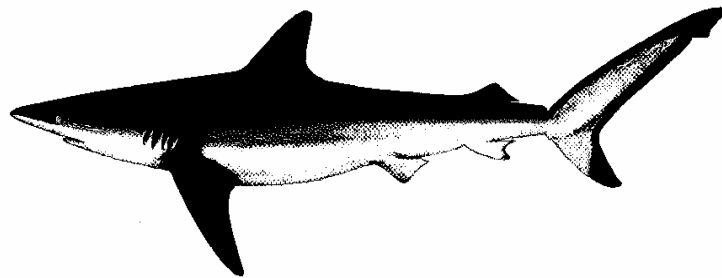


STOCK ASSESSMENT OF THE SANDBAR SHARK, *CARCHARHINUS PLUMBEUS*, IN WESTERN AUSTRALIA

**Shark Section Research Advice
Number 16**



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Date: 29 April 2005**

Information supplied herein is the best possible given the available data and resources



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Executive summary

This report documents the methodology and results of the stock assessment of the sandbar shark, *Carcharhinus plumbeus*, in Western Australian waters. This assessment was undertaken using a technique known as demographic analysis, which is widely used in assessing the status of long-lived shark species such as *C. plumbeus*. The demographic model estimates the potential capacity (or rate) for a stock to increase or decrease, using biological information and fishing mortality rates calculated from capture rates of tagged sharks. All biological and tagging data were derived from the recently completed FRDC-funded project (no 2000/134).

Results of the demographic analysis indicated that under zero fishing mortality the *C. plumbeus* stock had the capacity to grow at 2.5% yr⁻¹. This rate is at the lower end of the rates estimated for this species elsewhere. Furthermore, this result for *C. plumbeus* is lower than the estimated capacity for population growth (4.2% yr⁻¹ under zero fishing mortality) of the closely related and co-occurring dusky shark (*Carcharhinus obscurus*). The contrast with *C. obscurus* and a potential capacity for population growth that is lower than, or at best comparable to, *C. plumbeus* elsewhere indicate that the Western Australian stock must be managed carefully. This need for caution is further supported by the fact that *C. plumbeus* stock in Western Australia is currently exploited across almost all age-classes, a practice which is now widely recognized as being an unsuitable exploitation strategy for long-lived sharks.

Under the estimated rates of fishing mortality, the WA sandbar shark stock had negative capacity for population growth during 2001/02, 2002/03 and 2003/04. The rate of decline was greatest in 2003/04 when catches in both of the target fisheries, i.e. the WA North Coast Shark Fishery (WANCSF) and the Temperate Demersal Gillnet and Demersal Longline Fishery (TDGDLF¹), increased sharply. Given the empirically measured biological parameter ranges, the stock's capacity for growth was estimated from the model to be -4.9% yr⁻¹. Based on the catch recorded from the target fisheries during the second half of 2004, it is probable that annual fishing mortality has increased substantially since the conclusion of the tagging project. A projected intrinsic population growth rate of -7.9% yr⁻¹ was therefore estimated for the current fishing season (2004/05).

Given the negative capacity for growth and the increasing catches of this key target species in both the West Coast Demersal Gillnet and Demersal Longline Fishery (WCDGDLF) and the WANCSF, the stock is currently being depleted. There is an urgent need for a reduction in *C. plumbeus* fishing mortality if the present decline is to be arrested.

To examine potential fishery management strategies, 65 hypothetical scenarios of fishing mortality in the various fishing sectors that catch *C. plumbeus* were tested in the model. Potential fishing mortality combinations that would deliver neutral or positive population growth rates were identified and are provided in the body of the report. As both of the target fisheries contribute to the exploitation of the stock, appropriate levels of exploitation in the WANCSF could not be determined independently of exploitation by the TDGDLF (mainly in the WCDGDLF) and *vice versa*. The demographic model indicated that to achieve the capacity for positive growth in the population, and thus

¹ The TDGDLF refers to the combined West Coast Demersal Gillnet and Demersal Longline Fishery (WCDGDLF, Region 2 on Fig. 1) and the Joint Authority Southern Demersal Gillnet and Demersal Longline Fishery (JASDGLF, Region 1 on Fig. 1).

reverse the current declining trend in this stock, major reductions in fishing mortality are necessary in both the WANCSF and in the TDGDLF, unless the fishing mortality in one or other fishery is reduced to zero.

1. Introduction

In response to rapidly escalating catches of the sandbar shark, *Carcharhinus plumbeus*, in the Temperate Demersal Gillnet and Demersal Longline fishery (TDGDLF) and the WA North Coast Shark Fishery (WANCSF) during the late 1990s, the WA Department of Fisheries began a four-year research project in July 2000, to study the biology of this stock and to conduct an assessment of its status. Reported sandbar catches by these fisheries continued to grow throughout the project. In 2003/04 the total reported catch of *C. plumbeus* was 412 tonnes (live weight), the second largest single species component of the total Western Australian shark catch after gummy sharks (*Mustelus antarcticus*, 458 tonnes)². Based on a total reported catch of 439 tonnes from the first half of 2004/05, sandbar sharks are set to become the primary species in the State's shark catch during the current year.

Stock assessment of *C. plumbeus* in Western Australian waters was undertaken using a technique known as demographic analysis. This technique is widely accepted as being the most appropriate method for assessing the status of long-lived elasmobranch species such as *C. plumbeus* (e.g. Hoenig and Gruber, 1990; Cailliet, 1992; Cortés, 1995; Cortés and Parsons, 1996; Smith et al., 1998; Simpfendorfer, 1999a,b; Cortés, 1999; Brewster-Geisz and Miller, 2000; Cortés, 2002; Mollet and Cailliet, 2002; Simpfendorfer, 2004). Unlike other more sophisticated population-simulation models that rely on extensive and long-term information about catches, fishing effort, abundance, etc., demographic analysis is primarily based on biological parameters (particularly, age at maturity, maximum age and fecundity) and estimates of total mortality. In effect, demographic models calculate the survival of each age class in a population and the amount that each age class contributes to replenishment of the population. The principal result from demographic assessment is generally referred to as the intrinsic rate of population increase (r).

To avoid any later confusion, it should be explained that r reflects the population's biological potential for growth and cannot be considered to be a measure of the actual growth rate of that population. To illustrate this point, in an unexploited fish stock the actual rate of population growth is generally considered to be in equilibrium with natural mortality, so that the size of the population will remain more-or-less static over time. However, all fish stocks must have some inherent capacity for growth (r), to enable their recovery from increases in total mortality (such as is caused by disease, predation, environmental changes, fishing, etc.). Positive values of r therefore indicate that a stock which has the biological capacity to offset the level(s) of fishing mortality being applied, while negative values indicate a stock which does not have this capacity and will decline. It should also be noted that, in general, as demographic analyses are not dynamic over time, they do not take into account any density dependent changes in the biological or natural mortality rates of the population.

² WA Department of Fisheries, Catch and Effort Statistics (CAES), unpublished data.

Another limitation of previous demographic analyses of shark populations (e.g. Cailliet, 1992; Cailliet et al., 1992; Cortés, 1995; Sminkey and Musick, 1996; Au and Smith, 1997; Smith et al., 1998; Simpfendorfer, 1999a,b) has been in their use of deterministic estimates of biological parameters and mortality, which fail to account for the inevitable variability in these rates or the uncertainty associated with their estimation (Cortés, 1999; Cortés, 2002; Beerkircher et al., 2003; Simpfendorfer, 2004). Unlike previous analyses, this assessment was undertaken with stochastically estimated biological parameters and natural mortality estimates that account for uncertainty and/or variability in the empirically measured life-history characteristics of this stock. This sophisticated demographic approach also incorporates age-specific rates of fishing mortality, which were determined from a large-scale tagging project.

2. Methods

2.1. Demographic model structure and parameter estimation

Demographic analysis was undertaken using standard life table techniques (e.g. Krebs, 1985) to test the effects of fishing on the Western Australian *C. plumbeus* stock. For each scenario of fishing mortality, the model was run 1000 times with stochastically estimated biological parameters and natural mortality rates, so that the mean and 95% confidence intervals of results could be determined. Biological parameter ranges were derived by re-sampling (with replacement) from the empirical data collected during the FRDC project³. In addition to estimating the intrinsic rate of population increase (r), the model also calculated the net reproductive rate per generation (R_o), generation time (G), population doubling time (t_{x2}), proportion reaching maturity (PM) and stable age distribution (C_x). Negative values of r indicate population decline.

Life tables were based on the Euler-Lotka equation (Lotka, 1959):

$$\sum_{x=\alpha}^w l_x e^{-rx} m_x = 1.0,$$

where l_x is the proportion of females surviving to age x , m_x is the fecundity (i.e. number of female offspring produced per female) at age x , α is the age at maturity and w is the maximum reproductive age (i.e. maximum age).

Fecundity (m_x) was calculated by multiplying litter size by the proportion of female embryos and dividing by the number of years between litters. Values for litter size and the proportion of female embryos in each litter were randomly selected from normal distributions with means and standard deviations equal to the values of the empirical data. As there was no indication from the project results that breeding periodicity varied from 2 years, this value remained fixed.

Values of female age at maturity (α) were derived from 1000 bootstrapped estimates of

³ McAuley, R, Lenanton, R., Chidlow, J, Allison, R. 2005. Biology and Stock Assessment of the Thickskin (Sandbar) Shark, *Carcharhinus plumbeus*, in Western Australia and Further Refinement of the Dusky Shark, *Carcharhinus obscurus*, Stock Assessment. Draft report to the Fisheries Research and Development Corporation. Canberra, Australia.

the length at which 50% of female sharks were mature (L_{50}) and the von Bertalanffy growth parameters of $K=0.0402 \text{ yr}^{-1}$ and $L_{\infty}=239.6 \text{ cm FL}$, which were determined by fitting the growth curve to length at age data from vertebral analysis and a known size at birth (L_0) of 42.5 cm^4 . Bootstrapped estimates of L_{50} were generated by randomly re-sampling maturity at length data to produce 1000 samples. For each sample, the value of L_{50} was calculated as $-a/b$ using the parameters a and b that were estimated by logistic regression analysis of the proportions of mature shark in 2 cm FL size classes, where the equation relating the proportion of mature individuals in each size class (P_L) is :

$$P_L = 1/(1 + e^{-(a+bx_L)}),$$

where x_L is the mean length of size class L and a and b are parameters that determine the location and shape of this curve. Values of a and b were estimated using the Solver routine in Microsoft Excel to maximise the log-likelihood:

$$LL = \sum_L [(n_L - n_{m,L}) \ln(1 - \hat{P}_L) + n_{m,L} \ln(\hat{P}_L)]$$

where n_L is the number of sharks that were examined in size class L , $n_{m,L}$ is the number of mature sharks in size class L and \hat{P}_L is the estimated proportion of mature sharks in size class L .

Based on the results of vertebral analysis, maximum reproductive age (w) was determined to be between 30 and 40 years, i.e. the probability (P) of $30 \leq w \leq 40 = 1$. The probability of maximum age being greater than 30 was assumed to decrease by $10\% \text{ yr}^{-1}$, until there was a zero probability that it was 40 years (i.e. $P(w) = 31 = 0.9$, $P(w) = 32 = 0.8 \dots P(w) = 40 = 0.0$). Probabilities were scaled, so that their cumulative probability was 1 and values for w were inversely-selected at random from within the cumulative probability distribution.

The proportion of the population surviving at the beginning of each age class was derived from the modified survival equation:

$$l_x = l_{x-1} (1 - F_{x-1}) e^{-M_{x-1}},$$

where F_x is the instantaneous rate of fishing mortality of age-class x (see 2.3) and M_x is the instantaneous rate of natural mortality of age-class x .

2.2. Natural mortality

Natural mortality (M) was estimated with stochastically-derived biological parameters, using a variety of indirect methods (Table 1) including the age-independent methods of Pauly (1980), Hoenig (1983) and Jensen (1996) and the age-dependent methods of Petersen and Wroblewski (1984) and Chen and Watanabe (1989). Rates calculated by each method were initially applied individually to the demographic model with zero fishing mortality, to assess whether they resulted in realistic levels of survival in the stock. As the Petersen and Wroblewski (1984) method resulted in unrealistically low levels of M when calculated with dry weight (using a conversion of dry weight = $0.2 \times$ live weight, Cortés, 2002), live weight⁴ was used instead, as suggested by Beerkircher et

⁴ Based on the length to weight relationship developed for Western Australian *C. plumbeus*, given in: McAuley, R. and Simpfendorfer, C. 2003. Catch Composition of the Western Australian Temperate

al. (2003). Conversely, Jensen's (1996) methods (ii) and (iii) gave inconsistently high estimates of M , which resulted in overly optimistic rates of population increase with zero fishing mortality. Stochastic estimates of age-specific natural mortality rates were therefore drawn at random (with replacement) from within the ranges given by all methods except methods (ii) and (iii) from Jensen (1996) (Table 1).

