Minimising the cost of future stock monitoring, and assessment of the potential for increased yields, from the oceanic snapper, *Pagrus auratus*, stock off Shark Bay

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Objectives

1 Estimate annual recruitment and fishing mortalities in the snapper fishery throughout the 1980s and 1990s.

2 Assess the risks to the snapper stock of a range of annual commercial and recreational catches, taking into account the mortality of discarded fish and variability in recruitment.

3 Devise a minimal cost method for future monitoring of the snapper fishery.

1.0 Non-technical summary

Outcomes Achieved

The investment in this project has resulted in a substantially more extensive set of age composition data than would have otherwise been possible. This in turn has underpinned stock assessment modeling that has provided the basis for determining that the commercial fishery for snapper in Shark Bay needed a substantial decrease the total allowable catch. The modeling was able to determine that the stock was at a low size following a period of low recruitment during the late 1990s. The suspected low recruitment, evident once the age date were collated, and anticipated negative effects on the stock were both quantitatively described; this mathematical treatment has been a critical input to the series of management meetings for the fishery. The significant outcome for this project was that there was no potential to increase yields in the fishery. The fishery is considered to be sustainable since the reductions in catch were instigated. The effort and catch levels typical of the 1990s were curtailed to allow the stock to recover – this ongoing maintenance of the fishery at a level that will allow the stock to increase in size, rather than implementing a complete closure associated with a more seriously depleted stock of snapper, is directly attributable to the research undertaken in this project. The occurrence of infrequent but drastic recruitment failure, as demonstrated in this project, dictates that ongoing monitoring of age-composition will be required to manage this fishery.

Assessments of the status of the oceanic snapper stock off Shark Bay were completed using catch and fishing effort data from the Shark Bay Snapper Managed Fishery, which takes the bulk of the catch, and data on the length-composition and age-composition of the commercial catch. Adjustments were made to take account of the estimated recreational catch, catch by unlicensed commercial fishers and allowances for the high mortality of fish returned to the water because they could not be legally retained. Two fishery stock-assessment methods using the age-composition of the catch were used, a cohort analysis and a more complex age-structured model. A high level of agreement was found between the results from the two methods. The conclusions are outlined below.

The strength of snapper year-classes entering the fishery (the recruitment) varied widely, particularly in the 1990s. A period of high recruitment in the early 1990s was followed by a period of low recruitment in the late 1990s. Such variations in recruitment occur in many marine species and occasionally can be correlated with environmental factors such as sea temperature in the year of birth.

The numbers and biomass of the reproductively mature snapper fell to the lowest level in the history of the fishery, estimated to be at less than 30% of the virgin biomass from 1998 to 2003. This occurred because quantities of mature fish similar to those taken when the stock was healthy continued to be taken from the stock during years when the replacement by young fish entering the stock was low.

Most fish stocks have some resilience to depletion of the breeding stock. It is assumed for fish like snapper that as long as the mature biomass is higher than 40% of the virgin level, the numbers of young produced will not be significantly less than the numbers produced by a virgin stock. For this reason, the target of management is to maintain mature biomass at or above 40% of the estimated virgin level.

Although catch-per-unit-effort (CPUE) in the managed fishery fell to levels outside the normal range of variability in CPUE in 2002 and 2003, this fall did not reflect the great reduction in the stock. Age-structured stock assessment using data up to 2000, however, was able to show the depletion. The depletion was confirmed when data for the period 2001 to 2003 were included.

Continued collection of age-structure data is considered essential to the monitoring of this snapper stock as catch and effort data cannot signal depletion of the stock to below the target level until that depletion has reached a stage where urgent and drastic management action to rebuild the stock is needed. An improved procedure for monitoring the fishery has been designed and will be trialled in 2004.

A number of management scenarios (catch limits) were evaluated for their impact on the risk of stock size falling below certain levels. A scenario was considered acceptable if the risk of the stock falling below 40% of virgin biomass was less than 0.5 and the risk of falling below 30% of virgin biomass was less than 0.05. Assuming the same degree of variability in recruitment that was seen in the 1980s and 1990s, a catch limit (commercial plus recreational) of 250 tonnes per year from 2005 to 2009 would allow the stock to rebuild to 40% of virgin level in that time (probability 0.5). Thereafter an annual catch limit of 500 tonnes is estimated to have a probability of 0.5 of maintaining the stock at that level.

The previous estimate of the sustainable yield from this stock, based on catch and effort data, was 600 tonnes. The TAC for the managed fishery was around 550 tonnes. These estimates are now considered to be too high, and would have led to unacceptable depletion of the spawning stock at some time, even without the recent low recruitment.

If significant amounts of undersize snapper are caught, the probabilities of achieving the stock level targets are reduced. The annual total catches (commercial and recreational) that have a probability of 0.5 of rebuilding and maintaining the stock at 40% of virgin biomass are 220 tonnes from 2005 to 2009 and 480 tonnes thereafter. With undersized snapper returned to the sea in deep water, post-capture mortality is likely to be in excess of 80%, so the effect on the stock is similar whether or not the fish are retained. It is worthwhile for managers to review the minimum legal length in this light.

The proportion of the catch that is undersize varies, depending largely on whether a strong year-class of young snapper is just approaching minimum legal size. There are indications that a strong recruitment is occurring in 2004, so the problem of catching large numbers of undersize fish is worse than normal. The other aspect of a strong recruitment in 2004, provided it is followed by years of average or strong recruitment, is that rebuilding the stock to the target level is likely to be accelerated.

Research recommendations:

1. That future monitoring include a component of on-board measuring of snapper, representative of the areas and seasons fished. This will allow description of the spatial distribution and abundance of fish of various sizes, possibly enabling spatial protection of small fish. It may also give advance warning of the occurrence of strong and weak year classes.
2. That consideration be given to surveys of abundance of 1-year old juveniles to give even more advance warning of extreme recruitment events.
3. That a representative sample of 500 snapper be sampled annually for age-determination, from at least 25 separate fishing trips, spread throughout the area of the fishery and the seasons in similar proportions as the catch.
4. That the age-structured model be updated annually, at least in the short term until mature biomass is estimated to be 40% or more of the virgin biomass.

Management recommendations:

1. That a catch limit of 220 tonnes per year be implemented for the years 2005 to 2009. This is combined recreational and commercial catch.
2. That the minimum legal size be reviewed to avoid wastage of the catch of undersize snapper which suffer high post-release mortality.
3. That the catch limit be reviewed annually using the risk assessment with the age-structured model to determine whether it can be safely increased.
4. That consideration be given to spatial closures (given spatial separation within the stock by age/size), possibly limited to the peak fishing season, to minimize the catch of snapper smaller than 41 cm.

Key words: pink snapper, recruitment, age-structured model, cohort analysis, risk assessment.

2.0 Acknowledgements

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The snapper industry has been very helpful in providing opportunities for sampling. Too many fishermen have helped to mention them all but particular thanks are due to Rodney and Mark Williamson, and George Greaves. The *Kai* fish factory has accommodated our technical officers on their busy factory floors for many years, formerly under the management of Kay Gellibrand and Ian Foster and recently Simon Little.

3.0 Background

The Shark Bay Managed Fishery exploits the oceanic stock of pink snapper, *Pagrus auratus*, in the waters off Shark Bay WA between 23° 34'S and 26° 30'S. It is the major snapper fishery in WA waters, taking approximately 75% of the State's catch. Management began in 1986, following rapidly escalating catch and effort in the mid 1980s. The annual commercial catch has been fairly stable at 470-570 tonnes for the last decade with a current landed value of $2.6 million. While there has been no stock assessment since 1986, the fishery is described officially as fully exploited but with adequate breeding stocks.

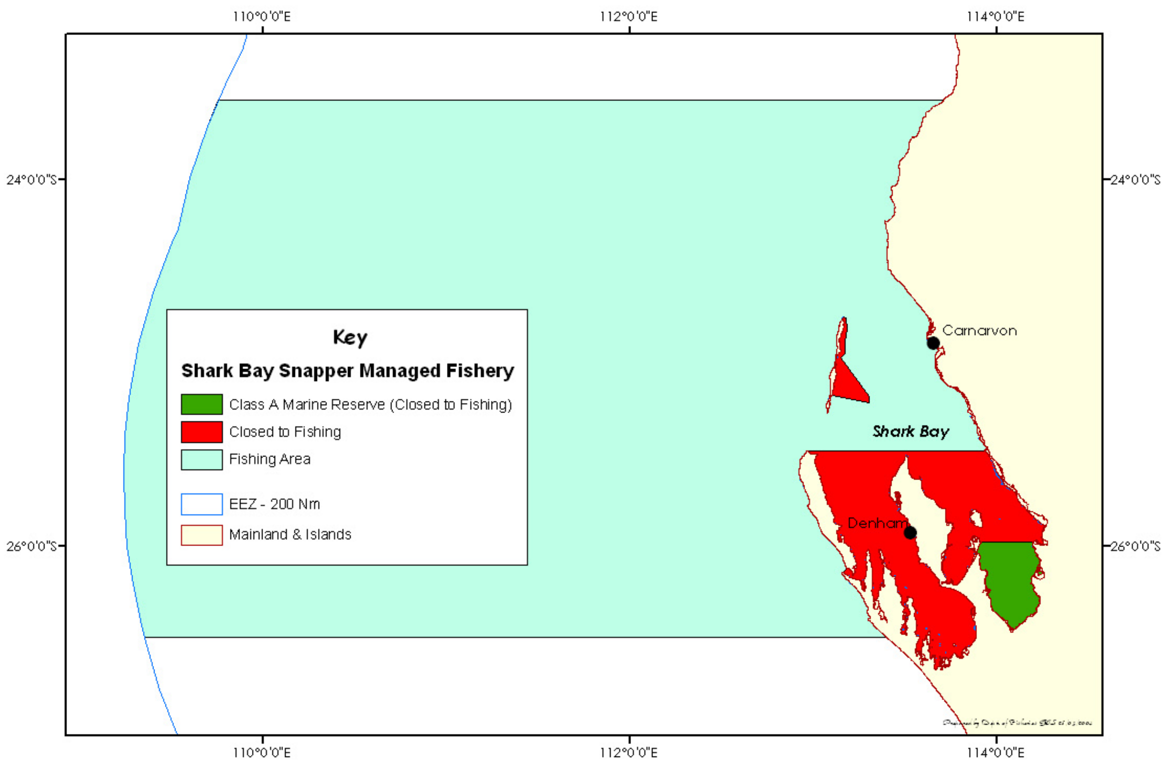

Figure 1. The Shark Bay Snapper Managed Fishery covers the waters of Australian Fishing Zone in the Indian Ocean between 23° 34'S and 26° 30'S.

Although there has been a nominal Total Allowable Commercial Catch (TACC) of 550 tonnes, the fishery was managed until 2001 by a mix of individual quotas and effort controls. From 2001, a new management plan resulted in management wholly by quota, with a TACC of 563.75 tonnes. This TACC is based on research in the early 1980s using the historic catch and effort data. In that analysis, there was not a high degree of confidence in the estimate of Maximum Sustainable Yield (MSY) due to the quality of some of the data. The response by management was to set the TACC conservatively and, while this has been successful in that the fishery has not declined, it was not known in the late 1990s whether substantial yields were being unnecessarily forgone.

The TACC was set without including the recreational catch, which in the early 1980s was in the order of 10 tonnes annually. This is now a cause for concern as the recreational catch from the ocean stock has been increasing in recent years and is likely to continue to do so, particularly as the snapper stocks of inner Shark Bay (genetically separate from the ocean stock) are depleted and the eastern gulf of Shark Bay was closed to snapper fishing from 1998 to 2003. While the department of Fisheries WA is still in the process of establishing regular monitoring of charter boats, it is estimated that the current annual recreational catch from the ocean stock, including charters, is more than 30 tonnes and has the potential to expand significantly under current management arrangements.

It is becoming essential that the recreational catch be taken into account in assessing the status of the stock. It is important for research to advise on the appropriate overall TAC so that management can allocate the resource to the fishing sectors. Although the current recreational catch is low, the rapid rise in recreational fishing effort in the eastern gulf of inner Shark Bay (the peak catch just before the collapse was estimated at 100 tonnes) is a warning that, with today's technology, increased recreational fishing on top of a commercial fishery which is taking close to the sustainable yield, can quickly place fish stocks in danger if management controls are inadequate.

The research in the early 1980s has provided a considerable knowledge of the snapper in this region. Tagging has shown that while a small proportion of snapper tagged off Shark Bay move south of the fishery boundary, the vast majority of recruited snapper remain within the fishery (Moran et al., 2003). The degree of separation between the ocean snapper and the inner bay snapper is even greater, with no evidence of any mixing. This is strongly supported by genetic, morphometric and otolith chemistry evidence (Edmonds et al., 1989; 1999; Johnson et al., 1986; Moran et al., 1998)

Catch rates vary seasonally, peaking in winter when the snapper aggregate inshore over patches of hard bottom for spawning, resulting in five times the summer catch rate. Consequently the majority of the fishing also occurs in winter. The minimum size was increased from 38 to 41 cm in 1987, based on yield and eggs-per recruit models (Moran, 1992). The initial management measures for the fishery in 1986 were effort restrictions which resulted in an approximately threefold increase in catching efficiency.

There has been no investigation of variability of recruitment in this snapper stock. Snapper in the southerly areas of the species distribution do exhibit variable recruitment, linked in New Zealand to water temperature (snapper at the southern end of their range are summer spawners). In an extreme case of variability, the snapper fishery in northern the Spencer Gulf, South Australia, has depended for a decade on one strong year-class.

Monitoring of the Shark Bay fishery since 1982 has included collection of scales or otoliths from several hundred fish each year (except 1997 & 1998) for age determination, with a larger number measured for length-frequency, including snapper returned to the water, and more detailed catch and effort information than was previously available. While this is potentially a very valuable data set that could enable calculation of appropriate TAC levels with greater precision, it requires a focused program of analysis.

An updated stock assessment for the Shark Bay Snapper Fishery would provide managers with information to set separate commercial and recreational TACs, taking account of the mortality of fish released, e.g. undersize snapper. Resources will not be available in the future for detailed annual stock assessments for this fishery so a minimal-cost method for future assessment needed to be developed. If recruitment variability is low, a TACC that does not vary from year to year is a cost effective management option. The greater the recruitment variability, the more the constant TACC needs to be reduced to provide a safety margin for years of poor recruitment.

Although on some of the main fishing grounds undersize fish are rare and discarding is negligible, on other grounds smaller fish are common. If fishers focus on the latter grounds because they have a market for small fish, discarding of undersize fish is common and, since these grounds are in deep water, mortality of discards is likely to be very high. This additional source of mortality must be taken into account in future management of the fishery.

