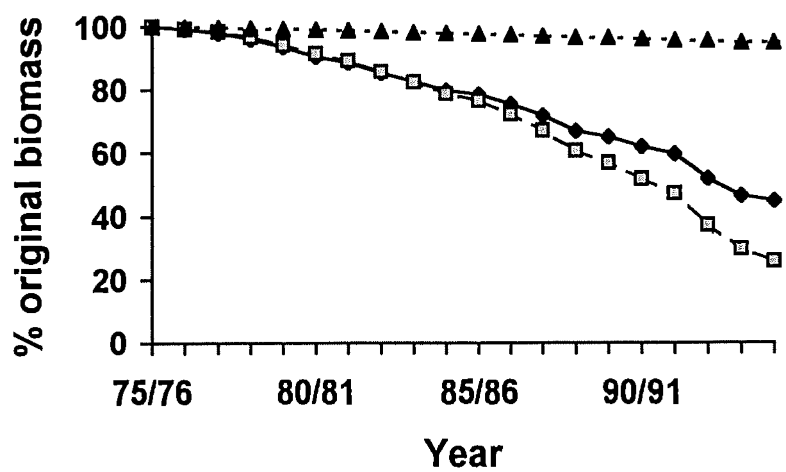
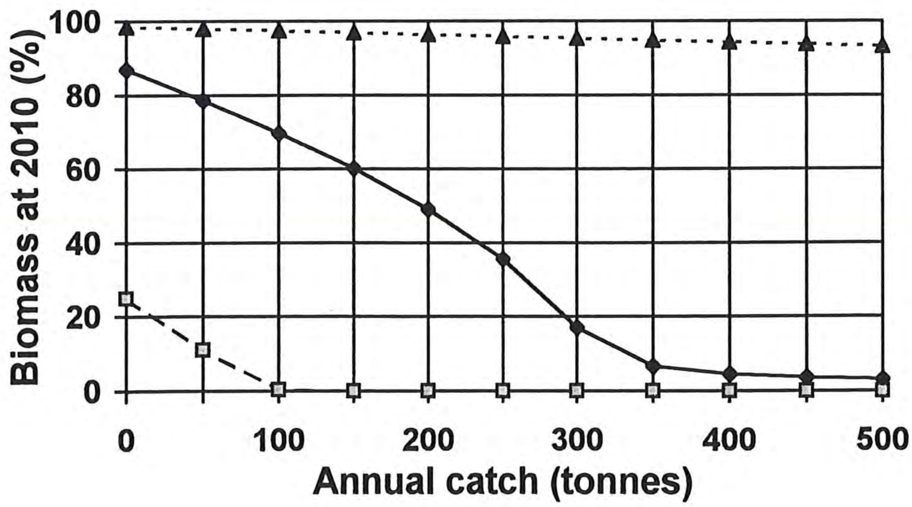


Table 20: Parameter values used in the *Mustelus antarcticus* age-structured population model.

Parameter	Value	Source
M, natural mortality	0.186	Estimate for gummy, similar biology
$P_a^{'}$, number of pups per litter	$e^{-4.134+0.0492.l_m}$ (to max. of 45)	Lenanton *et al.* 1990
$P_a^{''}$, proportion females pregnant	1	Lenanton *et al.* 1990
$P_a^{'''}$, sex ratio	0.5	Lenanton *et al.* 1990
m, age at maturity	5	Moulton *et al.* 1992
x, maximum age	20	Moulton *et al.* 1992
lwa, length-weight parameter	$1.22\text{x}10^{-9}$	Previous study, WA Fisheries
lwb, length-weight parameter	3.16	Previous study, WA Fisheries
l_∞, von Bertalanffy parameter	2019mm	Moulton *et al.* 1992
K, von Bertalanffy parameter	0.086	Moulton *et al.* 1992
t_0, von Bertalanffy parameter	-3.01	Moulton *et al.* 1992
θ_1, mesh selection parameter	184.3	Kirkwood and Walker 1986
θ_2, mesh selection parameter	29739	Kirkwood and Walker 1986

Figure 43: Evaluation of the effect of future catch levels on the level of biomass of *Mustelus antarcticus* at the year 2010/11. Annual catches are assumed to be constant from the present to 2010/11. Solid line, best estimate; dashed line, lower 95% confidence interval; dotted line, upper 95% confidence interval.