Values of t_{mat} (used in: Jensen, 1996; Chen and Watanabe, 1989) and t_{max} (used in: Hoenig, 1983) were calculated according to the methods for α and w , respectively (see 2.1). Values for the von Bertalanffy parameters, L_∞ and K (used in: Pauly, 1980; Jensen, 1996; Chen and Watanabe, 1989) were derived by refitting the modified form of the growth curve:

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

where L_0 is the size at birth (42.5 cm FL), L_T is the length at age T , L_∞ is the asymptotic length and K is the Brody growth coefficient, to 1000 bootstrapped length at age datasets using the non-linear regression function of Sigmaplot 9.0 (Systat, 2004). Bootstrapped length at age data were generated by re-sampling from the results of vertebral analysis. Values of t_0 were derived from the resulting estimates, using the standard definition of the von Bertalanffy curve:

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

Table 1. Methods used to determine natural mortality rates (M) in the WA *Carcharhinus plumbeus* stock. K and L_∞ are parameters of the von Bertalanffy growth curve (units: K , year^{-1} , and L_∞ , cm FL); T = average water temperature ($\approx 24^\circ\text{C}$, McAuley, unpublished data); $t_{mat} = t_m$ = age at maturity (units: year); t_{max} = maximum age (units: years); Z , total mortality (units: year^{-1}); wt =live weight.

Method	Relationship	Developed for
<i>Age independent methods</i>		
Pauly (1980)	$\ln(M) = -0.0066 - 0.297.\ln(L_\infty) + 0.6543.\ln(K) + 0.4627.\ln(T)$	175 fish stocks (including 2 shark species)
Hoenig (1983)	(i) $\ln(Z) = 1.46 - 1.01.\ln(t_{max})$	Teleosts
	(ii) $\ln(Z) = 0.941 - 0.873.\ln(t_{max})$	Cetaceans
	(iii) $\ln(Z) = 1.44 - 0.982.\ln(t_{max})$	Molluscs, teleosts and cetaceans
Jensen (1996)	(i) $M = 1.65/t_{mat}$	Theoretical
	(ii) $M = 1.5 K$	Theoretical
	(iii) $M = 1.6 K$	Pauly (1980) data
<i>Age dependent methods</i>		

Petersen and Wroblewski (1984)	$M_{wt} = 1.92wt^{-0.25}$	Particle-size theory and pelagic ecosystem data
Chen and Watanabe (1989)	$M(t) = \begin{cases} \frac{K}{1 - e^{-K(t-t_0)}}, t \leq t_M \\ \frac{K}{a_0 + a_1(t-t_M) + a_2(t-t_M)^2}, t \geq t_M \end{cases}$	Theoretical
where:	$\begin{cases} a_0 = 1 - e^{-K(t_M-t_0)} \\ a_1 = Ke^{-K(t_M-t_0)} \\ a_2 = -\frac{1}{2}K^2e^{-K(t_M-t_0)} \end{cases}$	
and:	$t_M = -\frac{1}{K} \ln 1 - e^{Kt_0} + t_0$	

2.3. Fishing mortality

To examine the effects of fishing on the Western Australian *C. plumbeus* stock, age specific rates of fishing mortality during the 2001/02, 2002/03 and 2003/04 fishing seasons (July-June) were derived from the capture rates of tagged sharks from a large-scale tagging study, which is summarised as follows.

2.3.1. Tagging data

A total of 1,654 *Carcharhinus plumbeus* were tagged between August 2000 and June 2004, in waters between Cape Leveque (16°S, 123°E) and Cape Leeuwin (34°S, 115°E, Figure 1). Prior to their release, sharks were sexed, measured and the date, location and depth of each release were recorded. Ages of tagged sharks were estimated from their measured lengths at release using the von Bertalanffy parameters. Sharks were tagged with uniquely-numbered Jumbo Rototags in the posterior half of their first dorsal fins, at approximately 30-50% of the height of the fin. The condition of tagged sharks was assessed on release as either 1 (swam away strongly), 2 (swam away slowly) or 3 (sluggish or unable to swim away). Only sharks with release conditions of 1 or 2 and which exhibited no other signs of being adversely affected by capture or tagging were included in determination of capture rates.

Information on tag captures was received from commercial and recreational fishers and from research staff during collection of samples from commercial catches and during fishery-independent sampling. Recapture data included the date and location of capture, length, sex, and condition of the shark and tag. The capture rates of *C. plumbeus* tagged inside the area between Steep Point and NW Cape, which has been closed to targeted shark fishing since the 1970s, were compared with the capture rates of sharks tagged in open areas to examine whether this closure afforded the stock any substantive protection.

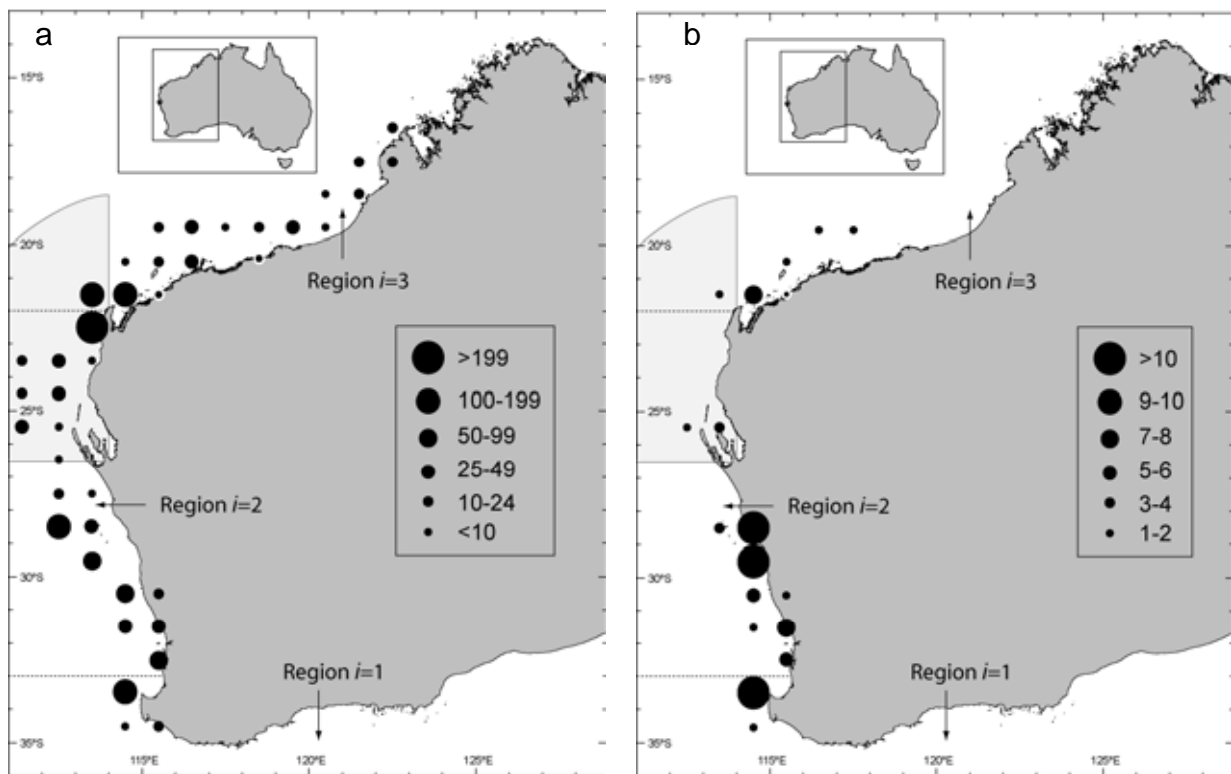


Figure 1. (a) release locations of 1,654 *Carcharhinus plumbeus*, tagged in Western Australian waters between August 1st 2000 and 15th June 2004 and (b) capture locations of 75 tags between August 14th 2001 and 24th May 2004. Dotted lines indicate the boundaries of regions 1, 2 and 3, used in analysis of regional tag non-reporting rates (see 2.3.2.). Region 1 is the Joint Authority Southern Demersal Gillnet and Demersal Longline Fishery (JASDGDLF); Region 2 is the West Coast Demersal Gillnet and Demersal Longline Fishery (WCDGDLF); Region 3 is the WA North Coast Shark Fishery (WANCSF). The light grey shaded area between 26° 30'S latitude and 114° 06'E longitude is closed to targeted shark fishing.

2.3.2. Estimation of fishing mortality rates

To ensure tagged sharks had been allowed adequate time to mix into the population, captures of sharks that were at liberty for less than 90 days ($n=5$) were excluded from analysis of capture rates. Captures reported by recreational fishers ($n=3$) were also excluded as these sharks were either reported or assumed to have been released alive. The single tag capture during a fishery-independent research-cruise in August 2003 was also excluded from this analysis.

To account for unreported tag captures, tag reporting behaviour was assessed separately for three regions (Figure 1), corresponding to the areas of the JASDGDLF ($i=1$), WCDGDLF ($i=2$) and the northern shark fisheries ($i=3$), using the method of Simpfendorfer (1999b). Fishers were classified as either “reporters” or “non-reporters” depending on whether they returned any tag information within a year. Regional non-reporting rates were then estimated as the proportion of each region’s annual *C. plumbeus* catch that was taken by “non-reporting” fishers. Catch figures were taken from compulsory monthly catch and effort returns supplied by all commercial fishers. The estimated number of captures of x year old tagged sharks during each month ($\hat{C}_{x,t}$) between July 2001 and June 2004, was calculated as:

$$\hat{C}_{x,t} = \sum_{i=1}^{i=3} \frac{C_{x,i,t}}{1 - D_{i,T}}$$

where $C_{x,i,t}$ is the number of reported captures of x year old sharks in region i during month t and $D_{i,T}$ is the non-reporting rate in region i during year T .

The number of tagged sharks of age x that were present in the population at the start of month $t + 1$ ($n_{x,t+1}$) was calculated as:

$$n_{x,t+1} = (n_{x,t} - \hat{C}_{x,t})e^{-(M_x+S)/12} + R_{x,t},$$

where $n_{x,t}$ is the number of tagged sharks present in the population at the start of month t , M_x is the instantaneous annual natural mortality rate of age-class x , S is the instantaneous annual tag shedding rate of 0.0358 yr⁻¹ calculated for *C. obscurus* (Simpfendorfer, 1999b) and $R_{x,t}$ is the number of sharks of age x tagged in month t . As results from reproductive sampling indicated that parturition in this population peaks between January and April, tagged sharks were assumed to move from age-class x into $x+1$ on the first of March each year.

The instantaneous annual rate of fishing mortality experienced by age class x during fishing season T , ($F_{x,T}$), was then derived from the Baranov catch equation (eg. Ricker, 1975; Quinn and Deriso, 1999):

$$\hat{C}_{x,T} = \frac{F_{x,T}}{Z_{x,T}} \cdot n_{x,T} (1 - e^{-Z_{x,T}}),$$

where $Z_{x,T}$ is the instantaneous annual total mortality rate.

To assess how the Western Australian *C. plumbeus* population was affected by fishing over this three year period, age-specific fishing mortality rates for fishing seasons 2001/02, 2002/03 and 2003/04 (referred to as $F_{x,2001/02}$, $F_{x,2002/03}$ and $F_{x,2003/04}$, respectively) were each applied separately in the demographic model, together with each of the rates of natural mortality calculated according to the methods described in 2.2. Additionally, a set of annual fishing mortality rates which accounted for the exploitation of age-classes for which no tag captures were reported, was calculated for each of the three years of the study (referred to as $\hat{F}_{x,2001/02}$, $\hat{F}_{x,2002/03}$ and $\hat{F}_{x,2003/04}$, respectively).

Adjusted rates were calculated by pooling tag captures from multiple age-classes to estimate fishing mortality for multiple year age-classes. Capture data were pooled for each 3-year age-class to 17+ years and a single fishing mortality rate was calculated for sharks aged between 18+ and 24+ years. Although *C. plumbeus* are probably caught in the fishery up to 30+ years, no sharks older than 24 years were tagged. Fishing mortality of sharks older than 25 years was therefore assumed to decrease uniformly from the rate experienced by the 18-24+ year old age-class, in each subsequent age-class, until it was zero for sharks older than 30 years of age. These age-class rates were assessed as providing the best representation of the actual levels of fishing mortality over the three years of the tagging project and have therefore been used to provide formal advice on the status of the Western Australian Sandbar shark stock.

2.4. Demographic analysis and assessment of potential management options for the WA sandbar shark fishery

In addition to the measured rates of fishing mortality, 65 hypothetical scenarios of exploitation were tested in the demographic model to predict the outcomes of potential management strategies for the various target and bycatch sectors (Appendix I). Namely, these sectors were the TDGDLF, the WANCSF, the Pilbara Fish Trawl Fishery (PFTF), other trawl fisheries and the Wetline Fishery. On the basis of recent discussions regarding options for the management of elasmobranch bycatch in Western Australian non-target-shark fisheries, it currently appears likely that the PFTF will be permitted to continue to land sharks for the foreseeable future (although the introduction of bycatch exclusion devices is likely to significantly reduce this fishery's catches of *C. plumbeus*), whilst the other trawl fisheries and the wetline sector are likely to be prohibited from landing sharks. Therefore, all hypothetical scenarios assumed unchanged fishing mortality in the PFTF and zero mortality in the other trawl and wetline sectors.

The relative contributions to the 2003/04 adjusted fishing mortality rates of these fishing sectors were attributed on the basis of each fishery's estimated catch at age of *C. plumbeus*. Catches at age were determined from the observed size compositions of *C. plumbeus* catches in the TDGDLF, WANCSF and the PFTF⁵, assumed size compositions in the Wetline Fishery and other trawl fisheries, the total or estimated *C. plumbeus* catch by each sector and the age and growth parameters calculated from vertebral analysis. The accuracy of reported *C. plumbeus* catches in the target fisheries, i.e. the TDGDLF and the WANCSF was assessed and, where necessary, corrected according to the following procedures.