This project incorporates the time series of age-structures since 1982. A cohort analysis enables an estimation of a time-series of fishing mortality rates, year-class strengths and spawning biomass. A model of the fishery was constructed, incorporating release mortality and recruitment variation enabling the potential for increased yields to be assessed in the form of a risk assessment of management options.

4.0 Need

A more precise stock assessment was needed for the Shark Bay Snapper Fishery in view of the wide confidence limits around the previous assessment in the mid 1980s. The increased precision was required because of the increased level of recreational effort on the stock and the implication in the new management plan that the commercial TAC (i.e. TACC) must be reduced to enable recreational catches to be included in an overall TAC. The material (e.g. otolith collection) was available for developing a precise stock assessment but resources were required for working up the data and performing the stock assessment. Thus, this project was developed to utilize the existing collections of otoliths and length- frequency information to provide better data for stock assessment.

Knowledge of the degree of variability in annual recruitment is required to assess the feasibility of a cost effective constant TACC management policy for the future.

Market preferences for fish of particular sizes, and the minimum legal length, can result in significant discarding. The mortality of these discarded fish and effects on the stocks need to be factored into TAC calculations. A minimal cost method needed to be devised for routine future monitoring of the fishery.

5.0 Objectives

1. Estimate annual recruitment and fishing mortalities in the snapper fishery throughout the 1980s and 1990s.

2. Assess the risks to the snapper stock of a range of annual commercial and recreational catches, taking into account the mortality of discarded fish and variability in recruitment.

3. Devise a minimal-cost method for future monitoring of the snapper fishery.

6.0 Methods

6.1 Catch & effort

Catch and fishing effort data have been reported monthly by commercial fishers to the Department of Fisheries in Western Australia since 1952. Initially the data were written onto cards, one card for each licensed fishing boat, but from 1975 the data were stored on computer by the Australian Bureau of Statistics on behalf of the Department. Since 1985 the Department has run its own computerized catch and effort system (CAES), also incorporating the data from 1975-1985. Data collected monthly for each boat includes gear used, number of days fished, and catch of various species by statistical blocks. The blocks are generally one-degree squares, with exceptions for enclosed bodies of water, i.e. for waters inside Shark Bay.

Most of the catch from the snapper fishery off Shark Bay has come from between 24° S and 26° S with smaller quantities from the one-degree latitude bands immediately to the north and south of these. Unfortunately from the viewpoint of ease of use of statistics, the managed fishery, which was gazetted in May 1987, extends from 23° 34' S to 26° 30' S, the boundaries thus falling halfway through the statistical blocks. While snapper are also caught both commercially and recreationally in inner Shark Bay south of 25° 30' S, the inner bay stocks have been shown by a variety of methods to be functionally distinct from the ocean snapper for the purposes of fisheries management and have been excluded from the managed snapper fishery.

Data from years prior to the gazettal of the managed fishery in 1987 have included the blocks between 26° and 27° S based on anecdotal information from fishers that most of the catches came from the northern half of this area, adjacent to the anchorages at South Passage and False Entrance. Since gazettal of the limited-entry fishery, fishers who were excluded from the snapper fishery have fished the waters in the southern half of this latitude band, from the port of Kalbarri. Data since 1987 have been separated based on whether the boat was licensed for the fishery, assuming that all catches from licensed boats were from the northern half and all catches from unlicensed boats from the southern half of this latitude band. The smaller catches from the 23° to 24° S area have been excluded from the data prior to 1987. Any catches since 1987 in this latitude band have been included or excluded in the fishery catch on the basis of licence as for the southern boundary. The excluded catches were not sampled as part of the Shark Bay snapper fishery; we assume that the bulk of the catch taken within the prescribed regions were highly representative the entire stock.

For most of the recorded history of the fishery, handline has been the main method of fishing. Trap fishing began in 1959 and continued alongside linefishing until 1987, after which only one vessel continued to trap until 1990. The fishery now uses mechanized handlines. Droplines were used by some vessels in the mid 1980s and a trawler operated during one year, 1977. Although droplines and handlines are approximately equivalent, average catch-rates (kg of whole snapper/boat-day) from traps were approximately three times those of lines and that of the trawler was many times higher. Because handline has been used throughout, catch per unit effort is based only on handline boats.

In addition to the marked effect of gear on catch-rate, the effect of season is significant. During summer, the snapper are thought to be dispersed in small schools over the continental shelf and upper slope to depths of 250 metres, wherever there is suitable habitat. In the winter spawning season this range contracts inshore and mature snapper are aggregated in huge schools over rocky patches mainly in depths of 15 to 80 metres. The locations of the aggregation sites are well known to the fishers. Catch-rates in the winter are consequently much greater than in summer, peaking in June and July. Many of the fishers only fish in these waters during the winter when catch-rates are high (Bowen, 1961; Moran et al., 2003). Because of the seasonal variation and the predominance of winter fishing, the standardized unit of catch per unit effort (CPUE) used here is *kg of whole snapper / June-July handline boat-day*. Fishing effort is similarly standardized to equivalent *June-July handline boat-days* and is calculated by dividing the total catch for the year by the CPUE.

Catches reported as gutted and gilled were multiplied by 1.14 to convert to whole weight, and fillet weights multiplied by 3.0 (Moran & Burton, 1990). Catches reported in pounds in the early years were multiplied by 2.2 to convert to kg.

There are a number of problems with the catch and effort data, the most serious of which is that a boat can fish in more than one statistical block in a day. As the day is the only unit of time used in this data set this can result in the total number of days fishing, calculated by summing the numbers of days in all the blocks, exceeding the number of days actually fished in a month. This is dealt with by using the total number of fishing days for the boat in that month, divided among the blocks in proportion to the reported number of days in the blocks.

Another major problem is that sometimes a boat operates in the fishery either with an inexperienced skipper or targeting species other than snapper, resulting in a low catch-rate well outside the range of the rest of the fleet. It has been decided to eliminate such misleading records by selecting only those vessels that caught more than 4 tonnes in the June-July period. Licence-holders who have >4 tonnes of quota usually employ an experienced skipper and the boat will usually be dedicated to snapper fishing during the winter period. The catch-rate using this selected sub-set of the fleet for 1976-1985 was greater than that for the fleet as a whole by an average factor of 1.42, reflecting a high turnover of boats, and hence inexperienced fishers, in the years before gazettal of the limited-entry fishery.

6.2 Age determination

Both scales and sectioned otoliths have been used for age determination in the past. The scales of the 1980s samples were mostly read in the 1980s and their estimated ages from scale reading were used as recorded at that time. Scales from a number of fish for which there were both scale and otolith samples were read by the same reader who read the 1980s samples to enable a calibration with otolith readings that were chosen as the best estimates of age.

The snapper for the 1990s and later were aged using transverse sections of sagittal otoliths, viewed with transmitted light. The axis-of-reading was a straight line running from near the core to the margin on the ventral region of the otolith section, remaining approximately parallel to the ventral edge of the sulcus (see Figure 2).

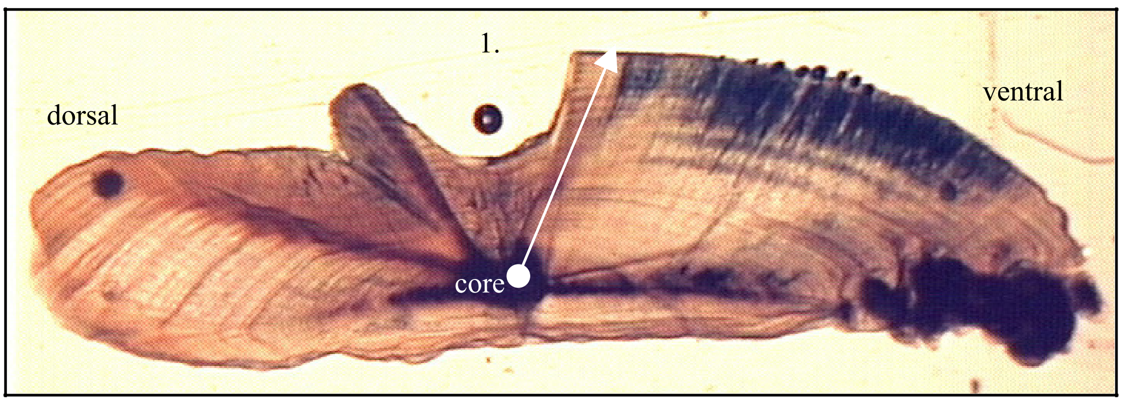

Figure 2. A transverse section of a sagittal otolith, showing the axis-of-reading used to age snapper.

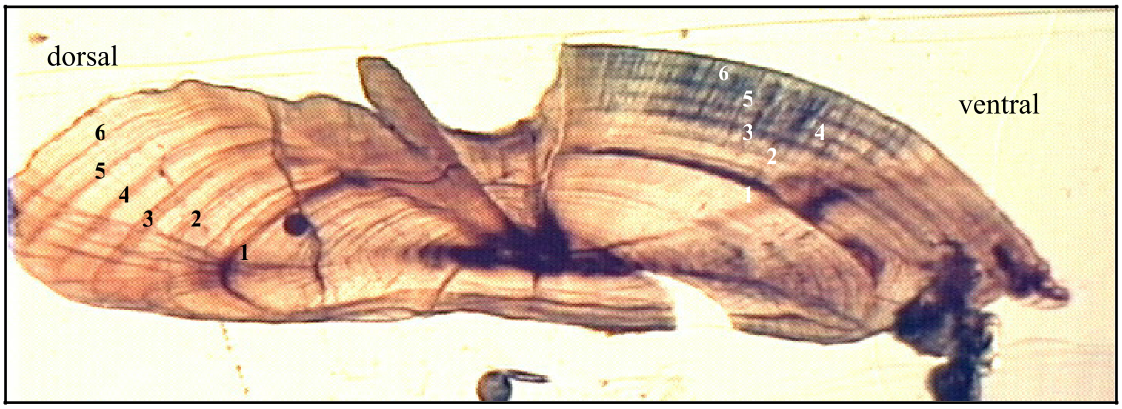

Figure 3. A sectioned snapper otolith with clear annual bands on both the dorsal and ventral ends of the otolith.

Annuli, i.e. increments on the otolith sections, appear as alternating opaque (dark) and translucent (light) zones under transmitted light (see Figures 2-4). As fish mature, their growth slows and so the distance between consecutive zones decreases as increments are counted from the core to the edge of the otolith.

Outer opaque zones generally appear darker, clearer and more evenly spaced those deposited nearer the core. Hence, the interpretation of increments in a younger fish's otoliths can pose difficulties, as it is likely that sub-annual marks are sometimes incorrectly included in annual band counts.
A dark line of material called the sagitta-subcupular meshwork fibre zone (the SMF, or 'Francis line') is often useful when identifying the position of the first opaque zone. The use of a deflection point in this 'Francis line' allows the position of the first annulus to be located (see Figure 4).

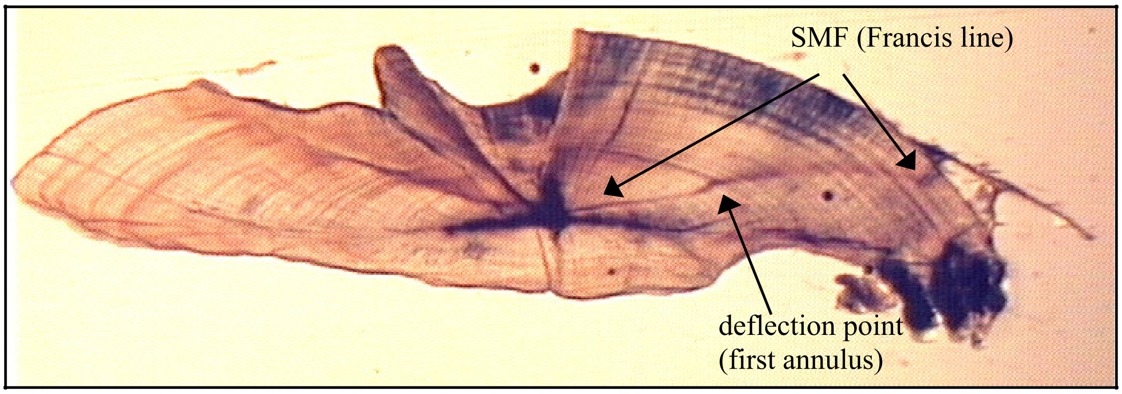

Figure 4. A sectioned snapper otolith with a clear first annulus and inflection point in the SMF.

Readability varied widely; scores were assigned as follows.

1. Hopeless, unreadable
2. Poor otolith, doubtful, guesswork
3. Reasonable otolith, some guessing, not 100% confident
4. Good otolith, confident

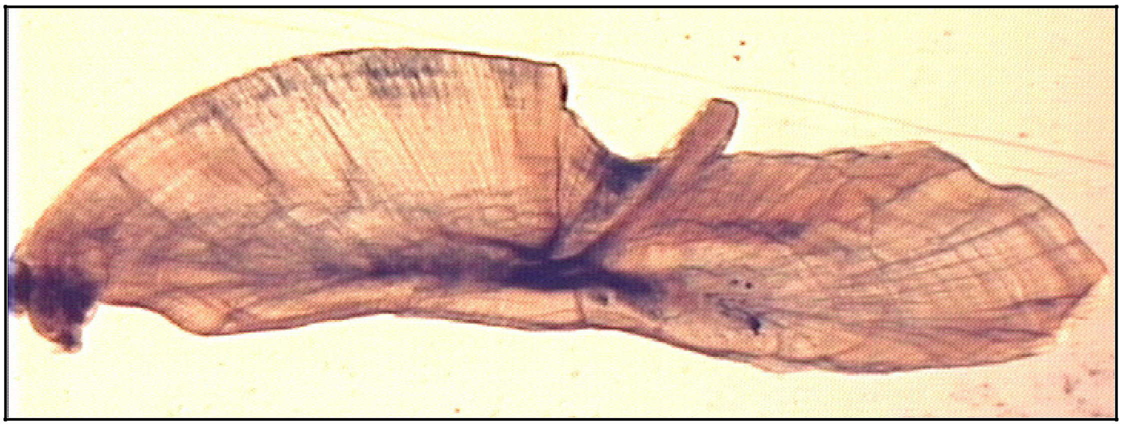

Figure 5. An otolith that is impossible to age with confidence. This sort of otolith was given a readability score of 1 (unreadable) and hence left out of the data set.

Due to time restrictions, sectioned otoliths for each year, 1990 to 1999 and 2001 to 2003, were not read more than once. The year 2000 otoliths, however, were read twice by both readers to investigate inter- and intra-reader precision.

As a validation of the interpretation of annuli, snapper were tagged and injected with tetracycline 25 mg / kg in June 1996. Of the recaptured snapper, at liberty for up to 7 years, 37 had visible fluorescent marks on otolith sections under UV light and had data on the time at liberty. The positions of the presumed annuli were marked on photographs of the otolith sections taken under normal light, without a visible tetracycline mark. These were overlaid on photographs taken with UV light and the number of marks outside the tetracycline mark were counted and compared with the number of years at liberty to assess the validity of annulus interpretation.