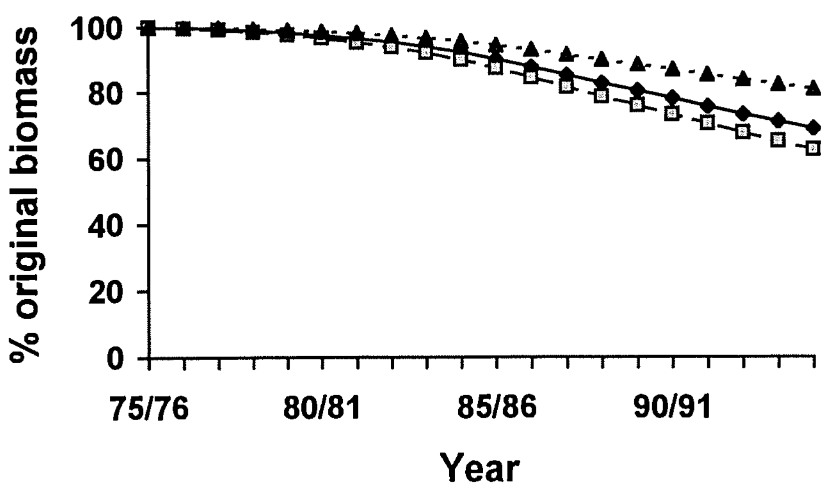
5.5.3 *Carcharhinus obscurus*

Parameter specifications for the whiskery shark model are given in Table 21. The results of the model indicate that the current level of biomass is 61-81% (best estimate 68%) of the 1975 level (Figure 44). This level of biomass is currently above the target reference point set for the stock. However, due to the long lag times in the dynamics of the stock that result from the high age at maturity and long time from exploitation to maturity this level of biomass will continue to decrease for many years into the future. The long time lags also mean that the model is not yet capable of building in any response of the stock to exploitation (eg increased growth, increased fecundity, decreased natural mortality of young). Such stock responses will only be able to be included when the catch and effort data series is considerably longer than the period from exploitation to maturity. It is anticipated that given the life history traits of *C. obscurus* that the catch and effort data set will begin to include this information within five to ten years. As such, the results of the model must be viewed with caution, particularly when it comes to the evaluation of future harvest strategies. As a consequence no results of harvest strategy evaluation are presented.

Table 21: Parameter values used in the *Carcharhinus obscurus* age-structured population model.

Parameter	Value	Source
M, natural mortality	0.1	Estimate from Hoenig 1982
P_a', number of pups per litter	12	Current study
P_a'', proportion females pregnant	0.5	Assumed
P_a''', sex ratio	0.5	Current study
m, age at maturity	17	Natansson *et al.* 199?
x, maximum age	45	Natansson *et al.* 199?
lwa, length-weight parameter	0.0000123	Previous study, WA Fisheries
lwb, length-weight parameter	2.855	Previous study, WA Fisheries
l_∞, von Bertalanffy parameter	3520mm	Natansson *et al.* 199?
K, von Bertalanffy parameter	0.04	Natansson *et al.* 199?
t_0, von Bertalanffy parameter	-6.43	Natansson *et al.* 199?
θ_1, mesh selection parameter	127.3	Current study
θ_2, mesh selection parameter	28017	Current study

Figure 44: Biomass of *Carcharhinus obscurus* stock in southern Western Australia relative to the 1975 level. Solid line, best estimate; dashed line, lower 95% confidence interval; dotted line, upper 95% confidence interval.



6 CONCLUSIONS

The improved stock assessments provided by the age-structured models developed as part of this project indicate that the catch levels of at least two (*F. macki* and *M. antarcticus*) of the three main commercial shark species need to be reduced to meet the current biomass targets set for the fishery. The model for *C. obscurus* requires a long series of catch and effort data before it can provide useful information. Since the fishery is currently managed by input controls, meaning that reductions in catches will need to be achieved by reductions in the amount of effort allowed in the fishery.

There is scope for further improvements in the stock assessments of the key commercial shark species in the southern Western Australian shark fishery. For example, there remain significant gaps in our knowledge of the biology of large *C. obscurus* and small *F. macki*, as these life-history stages are not normally caught by commercial fishers. There is also a need for a greater understanding of the relationship between the breeding stock of *C. obscurus* and the number of pups recruited to the fishery. The continued development of modelling techniques (eg incorporation of exploitation rate data, risk assessment, inclusion of new biological data) will provide improved stock assessment advice. Many of these identified data requirements and model development will be undertaken by a project recently funded by FRDC - Project 96/130 Biology and stock assessment of Western Australia's commercially important shark species.

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 the State.

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 the project:

Dr Colin Simpfendorfer
Mr Philip Unsworth
Mr Anthony Paust
Mr Justin Chidlow
Mr Adrian Kitchingman

Mr Justin Bellinger

11 FINAL COSTS

The total cost of the project could not be calculated as figures for the contribution by applicant were not available at the time of writing. The total FRDC funds expended were $365,583.47.

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