As *C. plumbeus* have historically been and remain a relatively minor component of the shark catch of most temperate demersal gillnet and longline vessels, many operators, particularly in the JASDGLF, do not identify catches of this species separately. Therefore, catch records from TDGDLF vessels, operating between the northern limit of the WCDGDLF and a line of longitude at 118°E on the south coast, which did not separately report any *C. plumbeus* catch within a financial year were adjusted by reapportioning their monthly unidentified shark catch using the ratio of sandbar to unidentified shark catch from vessels operating in the same area in the same month or year, which did report their *C. plumbeus* catches separately.

Due the small number of vessels which operated in the WANCSF, their sporadic patterns of fishing effort and the geographic scale of the northern fishery, the procedures used to validate catch and effort data in the TDGDLF could not be applied to records from the WANCSF. Instead, the accuracy of reported *C. plumbeus* catches in the WANCSF were examined by comparing the fishery's monthly reported CPUE in the area west of 120°E with the monthly CPUE recorded in voluntary research logbooks from the same area. Whilst reported effort (in terms of number of hooks and days fished per month) was consistent with both the logbook data and the values observed during commercial sampling on board the majority of WANCSF vessels, there were significant differences between reported and logbook catch rates. It was therefore necessary to re-estimate the northern fishery's total *C. plumbeus* catches to provide a more accurate representation of the overall level of catch. This was done by bootstrapping 1000 sets of estimated annual catches in the WANCSF, using the reported effort from the area between NW Cape and longitude 120°E and catch rates that were selected at random from within the range of the

⁵ Stephenson, P. and Chidlow, J. 2003. By-catch in the Pilbara Trawl Fishery. Final report to National Heritage Trust. WA Department of Fisheries. Perth.

mean annual logbook CPUE \pm the calculated level of precision (PC) of these rates. The precision of monthly logbook and CAES reported catch rates, i.e. the level of change in CPUE that should be detectable in each dataset, was determined using the equation:

$$n = \frac{8CV^2}{PC^2} [1 + (1 - PC)^2]$$

where n is the sample size and CV is the coefficient of variation, calculated as the ratio of the standard deviation to average catch rate (van Belle, 2004), of each dataset.

Shark catches in the PFTF are not reported to species level. The proportion of *C. plumbeus* in the fishery's unidentified shark catch was therefore re-estimated from species and size composition data collected by an experienced shark biologist during a bycatch monitoring survey in this fishery between February and June 2002⁵ and the previously mentioned length to weight relationship. The annual *C. plumbeus* catch was thereby estimated from the fishery's reported annual shark catch. As no precise estimates of the quantity or size composition of *C. plumbeus* catches could be made for the other trawl fisheries nor the wetline sector, a combined nominal catch of ten tonnes (live weight), evenly distributed between age classes, was assumed for these sectors.

3. Results

3.1. Biological parameter estimates

The ranges from which biological parameters were drawn accurately represented the levels of variability and/or uncertainty in the empirical data (Table 2). Although attaining maturity and maximum age at similar ages as have been reported in other *C. plumbeus* populations, Western Australian sandbar sharks generally exhibit smaller litter sizes than previously reported for this species in the western North Atlantic (Springer, 1960), western Indian Ocean (Cliff et al, 1988) and in the East China Sea (Joung and Chen, 1995). This combination of demographic characteristics is likely to make this population less fecund than others. However, whilst previous studies have found an embryonic sex ratio of 1:1, data collected during this project suggest that the proportion of female embryos in the Western Australian stock is significantly higher than 0.5. As this bias could potentially offset the apparently lower fecundity of the WA stock, it is important that the range of values from which the proportion of females (at birth) was chosen was appropriately skewed.

Table 2. Ranges of biological parameter used in calculating natural mortality and in the demographic analysis of *Carcharhinus plumbeus*. The parameters K , L_∞ and t_0 are coefficients of the von Bertalanffy growth curve, $w(t_{max})$ is the maximum age and $\alpha(t_{mat})$ is age at which 50% of females are expected to be mature.

	K	L_∞	t_0	$w(t_{max})$	$\alpha(t_{mat})$	Litter size (n)	Sex ratio (prop. ♀)	Reproductive period (yr)
Mean	0.0398	244.2	-4.83	33	15.9	6.5	0.61	2
Lower 95%CI	0.0334	221.6	-5.13	30	15.6	3.7	0.29	2
Upper 95%CI	0.0466	271	-4.55	38	16.1	9.2	0.97	2

3.2. Natural mortality rates

Estimates of instantaneous annual natural mortality rates (M) obtained from the Pauly (1980) and Hoenig (1983) methods were reasonably consistent (Table 3). The median rates calculated by each of these methods were within the 95% confidence limits of the other methods and all yielded realistic population growth rates when applied in the demographic model. Estimates of M from the Jensen (1996) methods were generally lower than those calculated from the Pauly (1980) and Hoenig (1983) methods. In particular, Jensen's (1996) methods (ii) and (iii) gave inconsistently low estimates, with upper confidence intervals that were lower than the lower confidence intervals of all other age-independent estimates. These values of M were therefore omitted from the ranges from which the stochastically-estimated rates of natural mortality were calculated.

Table 3. Age-independent estimates of instantaneous annual rate of natural mortality. M = median of 1000 estimates (units yr^{-1}); CI = confidence intervals of estimates.

Method	M	Min	Max	95% CI
Pauly (1980)	0.113	0.081	0.139	(0.098 - 0.129)
Hoenig (1983), method i	0.126	0.106	0.139	(0.109 - 0.139)
Hoenig (1983), method ii	0.124	0.105	0.132	(0.107 - 0.132)
Hoenig (1983), method iii	0.136	0.116	0.150	(0.119 - 0.150)
Jensen (1996), method i	0.098	0.095	0.106	(0.096 - 0.099)
Jensen (1996), method ii	0.060	0.040	0.077	(0.050 - 0.071)
Jensen (1996), method iii	0.064	0.043	0.082	(0.054 - 0.075)

Whilst the age-independent methods of Petersen and Wroblewski (1984) and Chen and Watanabe (1989) yielded higher estimates of M for the youngest and oldest sharks, rates for those age-classes that are caught by the fisheries were generally lower than were estimated by age independent methods (Table 4). Substituting live weight for dry weight in the Petersen and Wroblewski (1984) method resulted in natural mortality rates that were consistent with estimates from the other methods and which, unlike the rates calculated using dry weight, gave positive population growth rates with zero fishing mortality in the demographic model. The stochastically-estimated rates of natural mortality used in the stock assessment retained some of the U-shaped characteristics of the Chen and Watanabe (1989) method, although the rates of the youngest and oldest age-classes were not as high as were estimated directly from this method.

Table 4. Age-dependent estimates of natural mortality rates. \bar{M} = mean of 1000 estimates from bootstrapped biological parameter estimates (units yr^{-1}); CI = confidence interval.

Age class	Petersen &	Chen & Watanabe		Stochastically estimated	
	Wroblewski (1984)	M	95% CI	M	95% CI
0+	0.216	0.228	(0.214 - 0.245)	0.160	(0.101 - 0.226)
1+	0.194	0.193	(0.182 - 0.205)	0.146	(0.100 - 0.192)
2+	0.177	0.168	(0.159 - 0.178)	0.136	(0.100 - 0.176)
3+	0.164	0.149	(0.141 - 0.158)	0.132	(0.100 - 0.163)
4+	0.153	0.135	(0.128 - 0.142)	0.126	(0.099 - 0.152)
5+	0.144	0.123	(0.117 - 0.130)	0.121	(0.099 - 0.144)
6+	0.137	0.114	(0.108 - 0.120)	0.119	(0.099 - 0.143)
7+	0.131	0.106	(0.101 - 0.112)	0.117	(0.098 - 0.143)

8+	0.125	0.100	(0.095 - 0.106)	0.116	(0.098 - 0.144)
9+	0.120	0.094	(0.089 - 0.100)	0.115	(0.094 - 0.143)
10+	0.116	0.090	(0.085 - 0.095)	0.112	(0.090 - 0.143)
11+	0.112	0.085	(0.081 - 0.091)	0.110	(0.086 - 0.143)
12+	0.109	0.082	(0.077 - 0.087)	0.108	(0.082 - 0.141)
13+	0.106	0.079	(0.074 - 0.084)	0.108	(0.079 - 0.143)
14+	0.103	0.076	(0.071 - 0.081)	0.106	(0.076 - 0.142)
15+	0.101	0.073	(0.069 - 0.078)	0.103	(0.074 - 0.142)
16+	0.099	0.071	(0.066 - 0.076)	0.103	(0.072 - 0.141)
17+	0.097	0.069	(0.064 - 0.074)	0.101	(0.069 - 0.141)
18+	0.095	0.067	(0.063 - 0.072)	0.101	(0.067 - 0.141)
19+	0.093	0.065	(0.061 - 0.070)	0.102	(0.066 - 0.143)
20+	0.091	0.064	(0.059 - 0.069)	0.099	(0.065 - 0.141)
21+	0.090	0.062	(0.058 - 0.067)	0.100	(0.063 - 0.140)
22+	0.089	0.061	(0.057 - 0.066)	0.099	(0.063 - 0.142)
23+	0.087	0.060	(0.055 - 0.065)	0.097	(0.061 - 0.140)
24+	0.086	0.059	(0.054 - 0.064)	0.096	(0.059 - 0.140)
25+	0.085	0.057	(0.053 - 0.063)	0.095	(0.058 - 0.142)
26+	0.084	0.057	(0.052 - 0.062)	0.096	(0.058 - 0.140)
27+	0.083	0.056	(0.051 - 0.061)	0.096	(0.057 - 0.140)
28+	0.082	0.055	(0.050 - 0.060)	0.094	(0.056 - 0.141)
29+	0.081	0.054	(0.050 - 0.059)	0.094	(0.055 - 0.142)
30+	0.081	0.053	(0.049 - 0.059)	0.093	(0.055 - 0.145)
31+	0.080	0.053	(0.048 - 0.644)	0.094	(0.053 - 0.149)
32+	0.079	0.052	(0.047 - 0.660)	0.095	(0.054 - 0.333)
33+	0.079	0.051	(0.047 - 0.675)	0.097	(0.052 - 0.428)
34+	0.078	0.051	(0.046 - 0.690)	0.098	(0.052 - 0.525)
35+	0.077	0.050	(0.046 - 0.704)	0.100	(0.052 - 0.562)
36+	0.077	0.050	(0.045 - 0.717)	0.103	(0.051 - 0.580)
37+	0.076	0.049	(0.045 - 0.730)	0.107	(0.051 - 0.587)
38+	0.076	0.049	(0.044 - 0.741)	0.119	(0.051 - 0.615)
39+	0.075	0.587	(0.044 - 0.752)	0.128	(0.050 - 0.628)
40+	0.075	0.603	(0.043 - 0.762)	0.162	(0.051 - 0.656)

3.3. Fishing mortality

3.3.1. Sources of tag capture data

A total of 75 tagged *C. plumbeus* captures were reported between March 2001 and May 2004 (Table 5). More than 85% of these were reported from the target shark fisheries, of which 44 were caught by gillnets in the WCDGDLF, 12 by gillnets in the JASDGDLF and eight by longlines in the WANCSF. Of these, 9 sharks were at liberty for less than 90 days, 3 were captured by recreational fishers and one was caught during a fishery independent survey. These thirteen sharks were therefore excluded from analysis of exploitation rates.

Table 5. Sources of tagged *C. plumbeus* captures between August 2000 and May 2004 by fishery and method. Managed fisheries are abbreviated as follows: WCDGDLF= West Coast Demersal Gillnet and Demersal Longline Fishery; JASDGDLF= Joint Authority Southern

Demersal Gillnet and Demersal Longline Fishery; WANCSF=WA North Coast Shark Fishery; PFTF=Pilbara Fish Trawl fishery; SBPTF=Shark Bay Prawn Trawl Fishery.

Fishery	n	Method	n
WCDGDLF	44	Demersal gillnet	53
JASDGDLF	12	Demersal longline	8
WANCSF	8	Unspecified hook methods	5
Wetline Fishery	4	Handline	3
Recreational	3	Dropline	3
SBPTF	2	Trawl	3
PFTF	1		
Research	1		

A total of 664 sharks were tagged in the closed area during between August 2000 and June 2004, compared to 1080 tagged in open areas over the same period. Thirteen of the sharks tagged in the closed area were captured before the end of 2003/04, compared to 63 captures of sharks tagged in open areas. Seven of the sharks tagged in the closed area were captured in the area of the WANCSF (five by WANCSF vessels, one by a 'wetline' vessel and one by a recreational fisher); three occurred inside the closed area (one by a recreational fisher, one during a fishery-independent research survey and one in the bycatch of a Shark Bay prawn trawler) and three were caught by WCDGDLF vessels.

The capture rate of sharks tagged in the closed area (n=13, 2.0%) was marginally higher but not significantly different to that of sharks that were tagged in the area of WANCSF (n=6, 1.7%; $\chi^2 = 0.007$, $df=1$, $P=0.931$), indicating that sharks occurring in the closed area were no less likely to be caught than those in the adjacent area of the WANCSF. Although, overall the sharks tagged in the area of the TDGDLF were caught at a significantly higher rate (n=57, 7.9%) than those tagged in the closed area ($\chi^2 = 23.087$, $df=1$, $P=1.548 \times 10^{-6}$) and in the WANCSF ($\chi^2 = 15.018$, $df=1$, $P=1.065 \times 10^{-4}$), most of the sharks tagged in the TDGDLF were juveniles, whilst most of those tagged in the area north of Steep Point were sub-adults and adults. However, when capture rates only for sharks older than seven years were compared between areas, there was found to be no significant difference between the capture rate of sharks tagged in the closed area (n=10, 1.9%) and that of sharks tagged in open areas (n=20, 2.8%; $\chi^2 = 0.765$, $df=1$, $P=0.382$). These results strongly suggest that the closed area in the centre of this stock's range provides no significant protection to the sub-adult and adult age classes which primarily reside in the area north of Steep Point.