6.3 Calculating age structures for commercial snapper catches 1982–2003

Annual monitoring of the commercial snapper fishery, since 1982, has included measuring several hundred (or thousand) fish for length frequency, collecting a smaller number of scales or otoliths for age determination (see Table 1) and collecting more detailed catch and effort information than was previously available.

Approximately 80% of annual snapper catches are taken during the peak spawning season (May to August) and, hence, the annual sampling has concentrated on these months. For the years 1982 to 1987, random samples of snapper caught on commercial fishing boats enabled length frequencies to be calculated and ageing of fish samples was achieved by reading scales. From 1988 onwards to 2003, annual sampling of length frequencies was conducted at snapper processing factories in Carnarvon. Age determination by reading scales was phased out in 1990 when sectioned otolith readings were commenced as they were considered to be more accurate at determining the age of snapper.

Table 1. The number of fish sampled from the Carnarvon commercial snapper fishery for length frequency and age determination, 1982 – 2003 (* denotes scale readings, @ denotes otolith readings).

Year	Fish lengths sampled (n)	Fish aged (n)
1982	1525	909 *
1983	2198	1374 *
1984	3317	1596 *
1985	5847	375 *
1986	6233	665 *
1987	7142	349 *
1988	1417	227 *
1989	891	354 *
1990	1486	-
1991	5030	158 @
1992	5165	200 @
1993	5553	402 @
1994	-	475 @
1995	3933	350 @
1996	1320	458 @
1997	Factory grade data used	-
1998	“	-
1999	“	254 @
2000	“	280 @
2001	“	244 @
2002	“	-
2003	“	305 @

6.3.1 Calculation of annual length frequencies

A length frequency of the total annual catch for each year, 1982 to 2003, was calculated by applying the length frequency of each annual sample, from either boat or factory, to each year’s entire catch numbers. The entire catch numbers were estimated by dividing the total catch (kg), available from Australian Bureau of Statistics or The Department of Fisheries WA Catch and Effort Statistics (CAES), by an average weight of a snapper from each year.

Until the late 1980’s, trap fishing contributed considerably to the annual catches in the snapper fishery. During the spawning season (May to August), larger snapper migrate to more inshore waters while smaller fish remain in more offshore waters, where trap fishing generally operated. Consequently, size composition of trap-caught snapper was quite different. For this reason, the calculation of 1982 to 1987’s annual length frequencies required trap and line catches to be applied separately to length frequency samples and then subsequently summed. Following the introduction of limited entry management in 1987, and new demands from the export market for healthier looking fish, trap fishing declined in favour of the better-looking product from the line fishery. Hence, the 1988 to 2000 length frequencies were calculated by applying length frequency samples to annual line catch numbers only.

In 1991, a snapper processing factory in Carnarvon, *Kai*, which processed the majority of the snapper catch, began to supply accurate records of how many snapper were processed each year in the form of ‘bin count’ data. Snapper were graded by size when packed for export and the number of fish in one box is referred to as the ‘bin count’. With this new data available, an extra step was added in the annual length frequency calculations for years 1991 to 1995. Annual length frequency sampling in *Kai* always recorded the 'bin count' of the measured samples and so the length frequency samples could be applied to the annual 'bin count' data and then to that year's entire annual catch numbers, to obtain a more accurate length frequency.

A second snapper processing factory in Carnarvon, *Abacus*, began providing processor records in 1994. *Abacus* used a slightly different method of processing and packing snapper and so, it was necessary to sort the pooled length frequency measurements by individual fish weight, rather than 'bin count'. Both *Abacus* and *Kai* processor records could then be applied to the pooled length frequencies to produce a length structure of all snapper that were processed in the two main factories in a particular year. For 1996 – 2001 there is a length frequency for both *Abacus* and *Kai* factories. The entire year's catch data (CAES) was then sorted into that caught by either *Abacus* or *Ka*i boats. The *Abacus* portion of the catch was applied to the length frequency of snapper processed at *Abacus* while the remaining *Kai* portion of the catch was applied to the length frequency of snapper processed at *Kai*. The separate length frequencies were then summed to produce a length frequency which was considered representative of the entire year's snapper catch.

6.3.2 Calculation of annual age structures

Calculating annual age structures, for each year between 1982 and 2000, involved applying age-length keys to the calculated annual catch length frequencies (see above). For the years 1982 to 1989, age-length keys were generated from previously read scales and recorded lengths, and for otolith sections for 1990 to 2003. The two readers spent considerable time reading otolith sections together and creating a protocol for ageing. This protocol served as a reference guide for the readers, so as to maintain consistency and repeatability in the method used to estimate the age of the snapper. The axis of reading decided upon was a straight line running from the core to the margin of the otolith, close to and approximately parallel to the ventral edge of the sulcus. The use of an inflection point in the 'Francis line' was also recognized as very useful in identifying the position of the first annulus (Francis et al., 1992). Typical measurements from the core to the first band were known to be approximately 600 to 800 μm (unpublished data, Gary Jackson) and so before deciding upon the location of the first band, its distance from the core was measured. Various other helpful guidelines and 'rules' for deciding on the location of bands were established in the ageing protocol.

No otoliths were available to age for the years 1990, 1997, 1998 and 2001, so age-length keys were produced for these years by averaging the age-length key data for adjacent years. For example, to produce an age-length key for 1990, the 1989 and 1991 age-at-length proportions were averaged.

Fish age and length were plotted for each year, 1982 to 2003, and any extreme outliers in the years after 1990 (i.e. sectioned otoliths read) were identified visually and those individual otoliths were read a second time by one of the readers. If this reader found the otolith difficult and ambiguous to age then that particular fish was omitted from the analysis. If the reader was confident about a change to the fish's age then the age-length table was modified to account for this new age estimate.

The proportion of snapper at particular ages, for each length group, was calculated to generate age-length keys for each year, 1982 to 2003. These were then applied to the total catch length frequency for each year to produce an age-frequency of the total catch of the commercial snapper fishery for each year, 1982 to 2003. Finally, the total numbers of fish in each age class were adjusted for the additional catches by recreational fishers and by commercial fishers without snapper licences. Most of the catches by the latter group would have been returned to the water and it was assumed that 80% would die from effects of handling and barotrauma (St John & Moran, 2001).

6.4 Cohort analysis

The principle of cohort analysis is to follow the catches of a particular year-class through time, e.g. the number of 5 year-olds caught in 1990, 6 year-olds in 1991, 7 year-olds in 1992 and so on until the number of fish remaining in that year-class in its old age is very low. If the natural mortality rate is known, the number of fish in the population of this year-class, and the fishing mortality it experienced in each year, can be calculated from this time-series of catches at age.

The variants of Virtual Population Analysis/Cohort analysis are discussed by Haddon (2001) including one known as Pope's approximation (Pope, 1972) which simplifies the calculations and has been shown to be valid for values of natural mortality $M < 0.3$ and fishing mortality $F < 1.2$. Pope's method applies the natural mortality for half a year, takes out the whole catch at once in the middle of the year, then applies natural mortality again for the other half of the year. The Shark Bay Snapper Fishery, with the bulk of the catch taken in the middle of the calendar year, fits this model better than many other fisheries.

The age-structures of snapper in this fishery contain only occasional fish over 30 years old and the fish over 20 years old are rare enough that there are a lot of zeroes in the annual samples for catch at age. A maximum age for analysis always has to be set in cohort analysis to avoid this problem of too many zeroes, and we decided to set it at 20 for snapper. The existence of fish over 30 years old indicates that the natural mortality rate must be quite low and we set $M = 0.13$ (Table 2) by reference to Hoenig's (1983) equation for calculating the total instantaneous mortality rate from the age of the oldest fish in the sample. This natural mortality rate only refers to the age-classes taken by the fishery. Although the natural mortality rates for younger, pre-recruit snapper are undoubtedly much higher (Moran & Kangas, 2003) this does not affect the analysis of recruited snapper. The natural mortality rate used in New Zealand for snapper stock assessments is 0.075, just over half of the one used here, reflecting maximum ages in New Zealand waters up to 60 years (Gilbert et al., 2000; Davies et al., 2003).

The analysis estimates fishing mortalities (F) for each age-class in each year except for the final year of data, in this case 2003, and the final age-class used in each year, in this case 20 (Table 2). These Terminal F's have to be determined by the analyst on the basis of other information. It is a feature of cohort analysis that the further back from the final year and age-class, the more reliable are the estimates of F. Terminal F's for this analysis were therefore chosen to be consistent with the reliable values for the younger of the fully-recruited age-classes in the 1980's and early 1990s.

A catch curve for the whole period (1982 – 2003) was used to get an initial indication of likely F values (Figures 6,7). The slope of the curve for the 8-20 year olds was 0.535 and can be used as an estimate of average total mortality Z (=F+M). If M is assumed to be 0.13, average F would be in the vicinity of 0.4.

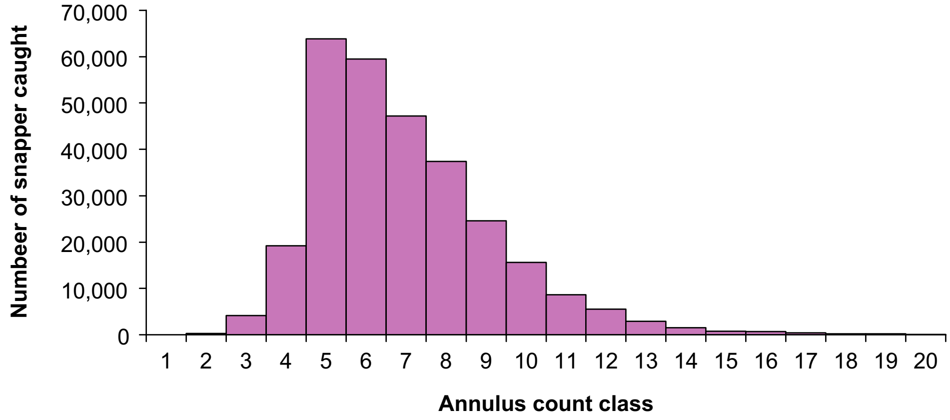

Figure 6. Shark Bay snapper fishery. Mean catch at age for the years 1982-2003.

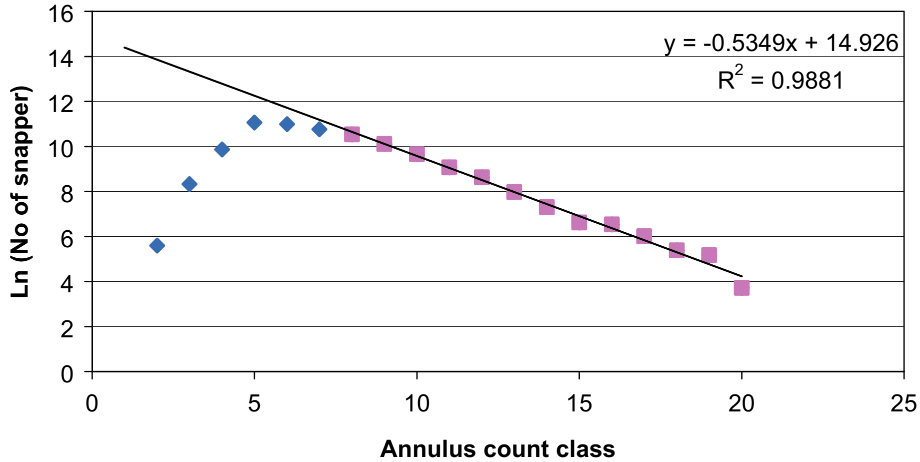

Figure 7. A catch curve fitted to the mean catch at age 1982-2003. The negative slope of the line fitted to the Log(catch at age) for the fully recruited age-classes is an estimate of the total instantaneous mortality rate Z. In this case Z is estimated to equal 0.5349.

For all years and ages except the final year and age,

$$N_{a,t} = (N_{a+1,t+1} \cdot e^{M/2} + C_{a,t}) \cdot e^{M/2}$$

and

$$F_{a,t} = -Ln\, [\, (N_{a+1,t+1} \cdot e^{M/2}\ ) /\ (N_{a+1,t+1} \cdot e^{M/2} + C_{a,t})\,]$$

where

$F_{a,t}$ is the instantaneous fishing mortality rate on age *a* in year *t*.

$N_{a,t}$ is the number of fish of age *a* at the beginning of year *t*

$N_{a+1,t+1}$ is the number of fish of age *a*+1 at the beginning of year *t*+1

$C_{a,t}$ is the number of fish of age *a* caught in year *t*

M is the instantaneous natural mortality rate.

In the final year and age,

$$N_{a,t} = ((F+M) / M\ ) \cdot C_{a,t} / (1 - e^{-(F+M)}\ )$$

where F is the terminal instantaneous fishing mortality rate.

The cohort analysis was implemented as a spreadsheet in Microsoft Excel. Initial runs were made to observe the patterns of F with age and to test the sensitivity of the output to changes in the assumed values of the input parameters. The F assumed for the oldest age-classes was found to have little influence on the outcome. As expected, F for the final year had more influence on later years but not on the earlier years.

Annulus (opaque zone) counts were used a proxies for age in the analyses. If the annulus forms in November, and the fish (spawned mid-year) do not form one in their first November at around five months old, the first annulus will form when the fish is one year and five months old. In the following year, these fish with one completed annulus would range from one year and six months to two years and five months old. The actual ages of most of the fish caught (catch peaking at spawning time) are therefore around a year older than the nominal age (number of annuli).

Table 2. Summary of parameters used in the base case cohort analysis.

Ages used in analysis	1 - 20	Annulus count classes
Years used	1982 -2003	
Terminal F (2003)	0.4	Mean for 5-8 year olds
Terminal F for 20 year olds	Mean 0.35, S.D. 0.13	
Natural Mortality Rate, M	0.13	

6.5 Sensitivity analysis

Cohort analysis suffers from a number of drawbacks. One is that the estimates of abundances of year-classes and of fishing mortality rates for the most recent years in the analysis are not very reliable if the terminal fishing mortalities used differ markedly from the real Fs in the fishery. Another drawback that cohort analysis shares with many other stock assessment methods is that it relies on an assumed value of the instantaneous rate of natural mortality M, which is not well known in most fisheries.

Sensitivity analyses were performed to evaluate how sensitive the results of the cohort analyses were to assumed values of M and terminal Fs which are different to the real, unknown values. The base case M used was 0.13, our best estimate. To cover a range wherein the true value of M is very likely to lie, the analysis was also performed using M values of 0.075 and 0.2. The base case used a mean terminal F (age classes 5-9) of 0.4. Values of 0.25 and 0.55 were also used.

We were concerned that the precision of age determination with Shark Bay snapper is not high compared to other fish species and to more southerly stocks of snapper. To evaluate the possible effects of ageing, we simulated three levels of increasing error by allocating proportions of the numbers caught in each age class to neighbouring age classes. Level 1 allocated 10% of each age class to the age-classes on either side. Level 2 allocated 20% of each age class to the age classes on either side and 10% to the age-classes nest to those i.e. an error of 2 years. Level 3 distributed ageing error evenly across that age class and the two classes above and below, i.e. 20% in each age class.

6.6 Age-structured fishery model

Population Model and Data

The snapper stocks in the oceanic area outside Shark Bay were assumed to be reproductively isolated and self-recruiting and further, after recruitment, assumed to have no mixing with the inner gulf stocks nor with the Ningaloo stock to the north and the Kalbarri stock to the south.

An age-structured model was constructed for each stock using AD Model Builder (Otter Research Ltd 1994). The number of 2 year old recruits was determined using a Beverton & Holt stock-recruitment relationship (SRR) with asymptotic recruitment at high stock levels. Random deviations from this recruitment were estimated to account for annual recruitment variability.

Catch records for the fishery began in 1952 and it is likely catches were low before this time (Figure 9). Thus the stock was assumed to be at unfished equilibrium at this time and the numbers of fish in each year class in 1952 reduced due to natural mortality only. In later years fish numbers were reduced in annual time-steps due to natural and fishing mortality.

The biomass of spawning females at the end of each year was determined from the model numbers-at-age and weight-at-age, enabling the recruits to be determined from the SRR and the estimated recruitment deviation.

The model was fitted on catch at age numbers from 1982 to 2003 and annual catch by weight from 1952 to 2003. Parameters estimated in the fitting were the asymptote of the SRR (R), the vulnerability at ages 2 to 8, and the random recruitment deviations from 1985 to 2003. The model outputs included annual exploitation rates and mature biomass estimates. The details of the assessment model are described in Appendix 3.

Estimates of Catch

Reported catches for the Shark Bay commercial snapper fishery since 1952 are available (Bowen 1961). Estimates of the recreational snapper catch are available for 1983 (aerial and boat ramp survey, M. Moran unpubl.) and from 1998 to 2002 from recreational fishing surveys based on the bus-route method (Sumner et al. 2002, Sumner & Malseed, 2001, 2002). The weight of the recreational catch from 1998 to 2002 was determined from the estimated numbers retained each year and an average weight of 2.5 kg (Sumner et al., 2002) (Table 3). Legal minimum size during this period was 41 cm.

Reference point

To determine the exploitation status, the biological reference points chosen were (i) that the probability of the biomass in 2014 being above 40% of the 1952 level should be >0.5 and (ii) that the probability of the biomass in 2014 being above 30% of the 1952 biomass should be >0.95.

Parameter estimation

For each stock, the parameters estimated (number of parameters used in brackets) were initial recruitment, R (1), the selectivity parameters (7), and recruitment deviations, ε_y (9). The initial recruitment, R, was assumed to have a uniform prior.

The recruitment residuals, ε_y, were constrained to lie between –0.6 and 0.6 with mean 0.

The posterior distributions of the mature biomass, B, were determined using the Markov Chain Monte Carlo (MCMC) technique. The results were based on 2000 values from the posterior distribution, which were obtained by saving every 1,000th from 2,500,000 cycles of the MCMC and rejecting the first 500 as these were considered to be generated during the "burn in" period.

6.7 Risk assessment of management options

The risk assessment involved determining what TACs would be appropriate in order to achieve the management targets:

$P(B_{2014}>0.4B_{1952}) > 0.5$

and

$P(B_{2014}>0.3B_{1952}) > 0.95$

To determine these probabilities the model was projected forward after 2002 using each of the 2000 draws from the posterior distribution, for different levels of TAC, using the "mceval" operation in AD model builder. Recruitment after 2003 was determined from the SRR with a recruitment deviation of $e^{\varepsilon_{Ry}}$, where $\varepsilon_{Ry} = N(0, \sigma_{Ry}^2)$.

From the 2000 draws, the median, 5th, and 95th percentiles of the mature biomass in the years 2005 to 2014 were determined as a percentage of the median 1952 mature biomass.

6.8 Cost-benefit of future monitoring

The options considered for future monitoring were:

Catch and effort only, with no age-structured analysis

Catch and effort with age structured monitoring based on:

1. Length frequencies only
    - random length sampling of catches
    - calculating length frequency from factory grade data
2. Otolith sampling followed by:
    - otolith weighing and thickness measuring
    - otolith sectioning and reading

Costs were based on man-days required in the lab and in the field, travel allowances, fares and car-hire, material costs and fees for external services, benefits were judged more qualitatively. The benefits of an annual survey of 1 year-old snapper abundance to predict future year-class strength in the fishery are also discussed.

7.0 Results/Discussion

7.1 Catch & effort

The catch for the managed fishery has been quite stable since the partial quota management system began in 1987 (Figure 8). The average catch from 1987 to 2003 was 492 tonnes and the average CPUE was 666 kg per standard June-July line-boat-day. Although there was not an explicit TAC for the managed fishery until the management plan was amended in 2001, the fishery was managed with a notional TAC of 550 tonnes. The downward trend in CPUE is now obvious but until the late 1990s it was not clear whether low points reflected inherent variability or really represented lower abundance of snapper.

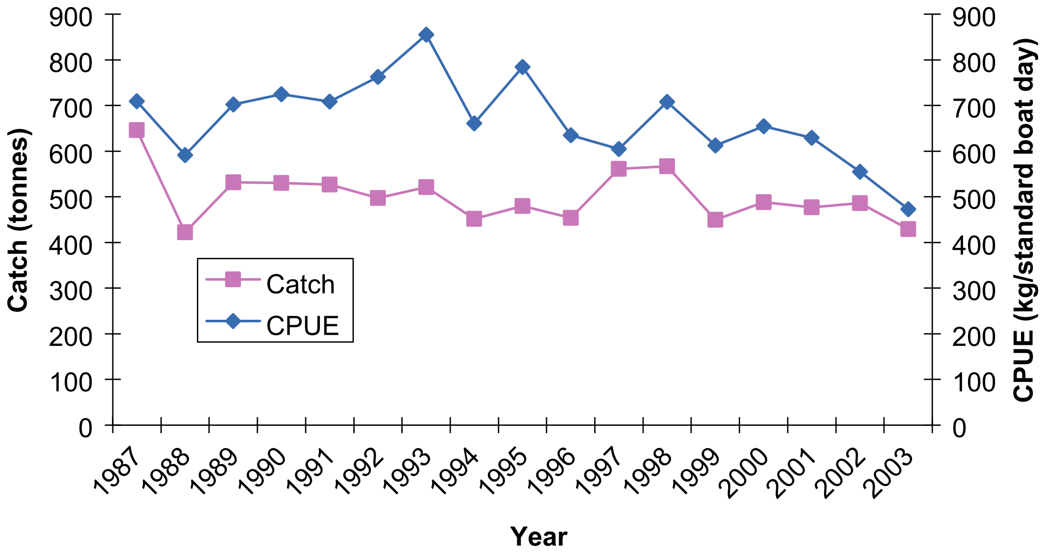

Figure 8. **Catch (tonnes) and Catch Per Unit Effort (CPUE, kg per standard June-July line-boat-day) by the Shark Bay Snapper Managed Fishery boats since management commenced in 1987.**

Catches taken within the designated area of the managed fishery but by vessels "outside" the management plan include recreational (own boat), recreational (charter boat), commercial unlicensed (either legal fishing returning snapper to the water or illegal boundary infringements retaining the snapper) and legal trawling in waters deeper than 200 metres by Commonwealth licensed trawlers. There is an overlap in jurisdiction in waters deeper than 200 metres whereby the State manages line fishing and the Commonwealth manages trawling.

Since these non-managed-fishery catches cannot be known precisely, they have been estimated based on occasional recreational fishing surveys and other limited data sets. Since 2000, these extra catches have been estimated to total approximately 50 tonnes annually, i.e. >10% of the managed fishery catch.

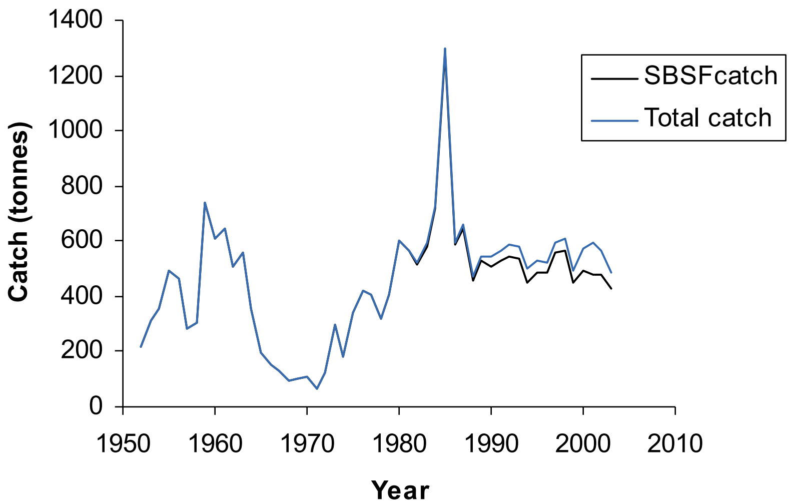

Figure 9. **The total catch and the Shark Bay Snapper Managed Fishery catch from 1952 to 2003. Prior to 1987 the catch is the total taken by traps and lines from 24° S to 27° S. After the fishery became managed in 1987 the catch is that estimated from the managed area of 23° 34'S to 26° 30'S.**

7.2 Age determination

2000 otoliths were read twice by both readers to investigate inter- and intra-reader precision. Figure 10 shows the inter-reader relationship where the average percent error was calculated to be 22.2% (Campana, 2001), which is quite high and reflects the generally low readability of snapper otoliths from oceanic waters off Shark Bay. As is evident from Figure 10, age estimates by Reader 1 were generally one less than those of Reader 2. After involving a third reader and re-viewing several otolith sections together, it was discovered that Reader 2 was consistently counting an extra band between what Reader 1 referred to as the 1st and 2nd annuli. This 'extra' band was thought to be sub-annual. Hence, one count was removed from all of Reader 2's sectioned otolith age estimates before age and length relationships were calculated.

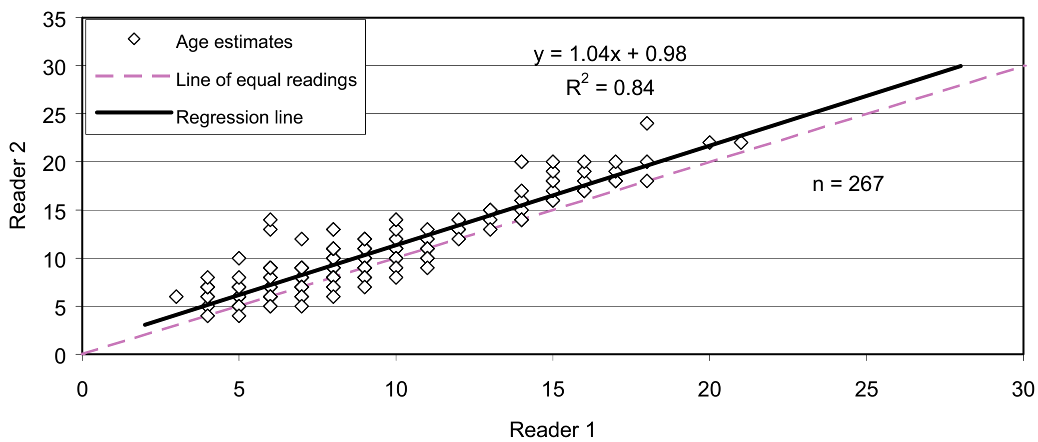

Figure 10. Relationship between Reader 1 and Reader 2's otolith readings for sectioned snapper otoliths from the year 2000. 'Line of equal readings' refers to identical age estimates from both readers.

Although the plotted relationships for inter- and intra-reader precision show similar strength relationships (see Figures 10, 11 and 12), the average percent error of intra-reader precision for Reader 1 and 2 were considerably lower at 7.8% and 8.3%, respectively.

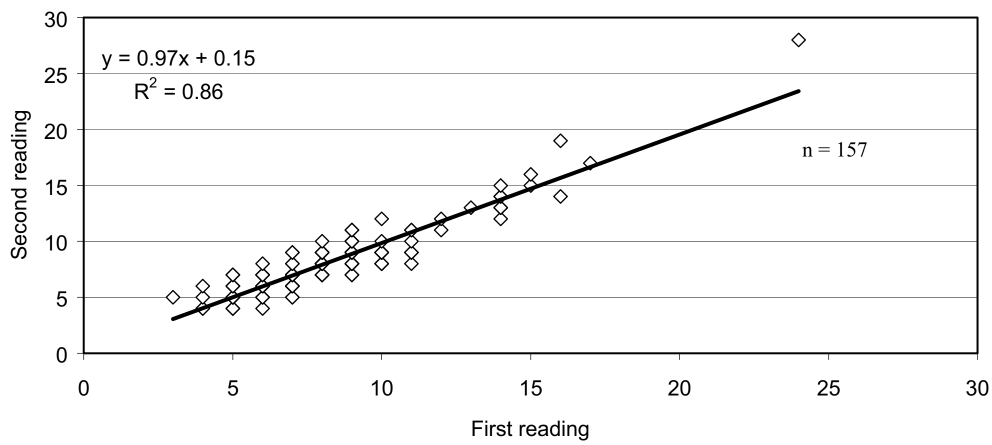

Figure 11. Intra-reader precision of Reader 1 for double readings of sectioned snapper otoliths from the year 2000.

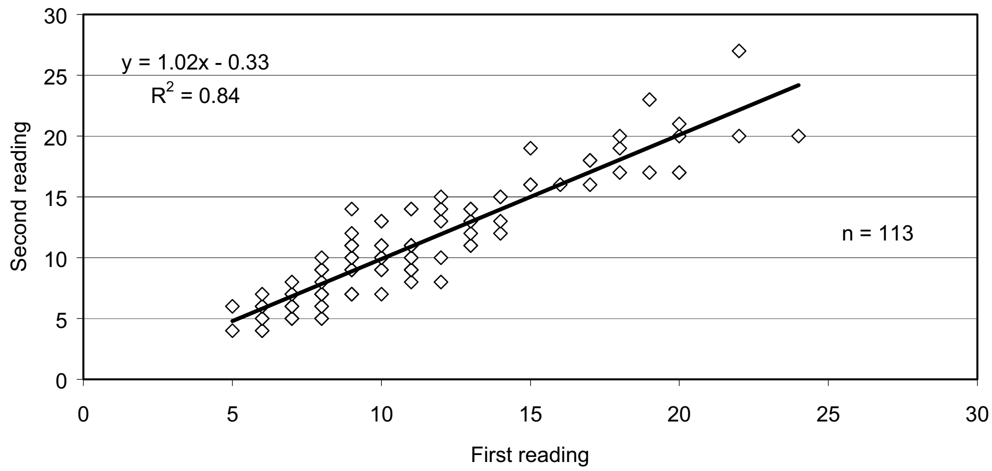

Figure 12. Intra-reader precision of Reader 2 for double readings of sectioned snapper otoliths from the year 2000.