In addition, longer-term tag recapture data from two sharks, which were released as juveniles (71 cm FL and 75 cm FL, respectively) in the south-west of the State (between 32°S and 34°S) and caught in the WANCSF 7½ - 8 years later, suggest that as *C. plumbeus* reach maturity, they migrate northwards up the West Coast and across the closed area to join the bulk of the adult stock residing in waters off the north coast.

3.3.2. Tag captures and fishing mortality rates

Estimated annual non-reporting rates (D_{iR}) of tag captures were lowest in Region 1, generally higher in region 2 and highest in region 3 (Table 6). Non-reporting rates

increased sharply in regions 2 and 3 during 2003/04 as a result of substantial increases in *C. plumbeus* catches by vessels which did not report any tag captures. It was estimated that a total of 29 tags were captured in 2001/02, 42 in 2002/03 and 80 in 2003/04. The majority of tags were captured in Region 2 in all years, although the number of estimated captures in region 3 increased by more than 300% between 2002/03 and 2003/04.

Table 6. Estimated annual tag non-reporting rates during the 2001/02, 2002/03 and 2003/04 fishing seasons and numbers of reported and estimated *C. plumbeus* tag captures by region (denoted by i).

Year	Non-reporting rates ($D_{i,t}$)			Reported captures ($C_{i,T}$)			Estimated captures $\hat{C}_{i,T}$		
	$i=1$	$i=2$	$i=3$	$i=1$	$i=2$	$i=3$	$i=1$	$i=2$	$i=3$
2001-02	0.23	0.50	0.39	3	11	2	4	22	3
2002-03	0.13	0.47	0.55	8	13	4	9	24	9
2003-04	0.09	0.67	0.84	0	16	5	0	48	31

Age specific rates of instantaneous annual fishing mortality (F_x) were similar for 0+ to 10+ age-classes during 2001/02 and 2002/03 (Figure 3). Fishing mortality rates of adult sharks during these years were generally lower than those experienced by juveniles and were limited to a few age-classes. While fishing mortality increased in most age-classes during 2003/04, rates were still highest for sharks younger than 14 years. With the exception of the unrealistically high fishing mortality rate experienced by the 24+ age-class in 2002/03 (which was based on the capture of 2 sharks), the highest levels of fishing mortality in all years were experienced by 6+ to 8+ age-classes. These ages correspond closely to the ages at which the mesh sizes used in the TDGDLF (16.5 - 17.8cm) attain their maximum selectivity (7.5 – 8.7 yrs)². As evidenced by the 95% confidence intervals around the median estimates, variations in fishing mortality due to stochastic estimation of natural mortality rates were negligible.

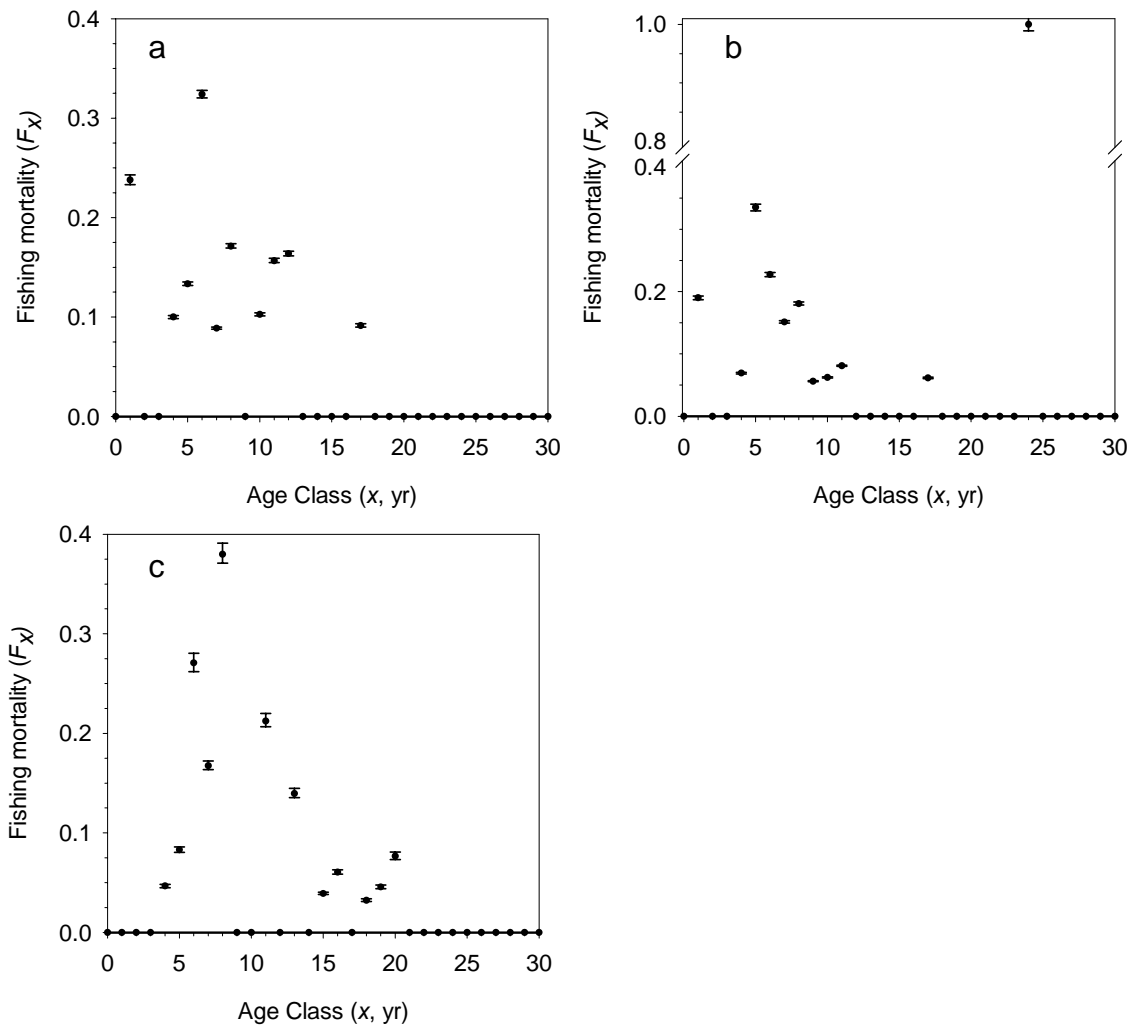


Figure 3. Age-specific rates of instantaneous annual fishing mortality experienced by individual age-classes of *C. plumbeus*, determined from estimated capture rates of tagged sharks in (a) 2001/02, (b) 2002/03, (c) 2003/04. Points indicate the median rates of 1000 estimates calculated with stochastic biological parameter values. Error bars indicate 95% confidence intervals of estimates.

The highest rates of fishing mortality determined for multi-year age classes ($\hat{F}_{x,2001/02}$, $\hat{F}_{x,2002/03}$ and $\hat{F}_{x,2003/04}$) were experienced by the 6-9 year age class in 2001/02 and 2003/04 and by the 3-6 year age class in 2002/03 (Figure 4). Rates of juvenile fishing mortality increased between 2001/02 and 2003/04, by between 11% in the 12-15 year age-class and 48% in the 6-9 year age-class. As no tag captures of sharks older than 17 years were reported during 2001/02, no estimates of fishing mortality could be made for the older age classes in the first year. Fishing mortality of the adult age-classes was estimated to have increased by between 108% (15-18 years) and 172% (18-24 years) between 2002/03 and 2003/04.

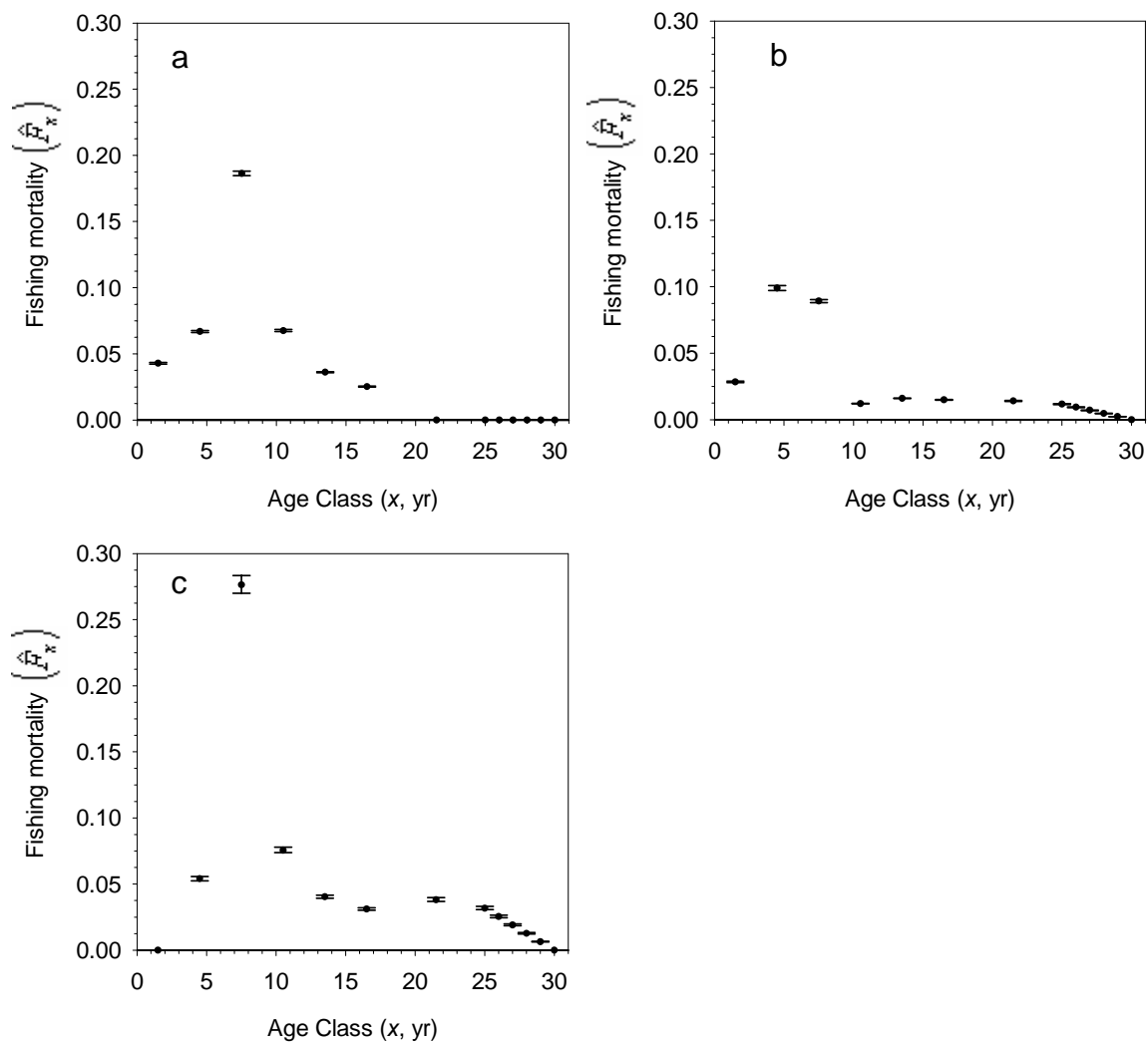


Figure 4. Rates of instantaneous annual fishing mortality, experienced by multi-year age classes of *C. plumbeus*, determined from capture rates of tagged sharks in (a) 2001/02, (b) 2002/03, (c) 2003/04. Points indicate the median rates of 1000 estimates calculated with stochastic biological parameter values, plotted at the midpoint of each multi-year age class. Error bars indicate 95% confidence intervals of estimates.

3.4. Demographic analysis for the WA sandbar shark fishery

Using stochastically estimated biological parameters and rates of natural mortality, the Western Australian *C. plumbeus* population was estimated to have an intrinsic rate of population growth of 0.025 (2.5% per year) with zero fishing mortality, with 95% confidence that r was between -0.018 and 0.055 yr^{-1} (Table 7; Appendix II, table i). Rates of natural mortality calculated from the Hoenig (1983) methods resulted in the lowest median population growth rates ($r=0.007$ to 0.023 yr^{-1}) with no fishing, whilst M calculated by Jensen's (1996) methods yielded the highest median values of r (0.046 to 0.086 yr^{-1}). The level of fishing mortality that would deliver Maximum Sustainable Yield, when applied evenly across all age classes, was calculated from the median estimate of r , using the stochastically estimated M , to be 0.017 year^{-1} . When tested in the demographic model, this rate resulted in a population growth rate of $r= 0.013$.