Otolith readings and scale readings of the same fish were only available for the years 1982, 1983 and 1987 (n = 68). The relationship between scale readings and otolith readings was investigated (see Figure 13) and found to be significant (regression analysis, $p < 0$). The relationship shows that, generally, snapper scale readings are one count below sectioned snapper otolith readings. To account for this difference, all scale readings were converted to equivalent otolith readings by adding one count to the age estimate.

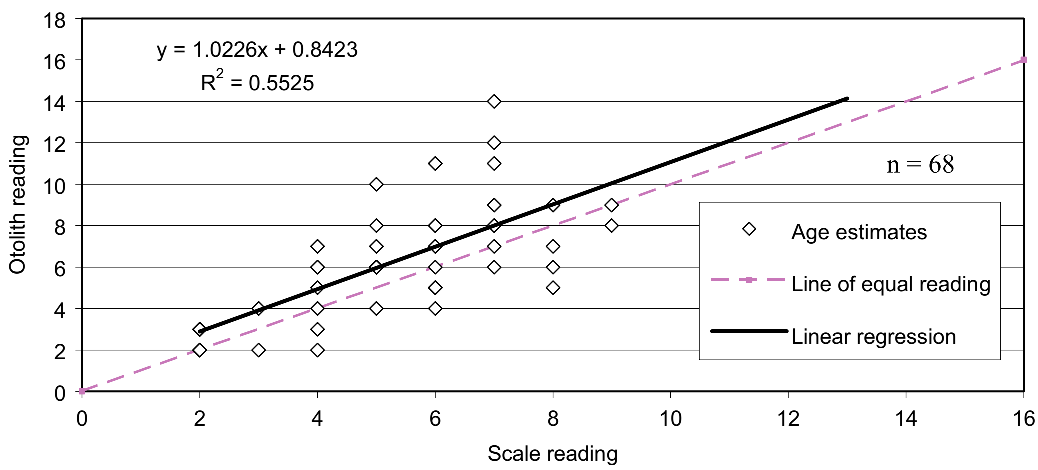

Figure 13. Scale readings versus sectioned otolith readings for snapper in 1982, 1983 and 1987. 'Line of equal readings' refers to identical age estimates from both scale and otolith.

7.2.1 Validation of annual periodicity of otolith annuli

There was fairly good correspondence between the number of opaque bands interpreted as annuli and the number of years at liberty (Table 3, $R^2 = 0.84$). However the match was not perfect, confirming the evidence from intra and inter-reader variability in readings (R^2 also = 0.84) that a proportion of snapper are aged with error. Of the 37 snapper with visible tetracycline marks and data on time at liberty, for 24 fish (65%) the number of opaque bands matched the years at liberty exactly, for 13 (27%) there was a discrepancy of 1, for two fish (5%) there was a discrepancy of 2 and for one fish (3%) a discrepancy of 3.

Table 3. The number of recaptured snapper with visible tetracycline marks on sagittal otoliths, by years at liberty and the number of opaque bands interpreted as annuli outside the tetracycline mark. Bold figures indicate the number of fish with equal years at liberty and opaque marks.

	Number of opaque bands outside the tetracycline mark							
Years at liberty	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
0								
1	3	**14**			1			
2		1	**1**	1				
3	1	1	2	**2**	1			
4					**1**			
5								
6						2	**3**	
7								**3**

7.3 Length- and Age-structure

Regular length-frequency sampling began in 1982 and it quickly became apparent that there were year-to-year differences when the length structure of the catch in 1983 contained noticeably larger fish than in 1982 (Figure 14). The sizes of trap-caught fish (from offshore grounds) in the following years fell consistently while the average size of line-caught fish remained the same. A study has indicated that traps caught slightly larger fish than lines (Moran and Jenke); hence, the higher proportion of "smaller" fish could not be attributed to gear selectivity. The change in length structure was interpreted at the time as evidence of higher exploitation of smaller length classes in the trapping area, whereas the inshore grounds were dominated by larger fish. There was little knowledge then of the variability in recruitment of snapper. Sizes fell again in the early-mid 1990s but this time it was seen as evidence of a strong year-class entering the fishery. In the late 1990s the size of fish increased markedly, which was interpreted as resulting from weak recruitment.

The time-series of length frequency structure highlights the difficulty of interpreting changes in length-frequency without a formal age-structured analysis. Nonetheless, the time series of age structure (Figure 15) also show evidence for weak recruitment (few younger fish) in the early 1980, strong recruitment in the early 1990s and weak recruitment again in the late 1990s. The first cohort analysis (i.e. age-based) in 2000 confirmed that there had been a series of consecutive years of low recruitment. While average size decreased after 2000, this evidence for strong recruitment was substantially more obvious from the age structure data, which indicated high numbers of pink snapper < 5 years old in each of three consecutive years from 2001 – 2003 (Figure 15).

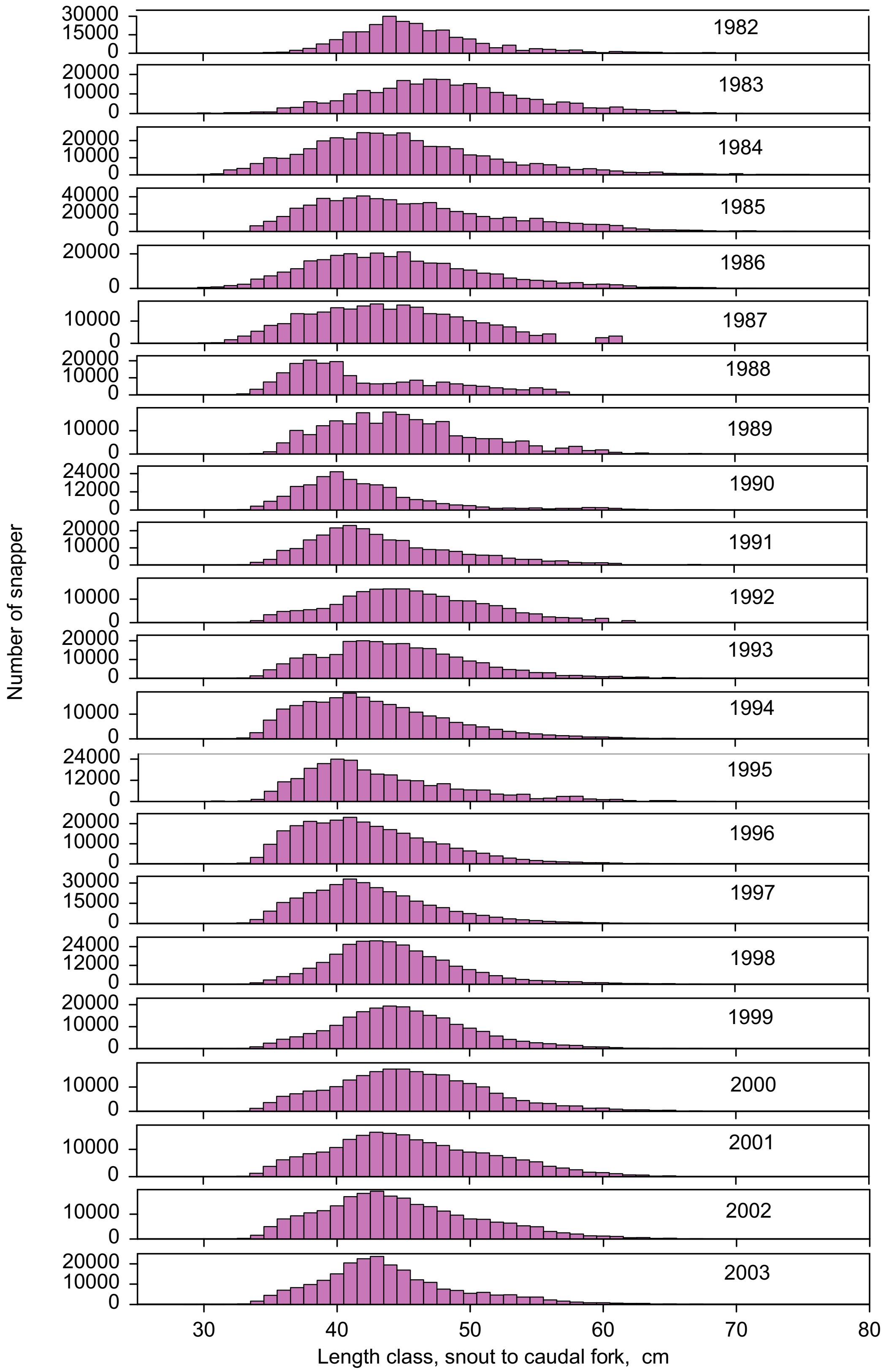

Figure 14. Length frequency structure of the commercial snapper catch by year from 1982 - 2003.

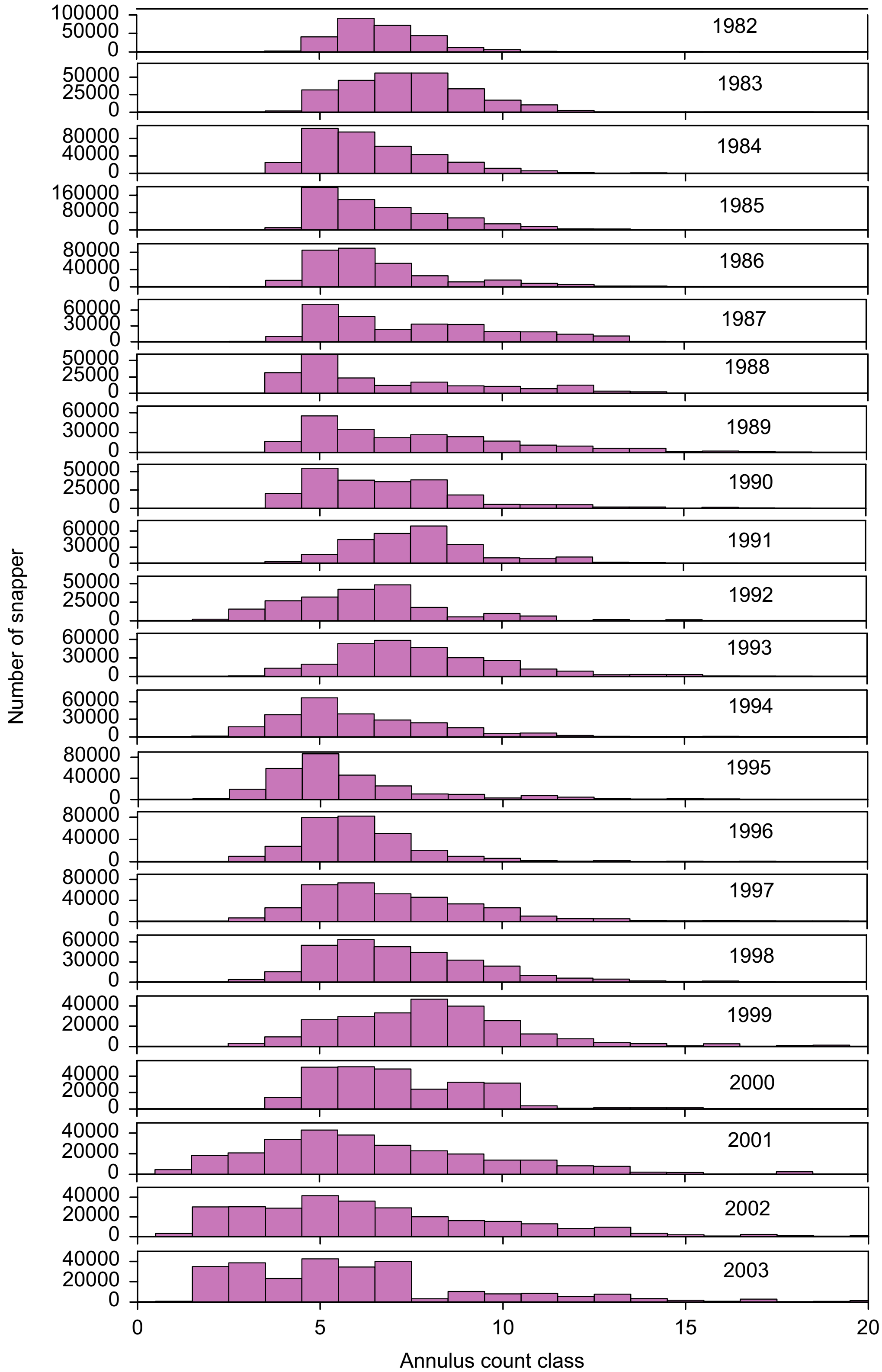

Figure 15. Estimated age structure of the total snapper catch by year from 1982 – 2003.

7.4 Cohort analysis

7.4.1 Base case

The cohort analysis using the best estimates for natural and terminal fishing mortality rates indicated that the numbers of mature snapper from 2001 to 2003 were less than one million, compared with over 2 million in the early 1980s (Figure 16). The numbers fell sharply in 1984 - 1985 when the highest catches in the history of the fishery were taken. The stock did not recover to the levels of the early 1980s but remained steady at around 1.5 million until 1992. Numbers increased to a peak of around 2 million in 1995 then fell steadily to a minimum in 2002. The increases and decreases in the 1990s clearly result from the strong recruitment in the early 1990s followed by a series of years of low recruitment in the late 1990s described below.

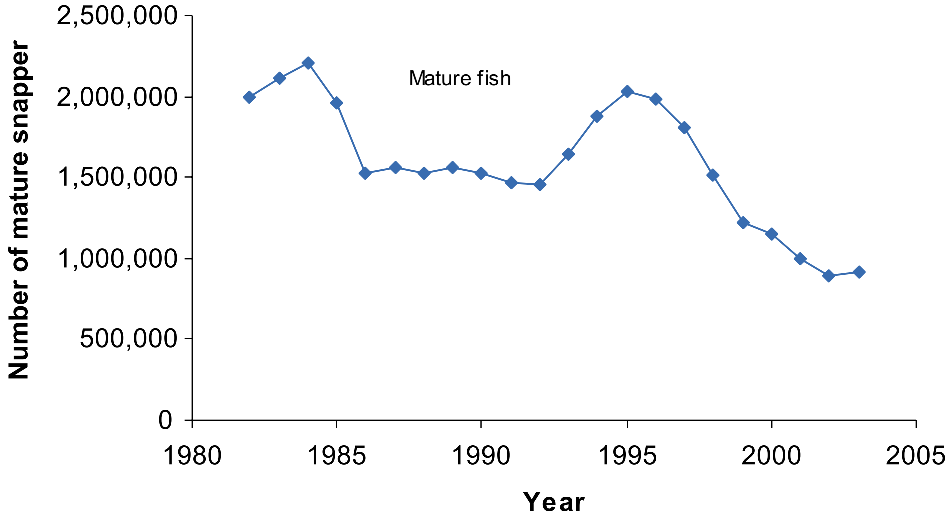

Figure 16. Estimates from the cohort analysis of the numbers of mature snapper by year in the oceanic stock off Shark Bay.

The estimates of abundance of young snapper (annulus class 1, age approximately 2 years) were fairly consistent from 1982 to 1989 (range 500,000 to 800,000) then increased rapidly in 1990 and peaked in 1991 (Figure 17). In 1992, numbers returned to the level of the 1980s but then fell to a minimum in 1996, staying low from 1996 to 1999 then increasing to average levels in 2000.

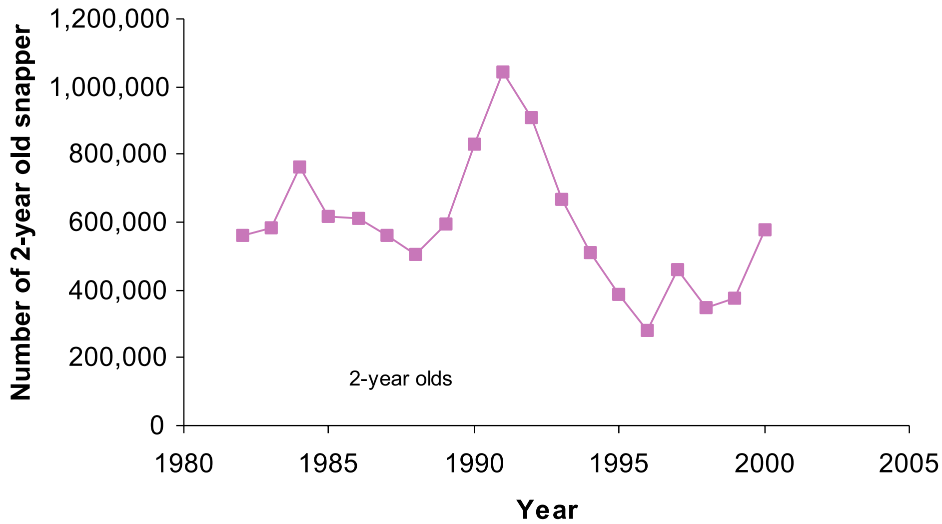

Figure 17. Estimates from the cohort analysis of the numbers of juvenile snapper by year in the oceanic stock off Shark Bay.

The cohort analysis estimates the instantaneous rate of fishing mortality F for each age class (Figure 18). The mean F for each age-class over the 1982-2002 period is an indicator of the relative vulnerability of age-classes to capture by the fishery. The pattern of fishing mortality, F, with fish age (mean for the years 1982-2002) indicated that snapper with three or less annuli were not vulnerable to the fishery, with little increase for annulus class 4. There was a sharp increase for annulus class 5 then vulnerability continued to increase, though more slowly, up to class 9. Mean estimated fishing mortalities for annulus classes 9 to 13 were comparatively steady followed by erratic variation for classes 14 to 19, reflecting the low numbers of these age classes in the catch not allowing good estimation of F. Age at 50% recruitment to the fishery is between classes 4 and 5 but full recruitment could not be said to occur until class 9.

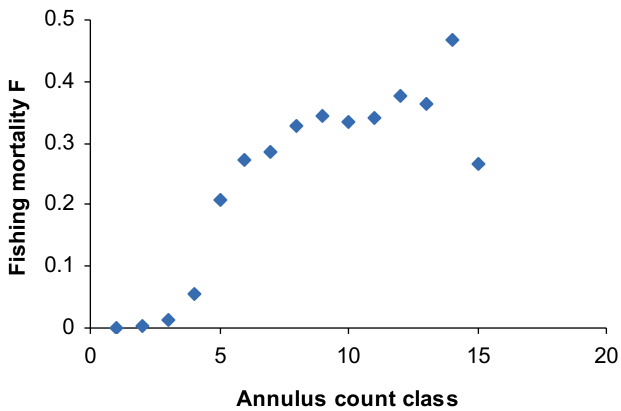

Figure 18. Rate of fishing mortality for each age class averaged over the years 1982 – 2002.

Annulus count classes 5-9 are the most abundant in the catch, so mean F for this age range is of most relevance for management of the stock. The estimated mean F (5-9) varied widely during the 1982-2002 period (Figure 19), peaking with the very high fishing effort of 1985, but also becoming high in the last few years of the analysis as similar catches to previous years were taken, but from a reduced stock, i.e. the proportion of the stock taken was increasing.

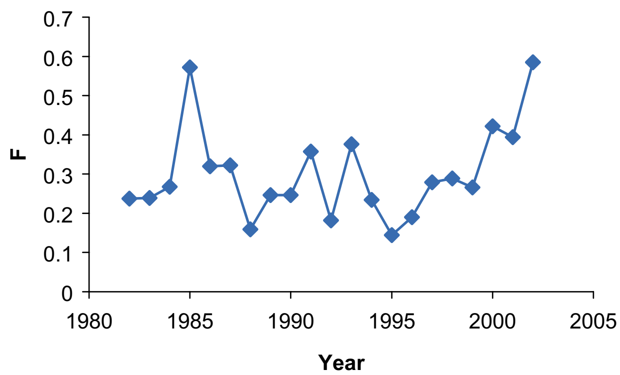

Figure 19. Estimated mean fishing mortality rate (5–9 year olds) by year.

7.4.2 Sensitivity to assumed values for M and terminal F

In the sensitivity analyses performed to evaluate how sensitive the results of the cohort analyses were to assumed values of M and terminal Fs (Figure 20), the base case M used was 0.13, our best estimate. To cover a range wherein the true value of M is very likely to lie, the analysis was also performed using M values of 0.075 and 0.2. The effect on the analysis of using these values was that the estimated numbers at age were higher or lower than the base case but the trends over time were very similar. Furthermore, for mature and recruit snapper, the trends for each value of M converged after the mid 1990s.

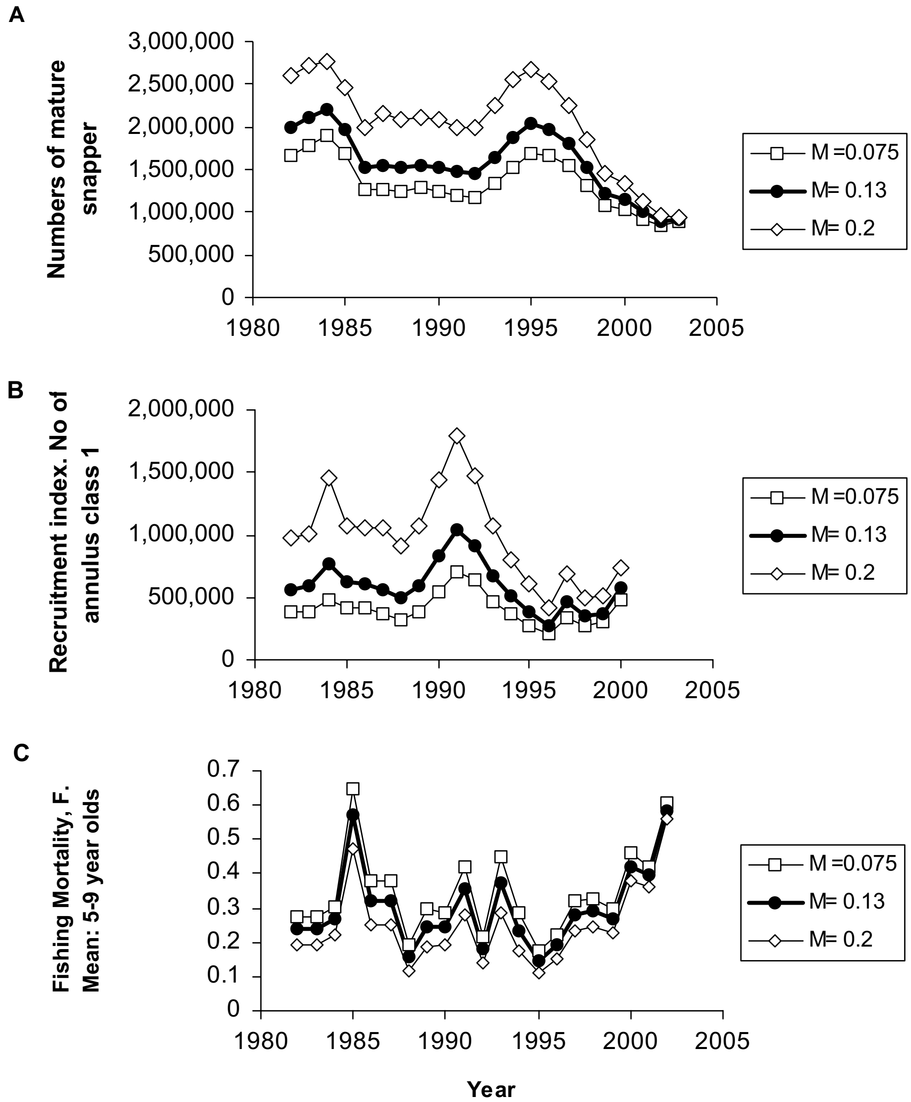

Figure 20. The sensitivity of the cohort analysis to assumed values of natural mortality M: A, the estimated number of mature snapper; B, The estimated numbers of young snapper (annulus class 1); C, the mean fishing mortality for 5 to 9 year-olds, by year.

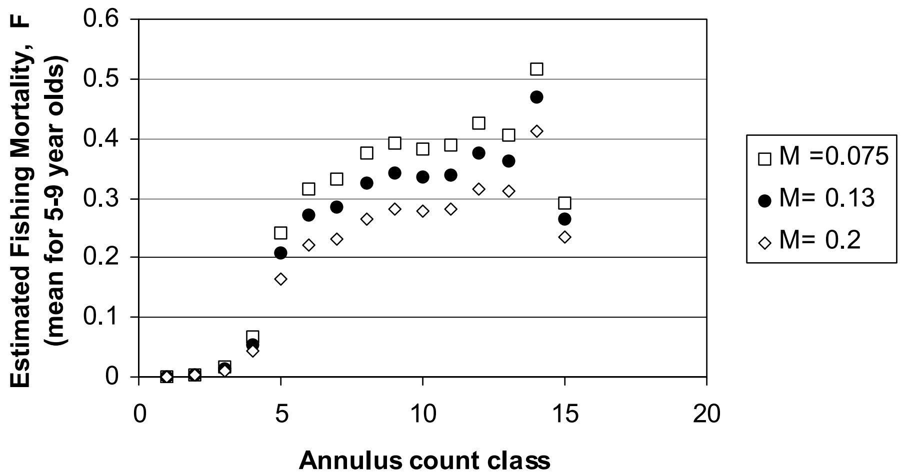

Figure 21. The sensitivity of the mean fishing mortality (from cohort analysis) for each age-class over the years 1982 - 2002 to assumed values of natural mortality rate M.

The mean F estimates over the years 1982-2002 for the fully recruited age-classes were affected in a straightforward way. When M of 0.075 was used, i.e. lower than the base case by 0.055, the F estimates were higher by the same amount. There was a similar compensating effect when the higher M of 0.2 was used. The pattern of change in mean F with age is not affected by the assumed M. The analysis demonstrates that total mortality can be estimated with confidence and hence that any mortality component not assumed to be natural was allocated by the analysis to fishing.

The base case used a mean terminal F (age classes 5-9) of 0.4. Values of 0.25 and 0.55 were also used and, as expected, while the effects on estimated numbers at age for the most recent years were moderate, estimates for years prior to 2000 were hardly affected (Figure 22). The cohort analyses from the base case for the years 1982-2002 are therefore robust to potential differences between assumed and actual terminal fishing mortality rates.

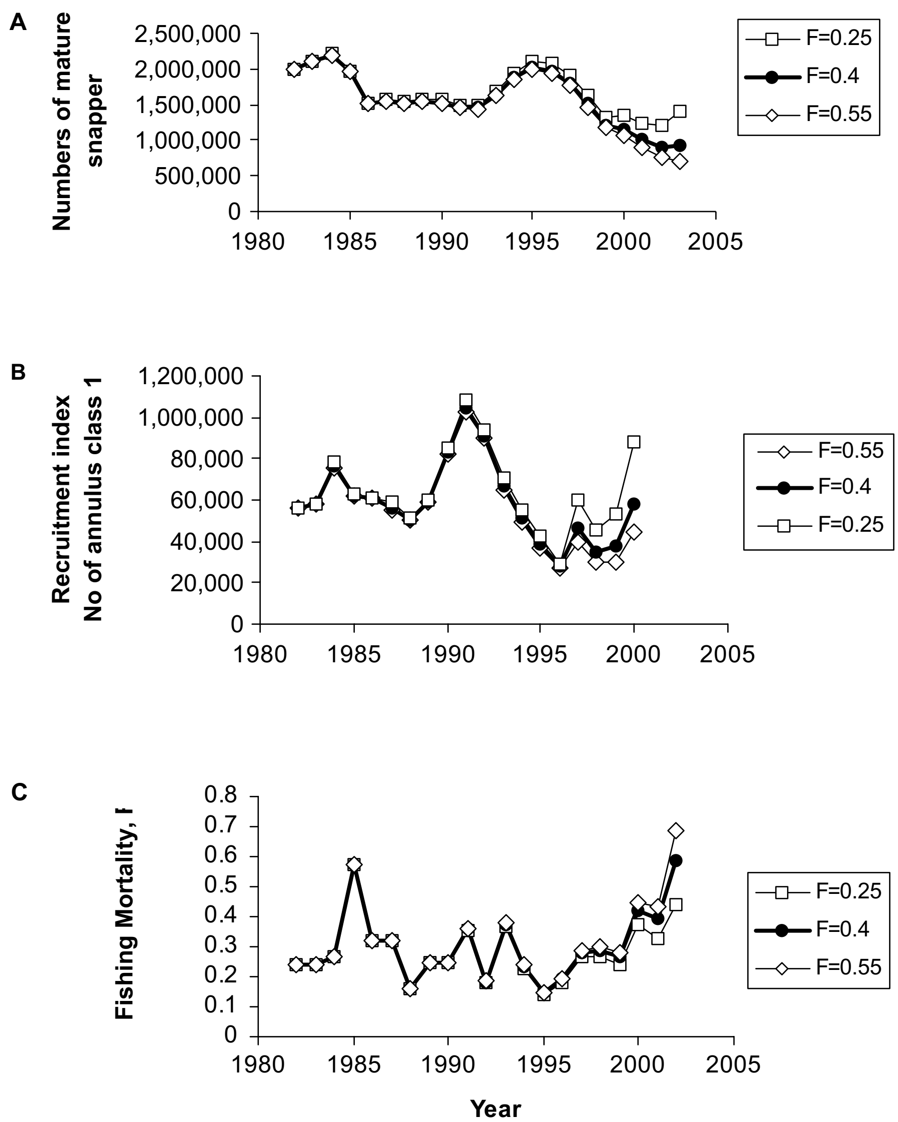

Figure 22. The sensitivity of the cohort analysis to assumed values of terminal F (mean for 5 to 9 year olds): A, the estimated number of mature snapper; B, The estimated numbers of young snapper (annulus class 1); C, the mean fishing mortality for 5 to 9 year-olds, by year.