Table 7. Summary of population growth rates (r) in the Western Australian *C. plumbeus* stock estimated by demographic analysis with zero fishing mortality (F_0), age-specific fishing mortality rates between 2001 and 2004 ($F_{2001/02}$, $F_{2002/03}$ and $F_{2003/04}$) and multi-year age-class fishing mortality rates between 2001 and 2004 ($\hat{F}_{2001/02}$, $\hat{F}_{2002/03}$ and $\hat{F}_{2003/04}$). Values are the medians (and 95% confidence intervals in parentheses) of 1000 estimates of r , calculated using stochastically estimated biological parameters, stochastically-estimated natural mortality rates (M) and minimum and maximum rates of M (Jensen, 1996, method i and Hoenig, 1984, method iii, respectively).

	Hoenig (1983, method iii) M		Jensen (1996, method i) M		Stochastically estimated M	
F_0	0.007	(-0.040, 0.041)	0.046	(-0.002, 0.077)	0.025	(-0.018, 0.055)
$F_{2001/02}$	-0.074	(-0.119, -0.039)	-0.032	(-0.077, -0.003)	-0.049	(-0.092, -0.019)
$F_{2002/03}$	-0.085	(-0.135, -0.047)	-0.041	(-0.087, -0.009)	-0.059	(-0.110, -0.026)
$F_{2003/04}$	-0.076	(-0.119, -0.038)	-0.029	(-0.073, 0.001)	-0.048	(-0.089, -0.017)
$\hat{F}_{2001/02}$	-0.056	(-0.101, -0.020)	-0.014	(-0.056, 0.012)	-0.032	(-0.075, -0.001)
$\hat{F}_{2002/03}$	-0.034	(-0.086, 0.004)	0.007	(-0.040, 0.038)	-0.009	(-0.054, 0.022)
$\hat{F}_{2003/04}$	-0.078	(-0.127, -0.039)	-0.030	(-0.078, -0.001)	-0.049	(-0.093, -0.018)

The age specific fishing mortality rates, $F_{2001/02}$, $F_{2002/03}$ and $F_{2003/04}$, all resulted in negative rates of population growth (r), under all but the most optimistic rates of natural mortality (Jensen, 1996, methods i and ii; Appendix II, Tables ii-iv). Using stochastically estimated rates of natural mortality, median estimates of the rates of population growth under these levels of fishing mortality were: -4.9% per year in 2001/02, -5.9% per year in 2002/03 and -4.8% per year in 2003/04 (Table 7). The most severe rates of natural mortality (Hoenig, 1983, method iii), gave median rates of population decline of -7.4% yr^{-1} , -8.5% yr^{-1} and -7.6% yr^{-1} in 2001/02, 2002/03 and 2003/04, respectively.

The adjusted multi-year age-class rates of fishing mortality, $\hat{F}_{2001/02}$, $\hat{F}_{2002/03}$ and $\hat{F}_{2003/04}$, provided slightly more optimistic estimates of r than the age specific rates. However, when combined in the demographic model with all but the lowest rates of natural mortality, r was nonetheless negative for all years of the study (Appendix II, Tables v-vii). Using stochastically estimated rates of natural mortality, median estimates of the intrinsic population growth rates under these levels of fishing mortality were: -3.2% per year in 2001/02, -0.9% per year in 2002/03 and -4.9% per year in 2003/04 (Table 7). Estimates of natural mortality from Hoenig (1983, method iii), gave median rates of intrinsic population growth of -5.6% yr^{-1} , -3.4% yr^{-1} and -7.8% yr^{-1} in 2001/02, 2002/03 and 2003/04, respectively.

3.5 Assessment of potential management options for the WA sandbar shark fishery

The relative contributions by each fishery to the adjusted multi-year age-class rates of fishing mortality were apportioned on the basis of best estimates of the catches at age by each sector. Validated gillnet catches in the temperate demersal gillnet and longline fishery were 162.0 tonnes, 170.1 tonnes and 144.2 tonnes in 2001/02, 2002/03 and 2003/04, respectively (Figure 5). Over the same three years, longline catches in this fishery were 0.9 tonnes, 0.0 tonnes and 55.9 tonnes. Estimated catches in the Pilbara Fish Trawl fishery were 13.1 tonnes, 17.3 tonnes and 12.1 tonnes. Estimated WANCSF catches were 174.6 tonnes, 196.3 tonnes and 423.9 tonnes. The proportion of the total *C. plumbeus* catch taken by the WANCSF increased from 48% in 2001/02, to 50% in 2002/03 and to 66% in 2003/04. The proportion caught by temperate demersal gillnetters

dropped from 45% in 2001/02 to 22% in 2003/04, whilst the proportion taken by temperate longliners increased from less than 1% to nearly 9% over the same period. The combined take by the Pilbara Fish Trawl fishery, other trawlers and by the wetline sector accounted for between 3% (2003/04) and 7% (2002/03) of the total *C. plumbeus* catch.

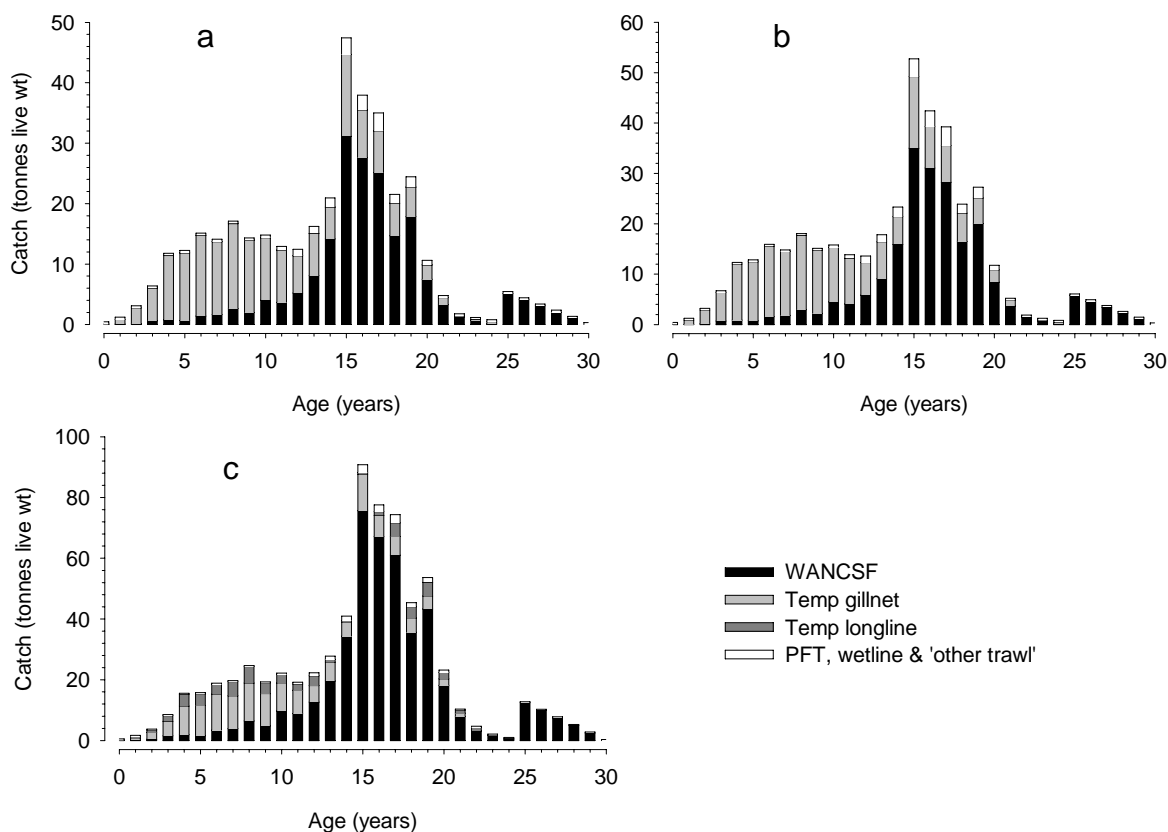


Figure 5. Relative catches at-age of *C. plumbeus* in the temperate demersal gillnet and longline fishery (dark grey bars) the Pilbara Fish Trawl fishery (white bars) and the WA north coast shark (dark grey bars) during (a) 2001/02, (b) 2002/03 and (c) 2003/04.

To test the outcomes of potential fishery management strategies, 65 hypothetical scenarios of fishing mortality in the various fishing sectors that catch *C. plumbeus* were tested in the model (Appendix 1). A range of potential fishing mortality combinations, that would deliver neutral or positive population growth rates, were identified.

Seventeen hypothetical combinations of fishing mortality that delivered neutral or positive intrinsic population growth rates were identified in the model (Table 8). Fifteen of these required zero fishing mortality in one or other of the target fisheries. The remaining two options required substantial reductions in both the WANCSF and the TDGDLF. These results are summarised as follows (unless otherwise stated, each case assumes zero fishing mortality in all other WA fishing sectors except the PFTF:

A. Maintaining the WANCSF at between 85 and 100% of its 2003/04 level of fishing mortality, requires closure of the temperate demersal gillnet and demersal longline fishery.

B. Reducing the WANCSF to 70% of its 2003/04 level of fishing mortality, would permit 25% of the 2003/04 level of exploitation by the temperate demersal gillnet fishery but would require closure of the temperate demersal longline fishery.

C. Reducing fishing mortality in the WANCSF to 50% of its 2003/04 level, would permit approximately 25% of the 2003/04 level of exploitation in the temperate demersal gillnet and demersal longline fishery.

D. Reducing fishing mortality in the WANCSF to 25% of its 2003/04 level, would permit either 25% of the 2003/04 level of exploitation in each of the temperate fisheries or 50% of the 2003/04 level of fishing in the temperate demersal gillnet fishery and no exploitation in the demersal longline fishery.

E. Maintaining the temperate gillnet fishery at between 70 and 85% of its 2003/04 level of exploitation, would permit 0% of the 2003/04 level of exploitation by the temperate longline fishery and the WANCSF.

F. Reducing the temperate gillnet fishery to 50% of its 2003/04 level of exploitation, would permit either 25% of the 2003/04 level of exploitation by the WANCSF and no exploitation by the temperate longline fishery (i.e. D above) or 50% of the 2003/04 level of exploitation by the temperate longline fishery and no exploitation by the WANCSF.

G. Reducing the temperate gillnet fishery to 25% of its 2003/04 level of exploitation, would permit either 70% of the 2003/04 level of exploitation by the WANCSF and no exploitation by the temperate longline fishery (i.e. B above) or 25% of the 2003/04 level of exploitation by the temperate longline fishery and no exploitation by the WANCSF. Other combinations are covered by the above points.

Table 8. Fishery management options for obtaining **neutral** or **positive** intrinsic population growth rates (r) in the Western Australian *Carcharhinus plumbeus* stock, determined from demographic analysis. $\hat{F}_{2003/04}$ is the proportion of the 2003/04 level of fishing mortality determined for each of the target fisheries and, for reference, is shown relative to the fisheries' proportional 2003/04 levels of catch and effort. The options are ranked by r . The letters in brackets refer to the summary options A-G in the text.

WANCSF			Temperate Gillnet			Temperate Longline			Population growth rate (r)	
$\hat{F}_{2003/04}$	Catch*	Effort [†]	$\hat{F}_{2003/04}$	Catch*	Effort ^{††}	$\hat{F}_{2003/04}$	Catch*	Effort [†]	Median	95% confidence intervals
0.25	106	130	0.00	0	0	0.00	0	0	0.024	(-0.021, 0.055)
0.00	0	0	0.25	36	60	0.00	0	0	0.022	(-0.023, 0.055)
0.00	0	0	0.25	36	60	0.25	14	69	0.018	(-0.030, 0.049)
0.50 (C)	212	259	0.00	0	0	0.00	0	0	0.017	(-0.028, 0.049)
0.00	0	0	0.50 (F)	72	120	0.00	0	0	0.014	(-0.031, 0.044)
0.25 (D)	106	130	0.25 (G)	36	60	0.00	0	0	0.012	(-0.032, 0.043)
0.25 (D)	106	130	0.25	36	60	0.25	14	69	0.012	(-0.033, 0.043)
0.70 (B)	297	363	0.00	0	0	0.00	0	0	0.011	(-0.033, 0.043)
0.85 (A)	360	441	0.00	0	0	0.00	0	0	0.008	(-0.036, 0.040)
0.50 (B)	212	259	0.25 (G)	36	60	0.00	0	0	0.007	(-0.042, 0.036)
0.00	0	0	0.50 (F)	72	120	0.50	28	138	0.006	(-0.040, 0.038)
0.00	0	0	0.70 (E)	101	168	0.00	0	0	0.006	(-0.043, 0.038)
0.50 (C)	212	259	0.25	36	60	0.25	14	69	0.005	(-0.040, 0.037)
1.00 (A)	424	519	0.00	0	0	0.00	0	0	0.005	(-0.042, 0.036)
0.00	0	0	0.85	123	204	0.00	0	0	0.001	(-0.042, 0.034)
0.70 (B)	297	363	0.25	36	60	0.00	0	0	0.000	(-0.045, 0.032)
0.25 (D)	106	130	0.50 (F)	72	120	0.00	0	0	0.000	(-0.046, 0.032)

* = tonnes live wt.