In the sensitivity analysis using mean Terminal F values of 0.25, 0.4 and 0.55 for the age-classes 5 to 9, the outputs of the cohort analysis were generally affected in the most recent 3 or 4 years of the analysis (Figure 23). The results for the earlier years were unaffected. This is a feature of cohort analysis; that reliable results can only be obtained for the state of the stock several years prior to the end of the catch-at-age data set.

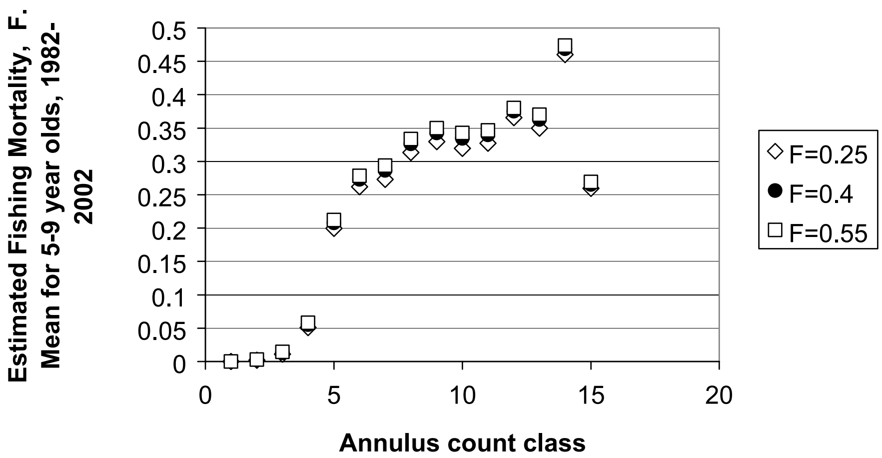

Figure 23. The sensitivity of the mean fishing mortality (from cohort analysis) for each age-class over the years 1982 - 2002 to assumed values of terminal F.

7.4.3 Sensitivity to ageing error

The results of the cohort analysis were remarkably robust to even the largest ageing errors simulated (Figures 24, 25). The trends in estimated numbers of mature fish over time were barely affected. The trends in recruitment were still strongly shown, but with the variation in year-class strength being reduced as the simulated ageing errors averaged out strong and weak year classes. We conclude that though we thought we had problems with ageing errors, they are unlikely to have significantly biased the outcome of the analysis because the much larger simulated errors did not have large effects on the outcome.

Effects of ageing errors on the base case cohort analysis were primarily (i) that real variation in recruitment was greater than estimated (Figure 24B), (ii) real age at 50% recruitment is slightly greater than estimated as some of the fish placed in the 4 annulus class would really belong in the 5 annulus class (Figure 25) and (iii) real fishing mortality on fully recruited age-classes is slightly higher than estimated (Figure 25) because a greater proportion of fish would erroneously be considered to survive to a greater age because of being allocated an age a year or two older than their real age.

Estimates of fishing mortality for age classes over the years 1982 – 2002 also indicated that ageing error was not a significant problem.

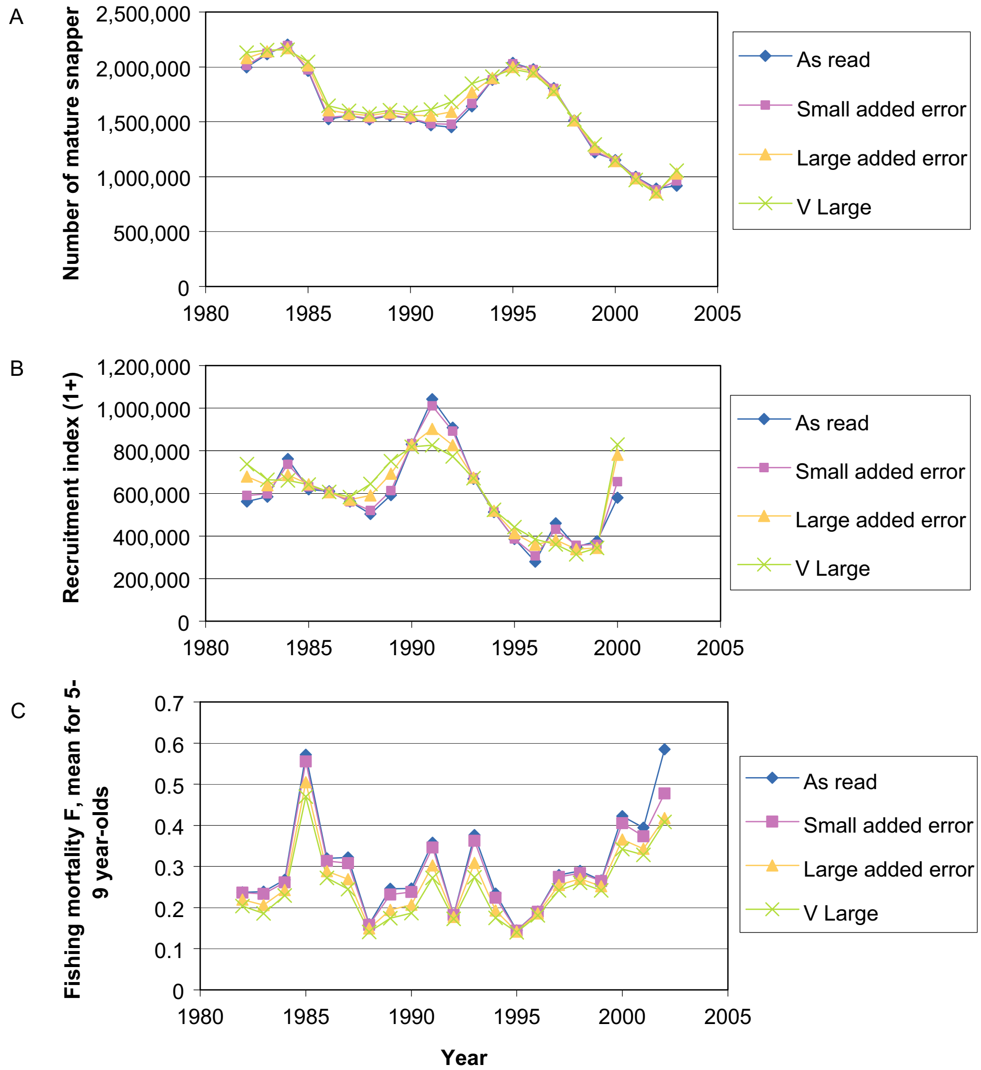

Figure 24. The sensitivity of the cohort analysis to additional ageing error: A, the estimated number of mature snapper; B, The estimated numbers of young snapper (annulus class 1); C, the mean fishing mortality for 5 to 9 year-olds, by year.

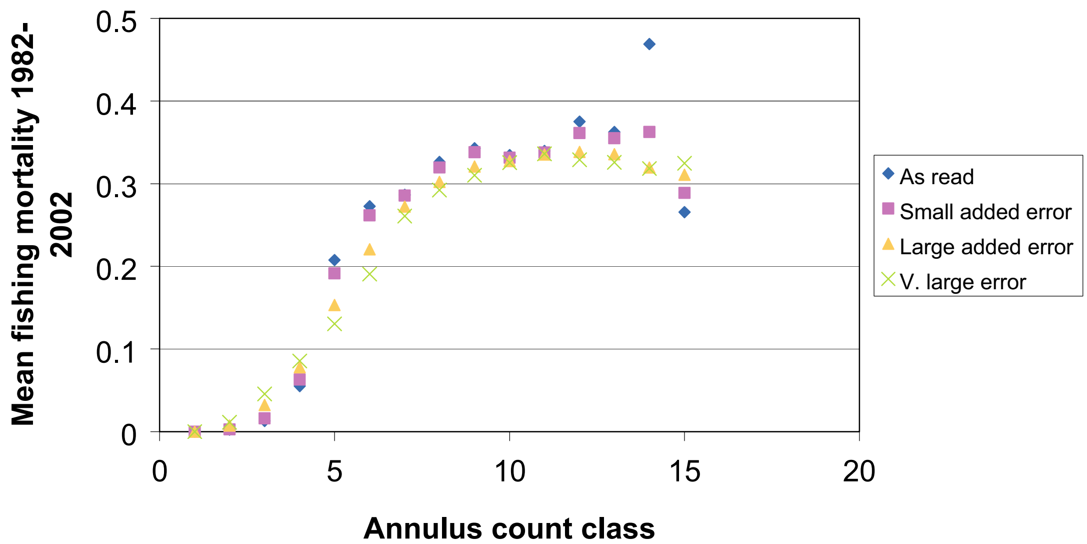

Figure 25. The sensitivity of the mean fishing mortality (from cohort analysis) for each age-class over the years 1982 - 2002 to additional simulated ageing error.

7.5 Age-structured fishery model

The estimate of virgin recruitment, with 90% confidence intervals was 690.2 ± 37.5

The estimates of the selectivity parameters (Table 4) indicated fish were 50% selected at between 4 and 5 years. This is similar to that determined for snapper in inner Shark Bay by Stephenson and Jackson (in press) in the Freycinet Estuary, but older than those in Denham Sound and younger than those from the eastern gulf of Shark Bay.

Table 4. Parameter estimates of vulnerability for fish aged 2 to 8 and virgin recruitment, *R*.

Age	2	3	4	5	6	7,8
vulnerability	0.055 ± 0.018	0.086 ± 0.024	0.224 ± 0.044	0.761 ± 0.107	0.981 ± 0.138	1.000 ± 0.001
R	690.2 ± 37.5					

The data indicated relatively large recruitment in 1992-1993 and 2002-2003 (Table 5). By way of comparison, the recruitment appeared high in Denham sound in 1990, high in Freycinet Inlet in 1992-1993, and high in the eastern gulf of Shark Bay in 1997 (Stephenson and Jackson, in press).

Table 5. Model estimates of the annual deviation from recruitment from 1982 to 2003.

year	Recruitment variation (ε_y)
1982	0.4 ± 0.21
1983	-0.1 ± 0.26
1984	0.01 ± 0.25
1985	0.25 ± 0.23
1986	0.09 ± 0.25
1987	0.16 ± 0.24
1988	-0.04 ± 0.26
1989	-0.22 ± 0.29
1990	0.00 ± 0.27
1991	0.3 ± 0.24
1992	0.52 ± 0.22
1993	0.48 ± 0.22
1994	0.03 ± 0.26
1995	-0.25 ± 0.29
1996	-0.54 ± 0.32
1997	-0.60 ± 0.06
1998	-0.51 ± 0.34
1999	-0.54 ± 0.36
2000	-0.38 ± 0.4
2001	0.32 ± 0.44
2002	0.60 ± 0.04
2003	0.60 ± 0.4

The spawning biomass, with 90% confidence intervals is illustrated in Figure 26. The model estimates indicated that the spawning biomass in 1965 had been reduced to about 60% of the 1952 level. A recovery occurred in the period 1965 to 1975 during a period of low fishing effort followed by abrupt decline in 1983 and continued decline to a level of 36% of the 1952 biomass in 1993.

The good recruitment resulted in a temporary recovery in the mid-1990s followed by a decline to 20% of the 1952 level in 2002.

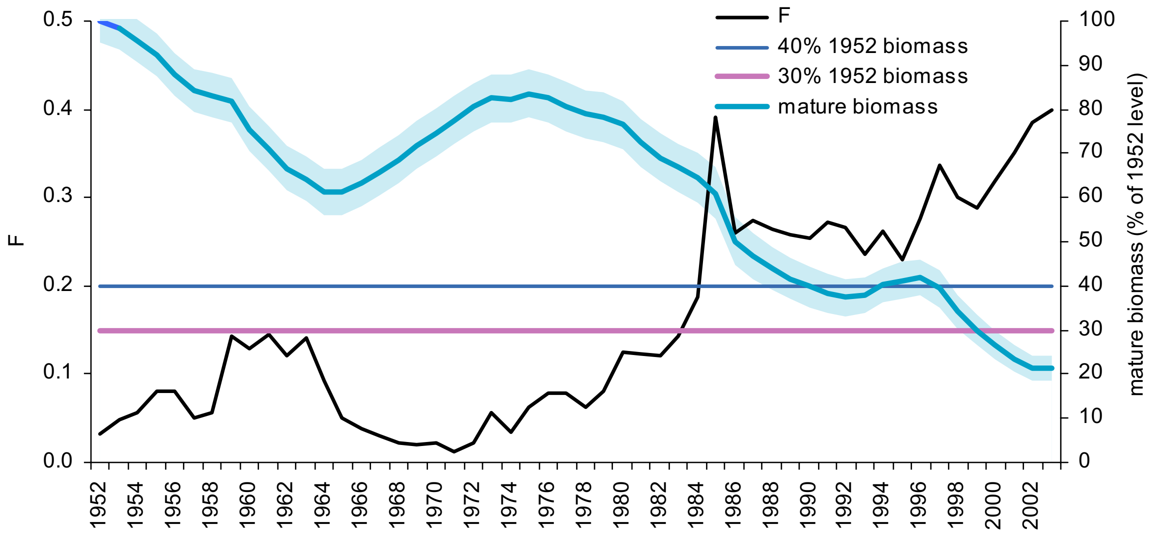

Figure 26. The spawning biomass (blue line), with 90% confidence intervals (blue shading) and biological reference points (40% and 30% of the 1952 level) on the right axis. The annual exploitation rate is shown in black (left axis).

7.6 Risk assessment of management options

The potential annual TACs that would achieve the $0.3B_{1952}$ and $0.4B_{1952}$ targets, i.e.