† = '000 hooks yr⁻¹

†† = '000 km gillnet hours yr⁻¹

To achieve positive rates of intrinsic population growth, major reductions in fishing mortality were deemed necessary in both the TDGDLF and in the WANCSF, unless either fishery was closed (Table 8, Appendix I). The only option for maintaining the WANCSF at between 85 and 100% of its 2003/04 level of exploitation, that would deliver a positive rate of population growth, was the total closure of the TDGDLF. By reducing fishing mortality in the WANCSF to 70% of its 2003/04 level, the model indicated that a minimal amount of fishing could occur in the TDGDLF (equating to less than 25% of the 2003/04 gillnet only fishing mortality). As reported catches of *C. plumbeus* in the WANCSF during the first half of 2004/05 indicate that exploitation in that fishery is continuing to increase, the effects of doubling WANCSF fishing mortality were also tested in the model (Scenario 57). Assuming the 2003/04 level of exploitation continues in the TDGDLF and PFTF, the median estimate of the rate of intrinsic population growth under this level of mortality was -0.079 (-7.9%) per year.

All options for maintaining the 2003/04 level of TDGDLF fishing mortality, including closure of the WANCSF, resulted in negative population growth rates (Appendix I). To ensure a sustainable catch by the temperate fishery, fishing mortality in the WANCSF would need to be zero and the combined temperate gillnet and longline fishing mortality be reduced to between 50% and 70% of its 2003/04 level. When all WANCSF and temperate longline mortality was removed, 85% of the 2003/04 gillnet-only mortality rate resulted in a very marginal intrinsic population growth rate ($r=0.001$), while a reduction to 70% resulted in an intrinsic population growth rate of 0.006 per year.

4. Conclusions

The results from this study suggest that the Western Australian population of *Carcharhinus plumbeus* is more susceptible to population decline than was indicated by previous demographic analyses of this species in the western North Atlantic (Sminkey and Musick, 1996; Brewster-Geisz and Miller, 2000). The best estimate of the rate at which the WA population could grow when unfished was 2.5% yr⁻¹ (95% confidence interval = -1.8 and 5.5% yr⁻¹). This rate is far lower than that of nearly 12% yr⁻¹, estimated by Sminkey and Musick (1996) and 7% yr⁻¹, by Brewster-Geisz and Miller, (2000). However, this rate is very similar to the rates of 1.3% and 2.9% yr⁻¹, that were estimated by Cortés (1999, 2002) for the western North Atlantic stock, using different sets of biological parameters. These results rank the WA *C. plumbeus* population's intrinsic population growth rate as amongst the lowest of all shark species, for which demographic analyses have been undertaken. This rate also makes this stock of *C. plumbeus* more susceptible to fishing than the closely related and co-occurring dusky shark, *Carcharhinus obscurus*, stock, which was estimated to have an intrinsic capacity for growth of 4.3% yr⁻¹ (Simpfendorfer, 1999) under zero fishing mortality. Not only do the results of this analysis highlight the inherent susceptibility of this stock to fishing but also, with a population doubling time of 23.1 years under zero fishing mortality, they indicate a lengthy recovery period for the stock should it be reduced to low levels.

By incorporating the best estimates (multi-year age class rates) of fishing mortality into the demographic model, the *C. plumbeus* stock's capacity for growth was estimated to have been between -0.9% yr⁻¹ (2002/03) and -4.9% yr⁻¹ (2003/04) during the three years for which tagging data were available. These results are far more pessimistic than those previously obtained from demographic analysis of the dusky shark, another primary target species of the TDGDLF (Simpfendorfer, 1999). This previous study found that, although the highest age-specific exploitation rates estimated for *C. obscurus* in 1994 and

1995 were similar to the maximum rates determined here for *C. plumbeus*, dusky shark catches by the TDGDLF were comfortably sustainable. However, the previous study also concluded that the selectivity of the mesh-sizes permitted in the temperate gillnet fishery, restricted catches of dusky sharks to a very limited number of age classes (0+ to 6+ years). In clear contrast to this, the same mesh sizes are far less size-selective for *C. plumbeus*². The *C. plumbeus* catch in the TDGDLF is primarily comprised of juveniles and young adults between the ages of 3+ and 14+ years. In addition, the targeted fishing of mainly adult sandbar sharks between the ages of 14+ and 20+ years in the WANCSF (which only has a relatively small bycatch of *C. obscurus*) means that the sandbar shark stock is currently being exploited across almost all age-classes. The negative rates of population growth capacity determined in this study, confirm the conclusions of several authors, that stocks of sharks with highly conservative life-history characteristics, such as these, can only be sustainably harvested when fishing mortality is restricted to a small number of age-classes (eg. Sminkey and Musick, 1996; Stevens et al, 1997; Walker, 1998, Simpfendorfer, 1999).

The negative increase in r during 2003/04, corresponds to a dramatic increase in fishing effort in the area of the WANCSF west of 120°E (i.e. the area of the fishery in which *C. plumbeus* occurs) and increased catches by longlines in the northern region of the WCDGDLF. Based on preliminary catch data from the two target fisheries from the first half of 2004/05, fishing mortality was predicted to double, resulting in a projected intrinsic population growth rate of $-7.9\% \text{ yr}^{-1}$. Given similar levels of catch from the two target fisheries during 1999/00 and 2000/01, it is likely that the stock also had a negative r for at least two years prior to 2001/02. In 2004/05 the stock is thus estimated to be in its sixth year of having a negative capacity for growth. Fishing mortality of the sandbar stock must therefore be reduced in an effort to ensure that the stock's capacity for growth becomes positive, or at the least, becomes neutral so as to minimise any ongoing depletion.

However, as both of the target fisheries contribute to the exploitation of the stock, appropriate levels of exploitation in the WANCSF could not be determined independently of exploitation by the TDGDLF (mainly in the WCDGDLF) and *vice versa*. The demographic model indicated that to reverse the current decline in this stock, major reductions in fishing mortality are necessary in both the WANCSF and in the TDGDLF, unless the fishing mortality in one or other fishery is reduced to zero (Table 8).

5. Acknowledgements

The northern shark industry is acknowledged for assisting with the collection of data used in this report. This assistance was provided for shark researchers over the course of several years and was crucial to developing the stock assessment. Likewise, the support of the Fisheries Research and Development Corporation (Canberra) for funding the collection of biological data and the development of the demographic model for sandbar shark is much appreciated.

The demographic model was developed with input from Dr Colin Simpfendorfer (Mote Marine Laboratory, Florida), who previously undertook such modelling for dusky shark in Western Australia. The detailed review of the stock assessment undertaken by Associate Professor Norm Hall (Centre for Fish and Fisheries, Murdoch University) greatly improved this report.

Various staff at the Department of Fisheries are thanked for discussions and suggestions which have also improved this report.

6. References

- Brewster-Geisz, K. K., and T. J. Miller. 2000. Management of the sandbar shark, *Carcharhinus plumbeus*: implications of a stage-based model. *Fishery Bulletin* 98: 236-249.
- Belle van, G. (2004) Statistical rules of thumb. <http://www.seattlecrc.org/vbelle>
- Cailliet, G. M. 1992. Demography of the central Californian population of the leopard shark (*Triakis semifasciata*). *Australian Journal of Marine and Freshwater Research* 43: 183-193.
- Chen, S., and S. Watanabe. 1989. Age dependence of natural mortality coefficient in fish populations dynamics. *Nippon Suisan Gakkaishi* 55: 205-208.
- Cliff, G., Dudley, S. F. J. and Davis, B. 1988. Sharks Caught in the Protective Gill Nets off Natal, South Africa. 1. The Sandbar Shark, *Carcharhinus plumbeus* (Nardo). *S. Afr. J. Mar. Sci.* 7: 255-265.
- Cortés, E. 1995. Demographic analysis of the Atlantic sharpnose shark, *Rhizoprionodon terraenovae*, in the Gulf of Mexico. *Fishery Bulletin* 93: 57-66.
- Cortés, E. 1999. A stochastic stage-based population model of the sandbar shark in the Western North Atlantic. p. 115-136. *In*, Life in the slow lane. Ecology and conservation of long-lived marine animals. J. A. Musick (ed.). American Fisheries Society Symposium 23, Bethesda, Maryland.
- Cortés, E. 2002. Incorporating uncertainty into demographic modeling: application to shark populations and their conservation. *Conservation Biology* 16: 1048-1062.
- Cortés, E., And G. R. Parsons. 1996. Comparative demography of two populations of the bonnethead shark (*Sphyrna tiburo*). *Canadian Journal of Fisheries and Aquatic Sciences* 53: 709-718.
- Hoenig, J. M. 1983. Empirical use of longevity data to estimate mortality rates. *Fishery Bulletin* 82: 898-903.
- Hoenig, J. M., And S. H. Gruber. 1990. Life history patterns in the elasmobranchs: implications for fisheries management. p. 1 – 16. *In*, Elasmobranchs as living resources: advances in the biology, ecology, systematics, and the status of fisheries. H. L. Pratt Jr, S. H. Gruber, and T. Taniuchi (eds.). NOAA Technical Report NMFS 90.
- Jensen, A. L. 1996. Beverton and holt life history invariants result from optimal trade-off of reproduction and survival. *Canadian Journal of Fisheries and Aquatic Sciences* 53: 820-822.
- Joung, S. J. and Chen, C. T. 1995. Reproduction in the Sandbar Shark, *Carcharhinus plumbeus*, in the Waters off Northeastern Taiwan. *Copeia*, 1995 (3): 659-665.

- Krebs, C. J. 1985. Ecology: the experimental analysis of distribution and abundance, 3rd ed. Harper and row, New York.
- Lotka, A. J. 1959. Principles of mathematical biology (Reprinted edition). Dover, New York.
- Mollet, H. F., And G. M. Cailliet. 2002. Comparative population demography of elasmobranches using life history tables, Leslie matrices and stage-based matrix models. *Marine and Freshwater Research* 53: 503-516.
- Pauly, D. 1980. On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks. *J. Cons. Int. Explor. Mer.* 39: 175-192.
- Peterson, I., And J. S. Wroblewski. 1984. Mortality rate of fishes in the pelagic ecosystem. *Canadian Journal of Fisheries and Aquatic Sciences* 41: 1117-1120.
- Quinn, T. J. II and Deriso, R. B. 1999. *Quantitative Fish Dynamics*. Oxford University Press, New York. 542pp.
- Ricker, W. E. 1975. Computation and Interpretation of Biological Statistics of Fish Populations. *Bull. Fish. Res. Board Can.* 191: 1-382
- Simpfendorfer, C. A. 1999a. Mortality estimates and demographic analysis for the Australian sharpnose shark, *Rhizoprionodon taylori*, from northern Australia. *Fishery Bulletin* 97: 978-986.
- Simpfendorfer, C. A. 1999b. Demographic analysis of the dusky shark fishery in southwestern Australia. P. 149-160. *In*, Life in the slow lane. Ecology and conservation of long-lived marine animals. J. A. Musick (ed.). American Fisheries Society Symposium 23, Bethesda, Maryland.
- Simpfendorfer, C. A. 2004. Demographic models: life tables, matrix models and rebound potential. *In*, Elasmobranch fisheries management techniques. Musick, J. A. and Bonfil, R. (eds.), pp. 187-203. APEC Secretariat, Singapore.
- Smith, S. E., D. W. Au, And C. Snow. 1998. Intrinsic rebound potential of 26 species of Pacific sharks. *Marine and Freshwater Research* 48:663-678.
- Springer, S. 1960. Natural history of the sandbar shark, *Eulamia milberti*. U.S. Fish Wildl Serv. Fish. Bull. 61: 1-38
- Stevens, J. D, Walker, T. I and Simpfendorfer, C. A. 1997. Are southern Australian shark fisheries sustainable? *In*, Hancock, D. A. , Smith, D. C., Grant, A. and Beumer, J. P. (Eds.) "Developing and Sustaining World Fisheries Resources. The State of Science and Management. 2nd World Fisheries Congress" pp 62-66. CSIRO, Melbourne.
- Walker, T.I., 1998. Can shark resources be harvested sustainably? A question revisited with a review of shark fisheries. *Marine Freshwater Res.* 49: 553-572.

Appendix I.

Population growth rates (r) in the WA *Carcharhinus plumbeus* stock, resulting from demographic analysis of 65 hypothetical rates of fishing mortality ($\hat{F}_{2003/04}$).

Proportion of $\hat{F}_{2003/04}$					Equivalent catch (tonnes live weight)					Equivalent Effort						Median r (lower 95% CI, upper 95% CI)
WANCSF	Temp GN	Temp LL	PFT	Others	WANCSF*	Temp GN**	Temp LL**	PFT***	Others***	WANCSF [†]	Western WANCSF ^{††}	Temp GN ^{†††}	Temp LL [†]	PFT ^{††††}	Others	
0.25	0.00	0.00	1.00	0.00	106	0	0	12	0	130	105	0	0	663	n/a	0.024 (-0.021, 0.055)
0.00	0.25	0.25	1.00	0.00	0	36	14	12	0	0	0	60	69	663	n/a	0.018 (-0.03, 0.049)
0.50	0.00	0.00	1.00	0.00	212	0	0	12	0	259	210	0	0	663	n/a	0.017 (-0.028, 0.049)
0.00	0.50	0.00	1.00	0.00	0	72	0	12	0	0	0	120	0	663	n/a	0.014 (-0.031, 0.044)
0.25	0.25	0.00	1.00	0.00	106	36	0	12	0	130	105	60	0	663	n/a	0.012 (-0.032, 0.043)
0.25	0.25	0.25	1.00	0.00	106	36	14	12	0	130	105	60	69	663	n/a	0.012 (-0.033, 0.043)
0.70	0.00	0.00	1.00	0.00	297	0	0	12	0	363	294	0	0	663	n/a	0.011 (-0.033, 0.043)
0.85	0.00	0.00	1.00	0.00	360	0	0	12	0	441	357	0	0	663	n/a	0.008 (-0.036, 0.04)
0.50	0.25	0.00	1.00	0.00	212	36	0	12	0	259	210	60	0	663	n/a	0.007 (-0.042, 0.036)
0.00	0.50	0.50	1.00	0.00	0	72	28	12	0	0	0	120	138	663	n/a	0.006 (-0.04, 0.038)
0.00	0.70	0.00	1.00	0.00	0	101	0	12	0	0	0	168	0	663	n/a	0.006 (-0.043, 0.038)
0.50	0.25	0.25	1.00	0.00	212	36	14	12	0	259	210	60	69	663	n/a	0.005 (-0.04, 0.037)
1.00	0.00	0.00	1.00	0.00	424	0	0	12	0	519	420	0	0	663	n/a	0.005 (-0.042, 0.036)
0.00	0.85	0.00	1.00	0.00	0	123	0	12	0	0	0	204	0	663	n/a	0.001 (-0.042, 0.034)
0.70	0.25	0.00	1.00	0.00	297	36	0	12	0	363	294	60	0	663	n/a	0.000 (-0.045, 0.032)
0.25	0.50	0.00	1.00	0.00	106	72	0	12	0	130	105	120	0	663	n/a	0.000 (-0.046, 0.032)
0.70	0.25	0.25	1.00	0.00	297	36	14	12	0	363	294	60	69	663	n/a	-0.001 (-0.046, 0.032)
0.25	0.50	0.50	1.00	0.00	106	72	28	12	0	130	105	120	138	663	n/a	-0.002 (-0.049, 0.032)
0.00	0.70	0.70	1.00	0.00	0	101	39	12	0	0	0	168	193	663	n/a	-0.003 (-0.045, 0.027)
0.85	0.25	0.00	1.00	0.00	360	36	0	12	0	441	357	60	0	663	n/a	-0.003 (-0.052, 0.028)
0.00	1.00	0.00	1.00	0.00	0	144	0	12	0	0	0	240	0	663	n/a	-0.004 (-0.05, 0.025)
0.85	0.25	0.25	1.00	0.00	360	36	14	12	0	441	357	60	69	663	n/a	-0.004 (-0.05, 0.027)
0.00	1.00	0.00	1.00	0.00	0	144	0	12	0	0	0	240	0	663	n/a	-0.005 (-0.049, 0.025)
0.50	0.50	0.00	1.00	0.00	212	72	0	12	0	259	210	120	0	663	n/a	-0.005 (-0.053, 0.025)
0.50	0.50	0.50	1.00	0.00	212	72	28	12	0	259	210	120	138	663	n/a	-0.007 (-0.052, 0.021)
1.00	0.25	0.00	1.00	0.00	424	36	0	12	0	519	420	60	0	663	n/a	-0.008 (-0.056, 0.024)
1.00	0.25	0.25	1.00	0.00	424	36	14	12	0	519	420	60	69	663	n/a	-0.008 (-0.053, 0.021)
0.25	0.70	0.70	1.00	0.00	106	101	39	12	0	130	105	168	193	663	n/a	-0.009 (-0.056, 0.022)
0.25	0.70	0.00	1.00	0.00	106	101	0	12	0	130	105	168	0	663	n/a	-0.01 (-0.053, 0.022)
0.00	0.85	0.85	1.00	0.00	0	123	48	12	0	0	0	204	235	663	n/a	-0.011 (-0.054, 0.02)
0.25	1.00	0.00	1.00	0.00	106	144	0	12	0	130	105	240	0	663	n/a	-0.012 (-0.06, 0.02)

0.70	0.50	0.50	1.00	0.00	297	72	28	12	0	363	294	120	138	663	n/a	-0.013 (-0.053, 0.018)
0.70	0.50	0.00	1.00	0.00	297	72	0	12	0	363	294	120	0	663	n/a	-0.013 (-0.059, 0.02)
0.85	0.50	0.00	1.00	0.00	360	72	0	12	0	441	357	120	0	663	n/a	-0.016 (-0.061, 0.013)
0.85	0.50	0.50	1.00	0.00	360	72	28	12	0	441	357	120	138	663	n/a	-0.017 (-0.062, 0.013)
0.50	0.70	0.70	1.00	0.00	212	101	39	12	0	259	210	168	193	663	n/a	-0.017 (-0.061, 0.016)
0.50	1.00	0.00	1.00	0.00	212	144	0	12	0	259	210	240	0	663	n/a	-0.017 (-0.066, 0.011)
0.50	0.70	0.00	1.00	0.00	212	101	0	12	0	259	210	168	0	663	n/a	-0.018 (-0.068, 0.014)
0.25	0.85	0.85	1.00	0.00	106	123	48	12	0	130	105	204	235	663	n/a	-0.018 (-0.066, 0.01)
0.25	0.85	0.00	1.00	0.00	106	123	0	12	0	130	105	204	0	663	n/a	-0.019 (-0.064, 0.012)
0.00	1.00	1.00	1.00	0.00	0	144	56	12	0	0	0	240	276	663	n/a	-0.02 (-0.062, 0.012)
1.00	0.50	0.00	1.00	0.00	424	72	0	12	0	519	420	120	0	663	n/a	-0.02 (-0.065, 0.012)
1.00	0.50	0.50	1.00	0.00	424	72	28	12	0	519	420	120	138	663	n/a	-0.021 (-0.07, 0.011)
0.70	0.70	0.00	1.00	0.00	297	101	0	12	0	363	294	168	0	663	n/a	-0.023 (-0.07, 0.008)
0.70	0.70	0.70	1.00	0.00	297	101	39	12	0	363	294	168	193	663	n/a	-0.023 (-0.066, 0.01)
0.70	1.00	0.00	1.00	0.00	297	144	0	12	0	363	294	240	0	663	n/a	-0.023 (-0.069, 0.01)
0.50	0.85	0.85	1.00	0.00	212	123	48	12	0	259	210	204	235	663	n/a	-0.025 (-0.071, 0.006)
0.50	0.85	0.00	1.00	0.00	212	123	0	12	0	259	210	204	0	663	n/a	-0.026 (-0.072, 0.007)
0.25	1.00	1.00	1.00	0.00	106	144	56	12	0	130	105	240	276	663	n/a	-0.026 (-0.066, 0.003)
0.85	0.70	0.00	1.00	0.00	360	101	0	12	0	441	357	168	0	663	n/a	-0.027 (-0.071, 0.004)
0.85	0.70	0.70	1.00	0.00	360	101	39	12	0	441	357	168	193	663	n/a	-0.028 (-0.072, 0.003)
0.85	1.00	0.00	1.00	0.00	360	144	0	12	0	441	357	240	0	663	n/a	-0.028 (-0.075, 0.001)
0.70	0.85	0.00	1.00	0.00	297	123	0	12	0	363	294	204	0	663	n/a	-0.03 (-0.074, 0.001)
1.00	0.70	0.00	1.00	0.00	424	101	0	12	0	519	420	168	0	663	n/a	-0.031 (-0.079, -0.001)
0.70	0.85	0.85	1.00	0.00	297	123	48	12	0	363	294	204	235	663	n/a	-0.031 (-0.071, -0.002)
1.00	0.70	0.70	1.00	0.00	424	101	39	12	0	519	420	168	193	663	n/a	-0.032 (-0.076, -0.001)
0.50	1.00	1.00	1.00	0.00	212	144	56	12	0	259	210	240	276	663	n/a	-0.033 (-0.077, -0.003)
1.00	1.00	0.00	1.00	0.00	424	144	0	12	0	519	420	240	0	663	n/a	-0.034 (-0.077, -0.002)
0.85	0.85	0.85	1.00	0.00	360	123	48	12	0	441	357	204	235	663	n/a	-0.035 (-0.078, -0.005)
0.85	0.85	0.00	1.00	0.00	360	123	0	12	0	441	357	204	0	663	n/a	-0.036 (-0.084, -0.004)
0.70	1.00	1.00	1.00	0.00	297	144	56	12	0	363	294	240	276	663	n/a	-0.038 (-0.084, -0.008)
1.00	0.85	0.85	1.00	0.00	424	123	48	12	0	519	420	204	235	663	n/a	-0.039 (-0.082, -0.008)
1.00	0.85	0.00	1.00	0.00	424	123	0	12	0	519	420	204	0	663	n/a	-0.04 (-0.082, -0.009)
0.85	1.00	1.00	1.00	0.00	360	144	56	12	0	441	357	240	276	663	n/a	-0.044 (-0.088, -0.014)
2.00	1.00	1.00	1.00	0.00	848	144	56	12	0	1038	839	240	276	663	n/a	-0.079 (-0.124, -0.05)

* Reported catch; **Validated catch; ***Estimated catch

†Total reported effort (‘000 hooks); ††Reported effort (‘000 hooks) between North West Cape (longitude 114°E) and Cape Leveque (longitude 120°E);

†††Validated effort (‘000 km gillnet hr); ††††Days

* CI = confidence intervals, (lower, upper)

Appendix II.

Table i. Results of demographic analysis of the Western Australian *Carcharhinus plumbeus* population under zero fishing mortality. PM = proportion of the population reaching maturity; R_0 = reproductive rate per generation; G = generation time; t_{x2} = population doubling time and r = intrinsic rate of population increase.

M	PM		R_0		G		t_{x2}		r	
	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
Pauly (1980)	0.16	(0.12, 0.21)	2.1	(0.8, 4.2)	22.5	(21.6, 24.0)	20.0	(-138.3, 194.0)	0.030	(-0.018, 0.063)
Hoening (1983), i	0.13	(0.09, 0.17)	1.6	(0.6, 3.7)	22.2	(21.4, 24.0)	24.3	(-310.0, 351.7)	0.017	(-0.028, 0.054)
Hoening (1983), ii	0.14	(0.11, 0.18)	1.8	(0.6, 3.9)	22.3	(21.5, 23.9)	22.2	(-307.2, 196.4)	0.023	(-0.027, 0.057)
Hoening (1983), iii	0.11	(0.08, 0.15)	1.3	(0.5, 2.7)	22.0	(21.2, 23.8)	24.9	(-362.2, 473.6)	0.007	(-0.040, 0.041)
Jensen (1996), i	0.21	(0.19, 0.21)	3.0	(1.1, 5.7)	22.8	(21.9, 24.3)	14.6	(-6.0, 70.5)	0.046	(-0.002, 0.077)
Jensen (1996), ii	0.38	(0.32, 0.45)	7.6	(2.7, 15.7)	23.5	(22.5, 25.5)	8.1	(5.9, 18.3)	0.086	(0.036, 0.117)
Jensen (1996), iii	0.36	(0.30, 0.42)	6.6	(2.2, 14.0)	23.5	(22.4, 25.3)	8.7	(6.0, 21.3)	0.079	(0.029, 0.114)
Petersen & Wroblewski (1984)	0.12	(0.11, 0.12)	1.9	(0.7, 3.6)	23.0	(22.1, 24.8)	24.8	(-166.0, 338.9)	0.023	(-0.019, 0.053)
Chen & Watanabe (1989)	0.17	(0.15, 0.19)	3.3	(1.3, 6.6)	23.6	(22.5, 25.5)	14.7	(8.0, 63.8)	0.046	(0.004, 0.077)
Stochastic M	0.13	(0.12, 0.13)	2.0	(0.8, 3.6)	22.7	(21.9, 24.2)	23.1	(-263.5, 193.0)	0.025	(-0.018, 0.055)

Table ii. Results of demographic analysis of the Western Australian *Carcharhinus plumbeus* population using **age specific** estimates of 2001/02 fishing mortality ($F_{2001/02}$). Definitions of demographic parameter symbols are given in Table i.

M	PM		R_0		G		t_{x2}		r	
	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
Pauly (1980)	0.03	(0.02, 0.04)	0.4	(0.1, 0.8)	22.4	(21.5, 23.9)	-14.3	(-49.6, -7.3)	-0.049	(-0.095, -0.014)
Hoening (1983), i	0.02	(0.02, 0.03)	0.3	(0.1, 0.7)	22.1	(21.3, 24.0)	-10.6	(-25.3, -6.3)	-0.065	(-0.110, -0.027)
Hoening (1983), ii	0.03	(0.02, 0.04)	0.3	(0.1, 0.7)	22.2	(21.4, 23.9)	-12.1	(-28.1, -6.9)	-0.057	(-0.101, -0.025)
Hoening (1983), iii	0.02	(0.01, 0.03)	0.2	(0.1, 0.5)	22.0	(21.2, 23.6)	-9.4	(-17.8, -5.8)	-0.074	(-0.119, -0.039)
Jensen (1996), i	0.04	(0.04, 0.04)	0.6	(0.2, 1.0)	22.7	(21.9, 24.5)	-21.4	(-106.4, -7.9)	-0.032	(-0.077, -0.003)
Jensen (1996), ii	0.08	(0.06, 0.09)	1.4	(0.5, 2.8)	23.5	(22.4, 25.5)	28.8	(-424.7, 417.9)	0.008	(-0.044, 0.039)
Jensen (1996), iii	0.07	(0.06, 0.09)	1.2	(0.4, 2.5)	23.4	(22.3, 25.3)	22.4	(-535.8, 498.0)	0.002	(-0.043, 0.034)
Petersen & Wroblewski (1984)	0.02	(0.02, 0.02)	0.3	(0.1, 0.6)	22.9	(22.1, 24.6)	-12.5	(-23.9, -7.2)	-0.056	(-0.096, -0.029)
Chen & Watanabe (1989)	0.03	(0.03, 0.04)	0.6	(0.2, 1.1)	23.5	(22.4, 25.4)	-22.5	(-138.4, -8.0)	-0.030	(-0.074, -0.002)
Stochastic M	0.03	(0.02, 0.03)	0.4	(0.1, 0.7)	22.7	(21.7, 24.4)	-14.0	(-34.9, -7.5)	-0.049	(-0.092, -0.019)

Table iii. Results of demographic analysis of the Western Australian *Carcharhinus plumbeus* population using **age specific** estimates of 2002/03 fishing mortality ($F_{2002/03}$). Definitions of demographic parameter symbols are given in Table i.

<i>M</i>	<i>PM</i>		<i>R₀</i>		<i>G</i>		<i>t_{x2}</i>		<i>r</i>	
	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
Pauly (1980)	0.04	(0.03, 0.05)	0.3	(0.1, 0.7)	19.9	(19.8, 20.6)	-12.2	(-33.0, -6.3)	-0.057	(-0.109, -0.021)
Hoening (1983), i	0.03	(0.02, 0.04)	0.2	(0.1, 0.5)	19.8	(19.8, 20.5)	-9.5	(-20.0, -5.7)	-0.073	(-0.122, -0.035)
Hoening (1983), ii	0.03	(0.02, 0.04)	0.3	(0.1, 0.6)	19.8	(19.8, 20.6)	-10.6	(-22.8, -5.7)	-0.065	(-0.122, -0.030)
Hoening (1983), iii	0.02	(0.02, 0.03)	0.2	(0.1, 0.4)	19.8	(19.7, 20.5)	-8.1	(-14.9, -5.1)	-0.085	(-0.135, -0.047)
Jensen (1996), i	0.05	(0.04, 0.05)	0.4	(0.2, 0.8)	20.0	(20.0, 20.6)	-16.9	(-71.0, -7.9)	-0.041	(-0.087, -0.009)
Jensen (1996), ii	0.09	(0.08, 0.11)	1.0	(0.3, 1.9)	20.2	(20.1, 20.8)	-12.6	(-445.3, 841.2)	-0.002	(-0.055, 0.031)
Jensen (1996), iii	0.08	(0.07, 0.10)	0.9	(0.4, 1.8)	20.1	(20.0, 20.8)	-20.3	(-494.8, 491.6)	-0.005	(-0.051, 0.028)
Petersen & Wroblewski (1984)	0.03	(0.02, 0.03)	0.2	(0.1, 0.5)	20.0	(20.0, 20.6)	-10.1	(-17.8, -5.9)	-0.069	(-0.118, -0.039)
Chen & Watanabe (1989)	0.04	(0.03, 0.04)	0.4	(0.1, 0.8)	20.1	(20.1, 20.8)	-15.5	(-53.7, -7.1)	-0.045	(-0.093, -0.012)
Stochastic <i>M</i>	0.03	(0.03, 0.04)	0.3	(0.1, 0.6)	20.0	(19.8, 20.6)	-11.7	(-26.5, -6.3)	-0.059	(-0.110, -0.026)

Table iv. Results of demographic analysis of the Western Australian *Carcharhinus plumbeus* population using **age specific** estimates of 2003/04 fishing mortality ($F_{2003/04}$). Definitions of demographic parameter symbols are given in Table i.

<i>M</i>	<i>PM</i>		<i>R₀</i>		<i>G</i>		<i>t_{x2}</i>		<i>r</i>	
	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
Pauly (1980)	0.03	(0.03, 0.05)	0.4	(0.1, 0.8)	22.3	(21.4, 23.9)	-14.9	(-53.2, -7.5)	-0.047	(-0.092, -0.012)
Hoening (1983), i	0.03	(0.02, 0.04)	0.3	(0.1, 0.6)	22.0	(21.1, 23.8)	-10.9	(-24.8, -6.6)	-0.064	(-0.106, -0.028)
Hoening (1983), ii	0.03	(0.02, 0.04)	0.3	(0.1, 0.7)	22.1	(21.2, 23.6)	-12.2	(-31.1, -7.1)	-0.057	(-0.098, -0.022)
Hoening (1983), iii	0.02	(0.01, 0.03)	0.2	(0.1, 0.5)	21.8	(21.0, 23.6)	-9.1	(-18.0, -5.8)	-0.076	(-0.119, -0.038)
Jensen (1996), i	0.05	(0.04, 0.05)	0.6	(0.2, 1.1)	22.5	(21.7, 24.1)	-22.2	(-154.7, 61.3)	-0.029	(-0.073, 0.001)
Jensen (1996), ii	0.10	(0.08, 0.12)	1.6	(0.6, 3.3)	23.4	(22.2, 25.4)	28.7	(-301.2, 320.2)	0.015	(-0.028, 0.044)
Jensen (1996), iii	0.09	(0.07, 0.11)	1.4	(0.6, 3.0)	23.3	(22.2, 25.2)	26.4	(-520.1, 509.4)	0.010	(-0.034, 0.044)
Petersen & Wroblewski (1984)	0.03	(0.02, 0.03)	0.3	(0.1, 0.6)	22.8	(21.9, 24.4)	-12.3	(-24.1, -7.1)	-0.057	(-0.098, -0.029)
Chen & Watanabe (1989)	0.04	(0.03, 0.04)	0.6	(0.2, 1.2)	23.4	(22.3, 25.4)	-23.4	(-165.5, -6.4)	-0.028	(-0.073, -0.001)
Stochastic <i>M</i>	0.03	(0.02, 0.04)	0.4	(0.2, 0.8)	22.5	(21.6, 24.0)	-14.6	(-40.6, -7.8)	-0.048	(-0.089, -0.017)

Table v. Results of demographic analysis of the Western Australian *Carcharhinus plumbeus* population using **adjusted age-class** estimates of 2001/02 fishing mortality ($\hat{F}_{2001/02}$). Definitions of demographic parameter symbols are given in Table i.

<i>M</i>	<i>PM</i>		<i>R₀</i>		<i>G</i>		<i>t_{x2}</i>		<i>r</i>	
	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
Pauly (1980)	0.04	(0.03, 0.06)	0.6	(0.2, 1.2)	22.4	(21.5, 23.8)	-21.0	(-145.1, 81.0)	-0.031	(-0.079, 0.002)
Hoening (1983), i	0.03	(0.02, 0.05)	0.4	(0.1, 1.0)	22.2	(21.4, 23.8)	-15.4	(-65.7, -6.9)	-0.045	(-0.096, -0.009)
Hoening (1983), ii	0.04	(0.03, 0.05)	0.4	(0.2, 1.0)	22.5	(21.5, 23.9)	-16.8	(-78.7, -8.0)	-0.041	(-0.082, -0.008)
Hoening (1983), iii	0.03	(0.02, 0.04)	0.3	(0.1, 0.7)	22.0	(21.2, 23.6)	-12.4	(-35.3, -6.8)	-0.056	(-0.101, -0.020)
Jensen (1996), i	0.06	(0.05, 0.06)	0.8	(0.3, 1.5)	22.7	(21.9, 24.5)	-30.5	(-525.2, 580.6)	-0.014	(-0.056, 0.012)
Jensen (1996), ii	0.11	(0.09, 0.13)	2.0	(0.7, 4.0)	23.5	(22.4, 25.6)	23.1	(-159.2, 312.8)	0.024	(-0.023, 0.055)
Jensen (1996), iii	0.10	(0.08, 0.12)	1.7	(0.7, 3.6)	23.5	(22.4, 25.3)	26.2	(-376.0, 332.2)	0.018	(-0.024, 0.051)
Petersen & Wroblewski (1984)	0.03	(0.03, 0.03)	0.5	(0.2, 0.9)	23.0	(22.1, 24.6)	-17.3	(-55.8, -8.3)	-0.040	(-0.082, -0.012)
Chen & Watanabe (1989)	0.05	(0.04, 0.05)	0.9	(0.3, 1.7)	23.6	(22.5, 25.5)	-29.5	(-450.1, 465.1)	-0.014	(-0.057, 0.015)
Stochastic <i>M</i>	0.04	(0.03, 0.05)	0.6	(0.2, 1.1)	22.8	(21.8, 24.2)	-21.1	(-158.4, -6.4)	-0.032	(-0.075, -0.001)

Table vi. Results of demographic analysis of the Western Australian *Carcharhinus plumbeus* population using **adjusted age-class** estimates of 2002/03 fishing mortality ($\hat{F}_{2002/03}$). Definitions of demographic parameter symbols are given in Table i.

<i>M</i>	<i>PM</i>		<i>R₀</i>		<i>G</i>		<i>t_{x2}</i>		<i>r</i>	
	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
Pauly (1980)	0.07	(0.06, 0.10)	0.9	(0.3, 1.9)	22.3	(21.4, 23.8)	-24.5	(-382.6, 661.7)	-0.009	(-0.056, 0.025)
Hoening (1983), i	0.06	(0.04, 0.08)	0.7	(0.2, 1.6)	22.0	(21.2, 23.6)	-23.9	(-410.4, 365.0)	-0.022	(-0.068, 0.015)
Hoening (1983), ii	0.06	(0.05, 0.08)	0.8	(0.3, 1.6)	22.1	(21.3, 23.6)	-27.0	(-397.1, 366.5)	-0.017	(-0.061, 0.017)
Hoening (1983), iii	0.05	(0.03, 0.07)	0.5	(0.2, 1.2)	21.8	(21.1, 23.3)	-19.0	(-145.4, 85.9)	-0.034	(-0.086, 0.004)
Jensen (1996), i	0.10	(0.09, 0.10)	1.3	(0.5, 2.6)	22.5	(21.8, 24.0)	29.0	(-532.4, 548.4)	0.007	(-0.040, 0.038)
Jensen (1996), ii	0.18	(0.15, 0.22)	3.1	(1.1, 6.2)	23.4	(22.3, 25.3)	14.7	(-28.8, 69.6)	0.046	(0.000, 0.075)
Jensen (1996), iii	0.17	(0.14, 0.21)	2.9	(0.9, 6.0)	23.3	(22.2, 25.1)	15.5	(-54.8, 97.0)	0.042	(-0.009, 0.076)
Petersen & Wroblewski (1984)	0.06	(0.05, 0.06)	0.8	(0.3, 1.4)	22.8	(21.9, 24.3)	-30.1	(-509.0, 340.5)	-0.017	(-0.059, 0.011)
Chen & Watanabe (1989)	0.08	(0.07, 0.09)	1.4	(0.5, 2.8)	23.4	(22.3, 25.4)	27.2	(-349.4, 427.5)	0.008	(-0.034, 0.038)
Stochastic <i>M</i>	0.07	(0.05, 0.08)	0.9	(0.3, 1.8)	22.6	(21.6, 24.1)	-25.1	(-460.5, 609.1)	-0.009	(-0.054, 0.022)

Table vii. Results of demographic analysis of the Western Australian *Carcharhinus plumbeus* population using **adjusted age-class** estimates of 2003/04 fishing mortality ($\hat{F}_{2003/04}$). Definitions of demographic parameter symbols are given in Table i.

<i>M</i>	<i>PM</i>		<i>R₀</i>		<i>G</i>		<i>t_{x2}</i>		<i>r</i>	
	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
Pauly (1980)	0.04	(0.03, 0.05)	0.4	(0.1, 0.9)	21.9	(21.1, 23.3)	-14.5	(-61.5, -7.2)	-0.047	(-0.092, -0.010)
Hoening (1983), i	0.03	(0.02, 0.04)	0.3	(0.1, 0.6)	21.6	(20.9, 23.2)	-10.7	(-24.9, -6.1)	-0.065	(-0.114, -0.028)
Hoening (1983), ii	0.03	(0.02, 0.04)	0.3	(0.1, 0.7)	21.8	(21.0, 23.2)	-11.9	(-29.1, -6.6)	-0.058	(-0.105, -0.024)
Hoening (1983), iii	0.02	(0.01, 0.03)	0.2	(0.1, 0.5)	21.6	(20.7, 22.9)	-8.9	(-18.0, -5.5)	-0.078	(-0.127, -0.039)
Jensen (1996), i	0.05	(0.04, 0.05)	0.6	(0.2, 1.1)	22.2	(21.5, 23.6)	-22.5	(-122.9, -6.7)	-0.030	(-0.078, -0.001)
Jensen (1996), ii	0.10	(0.08, 0.12)	1.5	(0.5, 3.1)	23.0	(22.0, 24.7)	26.4	(-382.2, 336.9)	0.013	(-0.034, 0.047)
Jensen (1996), iii	0.09	(0.07, 0.11)	1.3	(0.5, 2.7)	22.9	(21.9, 24.7)	27.9	(-492.2, 508.9)	0.008	(-0.038, 0.041)
Petersen & Wroblewski (1984)	0.03	(0.02, 0.03)	0.3	(0.1, 0.6)	22.4	(21.6, 24.2)	-12.1	(-23.1, -6.8)	-0.057	(-0.101, -0.030)
Chen & Watanabe (1989)	0.04	(0.03, 0.04)	0.6	(0.2, 1.1)	23.0	(22.0, 24.8)	-22.3	(-167.4, -7.0)	-0.030	(-0.074, -0.001)
Stochastic <i>M</i>	0.03	(0.03, 0.04)	0.4	(0.1, 0.8)	22.1	(21.3, 23.5)	-14.2	(-39.6, -7.5)	-0.049	(-0.093, -0.018)