$P(B_{2014}>0.4B_{1952}) >0.5$

$P(B_{2014}>0.3B_{1952}) >0.95$

are shown in Table 6 and illustrated in Figure 27. The highest total catch over the ten year period is achieved with a TACs of 200 t from 2005 to 2009 and then a TAC of 520 t from 2010 to 2014. If there is no substantial discarding of undersize snapper, the scenario of a total catch of 250 tonnes per year from 2005 to 2009, followed by annual total catches of 500 tonnes per year comes close to achieving a 50% probability of rebuilding the mature biomass to 40% of the 1952 level by 2009 and maintaining it above that level (i.e. until 2014). It is also close to the other criterion of a greater than 95% probability of maintaining the biomass above 30% of the 1952 level.

In the event that there is substantial discarding of undersize snapper, we modelled the taking of a large undersize catch by shifting the vulnerabilities at age downwards by one year, e.g. making the 4 year olds as vulnerable as the 5 year olds currently are, and so on for all ages (Figure 27 f, g). This also can be used to illustrate the effect of changing the minimum legal size from 41 cm total length to 38 cm total length. By taking some of the fish younger than currently permitted, the sustainable yield of the fishery is decreased. Instead of 5 years of 250 tonne catches followed by 500 tonne catches, the management targets can be met by 5 years of 220 tonne catches, followed by 480 tonne annual catches.

This modelling is approximate, as the abundance of under-41 cm snapper will vary from year to year, affecting the catch of these fish. The catch of undersize snapper will also be affected by the abundance of large fish, i.e. if large fish are extremely scarce, the catch of small fish will increase. This modelling would be able to be more accurate in the future if there was on-board monitoring of length-frequencies, including quantification of undersized discards.

Table 6. **TAC options (catch scenarios, in tonnes) for the periods 2005 – 2009 and 2010 – 2014 that give (i) P>0.5 of achieving B_{2014}/B_{1952} close to 04 and (ii) P > 0.95 of achieving B_{2014}/B_{1952} close to 0.3. These TAC values encompass all fishing sectors.**

TAC 2005 - 2009	TAC 2010 - 2014	(i) B_{2014}/B_{1952}	(ii) B_{2014}/B_{1952}	Total catch 2005 - 2014
200	520	0.42	0.29	3600
250	500	0.39	0.27	3750
300	400	0.42	0.28	3500
350	350	0.40	0.28	3500
400	300	0.39	0.26	3500

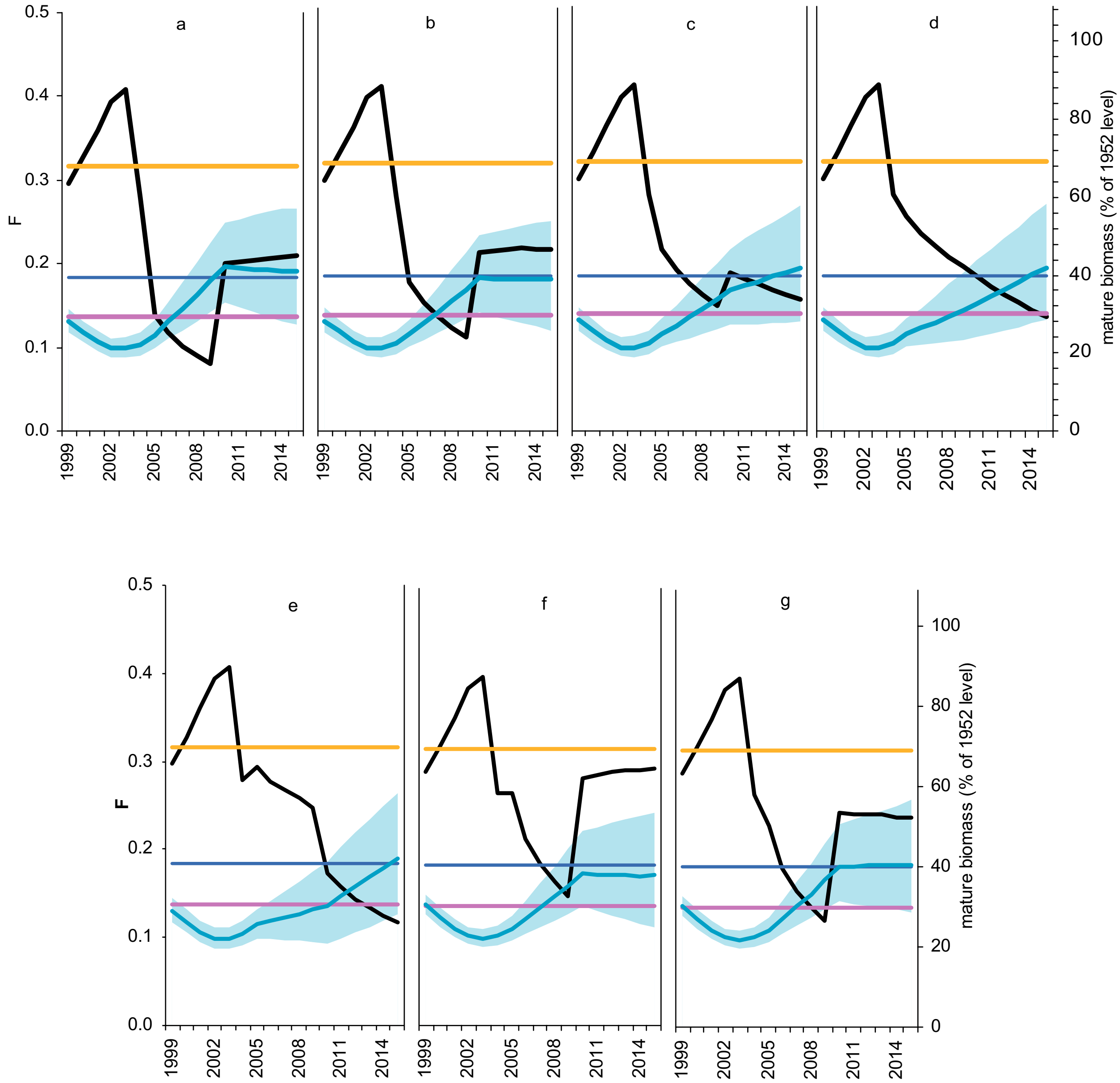

Figure 27. **Most likely mature biomass as a proportion of 1952 level (dark blue) with 90% confidence intervals (shaded area) for 7 catch scenarios with legal size 41 cm and 38 cm after 2004.**

a) catch 2005 to 2009 200 t, catch 2010 – 2014 520 t, and legal size 41 cm

b) catch 2005 to 2009 250 t, catch 2010 – 2014 500 t, and legal size 41 cm

c) catch 2005 to 2009 300 t, catch 2010 – 2014 400 t, and legal size 41 cm

d) catch 2005 to 2009 350 t, catch 2010 – 2014 350 t, and legal size 41 cm

e) catch 2005 to 2009 400 t, catch 2010 – 2014 300 t, and legal size 41 cm

f) catch 2005 to 2009 250 t, catch 2010 – 2014 500 t, and legal size 38 cm

g) catch 2005 to 2009 220 t, catch 2010 – 2014 480 t, and legal size 38 cm

7.7 Sustainable yield

The long-term or average maximum sustainable yield of the fishery is now estimated to be around 500 tonnes per year, significantly less than the previous estimate based on catch and effort data of 600 tonnes per year and less than the 2001-2003 TAC for the managed fishery of 564 tonnes.

While catches from the managed fishery have averaged around 500 tonnes per year, there have also been unrecorded catches by recreational and unlicensed commercial fishers which, in recent years were assumed to be around 50 tonnes per year, though they may in fact have been higher. The decline in mature biomass that could be expected from taking yields in excess of the maximum sustainable yield was obscured and delayed by the recruitment of strong year classes into the fishery in the mid-1990s, which sustained the fishery until the late 1990s.

The poor recruitments of the late 1990s have resulted in depleted stocks, probably similar to what they would have been if there had been average recruitment throughout. Catch Per Unit Effort data, although showing a decline in recent years, does not indicate the extent of the depletion, e.g. CPUE in 2002 was 70% of what it was in 1995, whereas the stock was around 45% of the 1995 level.

While management changes are in hand to bring all commercial catches in the area of the fishery under the managed fishery umbrella, the recreational catch is theoretically unlimited, though changes to bag limits will probably reduce it in the immediate future. If recreational catches can be kept to around 30 tonnes per year and significant catches of snapper smaller than 41 cm total length continue to be made, the maximum sustainable commercial catch will be around 450 tonnes.

The finding that recruitment does vary from year to year is consistent with more temperate snapper fisheries. The apparent autocorrelation in year class strengths, i.e. there seem to be runs of good years and runs of bad years, may be partially an artefact of ageing errors. An isolated strong year class could seem to be spread over adjacent years. However, the effect on numbers of mature fish is still there, regardless of ageing errors. The consequence for fishery management is that, while 480 tonnes may be an average or most likely sustainable yield, there will be times when a lower catch limit will need to be set because a run of low recruitment years has just happened. Similarly, there may be times when a run of good recruitment years will enable higher catches to be taken without reducing the mature biomass to below the 40% level.

Without some form of age-structured assessment on a regular and frequent basis, the information will not be available to decide what catch levels are sustainable at any given time.

7.8 Cost-benefit of future monitoring

7.8.1 Catch and effort data

The cheapest option for monitoring the fishery (Table 7, p.40) is to examine commercial catch and effort monitoring, which is done as part of the requirements for the annual State of the Fisheries Report to WA State Parliament and in future probably also for Environmentally Sustainable Development reporting to the Commonwealth. As this level of monitoring would require no fieldwork or sample processing, it could be achieved through the partial allocation of a research scientist, with input from data management staff, at a combined cost of around $30,000 per annum.

However, there are a number of disadvantages of only monitoring catch and effort, including:

1. Even when steps are taken to limit the variance (noise) in the data by only using data from the most consistent of the commercial fishers, the catch-rate is inherently variable from year to year, even when the population is very stable, such as in the late 1980s and early 1990s. Catch rates of 600-800 kg/day in June-July can be expected from a healthy stock. This makes it difficult to know whether a drop in catch rate reflects a drop in abundance or is simply noise.

2. The catch rate is not linearly related to snapper abundance. This is the phenomenon of hyperstability of catch-rate in fisheries based on large aggregations of fish (large compared with the number of fish you can catch in a day). The rate at which you can catch fish from a large school does not drop until there are almost no fish left in the school. Then, if there are more schools remaining, the catch-rate is maintained by moving to a new school.

3. There is no indication of events in the fishery such as strong and weak recruitments. Now that it is known that runs of years with weak recruitment can occur, it is important to have the earliest possible warning of such events so that fishing at a high level does not continue when there is little replacement stock entering the fishery, which is likely to cause spawning stock to drop to undesirable levels.

4. Changes in the efficiency of fishing can mask falls in fish abundance. It is rare for fisheries researchers to be able to quantify increases in efficiency. While we were aware that there had been changes in fishing practices from 1985 to 1987 which should have led to increased efficiency, we would not have been able to estimate how great the increase was without the age-structured assessments.

The indications from the cohort analysis are that the catch-rate remaining below 600 kg per day in June-July for consecutive years is a signal that abundance is below the desirable level. Unfortunately, by the time a problem with abundance can be recognized and a response mounted, the stock may have fallen to a level where future recruitment is jeopardized.

7.8.2 Size-structure monitoring

The addition of snapper size data to the basic catch and effort data can also be very cheap if grade information (the count and weight of snapper in each box) continues to be supplied by the main factories. The biggest problem that has arisen with this in recent years is the increasing trend to pack fish in "ungraded" 25 kg boxes. These may be truly ungraded fish, i.e. the whole of a boat's unload is packed without any sorting into size. They may also be fish left over after snapper of particular size categories have been taken out and packed in graded boxes for markets that have a preference for a particular size of snapper.

It would be necessary for the researchers to maintain an understanding of the packing practices by the main factories and also to collect length-frequency data on the two kinds of ungraded fish.

Around 16 field days per year, spread over four trips, would be required. About five days of time in the lab and fees of $200 - $500 to the programmers of the factory software to extract the data from factory computers would also be needed.

The interpretation of size data by itself is ambiguous. A change in length-frequency so that there is an increased proportion of small fish in the catch could either be a result of an unusually strong year-class entering the fishery, or of a big reduction in abundance of large fish due to excessive fishing mortality or a period of low recruitment several years earlier. Conversely, an increase in the number of large fish could reflect poor recent recruitment, strong earlier recruitment or low fishing mortality. Changes in fishing practises, which could potentially influence the sizes of fish caught, also need to be well understood when interpreting length-frequency data.

The best thing to do with length-frequency data is to somehow convert it to age-frequency data. This can be done with pre-existing data or concurrently collected age data.

A more expensive way, but more straightforward to analyse, of collecting length-frequency data is random sampling of catches prior to any grading. This means measuring fish as they are caught on the boats and/or intercepting them in the factory, e.g. on the chain between the cold storage room and the packing tables. The ideal method in the factory would be to take a tub of fish out of the chain as soon as it came out of the cold room, measure all the fish in the box then re-insert it in the chain while taking out another tub.

Advantages of on-board monitoring are that discards can be measured (mainly undersize snapper) and observations on bycatch of other species can be recorded. The former is necessary to get a complete picture of what sizes of snapper are killed by the fishery (assuming discard mortality to be high), the latter to satisfy requirements of ESD reporting to maintain the fishery's licence from the Commonwealth to export fish.

As fish size monitoring in some form is highly desirable, we recommend a focus on on-board monitoring, supplemented by measurements in the factory prior to any grading.

7.8.3 Age-structure monitoring

The conversion of length-frequency data to age-frequency can be done using pre-existing information from a growth equation, age-length keys based on fish that have been aged, or keys to convert length to some proxy for age such as sagittal otolith weight or medio-lateral thickness. This report provides a set of such pre-existing information upon which future conversions of length frequencies can be based if this is the chosen form of monitoring.

One of the potential problems of using earlier rather than concurrent data for conversion of length to age-frequencies is that growth rates can change. This occurred in a very dramatic way for lobsters off the west coast of South Africa (Pollock et al., 1997) but, more pertinently, for snapper in New Zealand. Davies et al. (2003) found that the effect of the change in growth by New Zealand snapper was such that stock assessments were badly out and sustainable yields were substantially lower than would have been estimated using pre-existing data.

Although there is extra expense involved in concurrent age-length data collection, we believe that it is worthwhile given that changes of growth of snapper have been demonstrated elsewhere and would occur without warning. New Zealand scientists have estimated that around 500 fish per stock per year, randomly sampled from the catch, are adequate.

Snapper sizes can vary from place to place within the fishery, and also from season to season. We consider that sampling of 25 catches per year, spread across seasons and localities in proportion to the catches from those seasons and localities, would be necessary to obtain a representative sample. Samples of 20 fish per catch from 25 catches would provide the 500 otolith samples. Length frequency samples of 200 fish per catch from the same number of catches would provide an adequate and representative length-frequency distribution for the fishery.

One of the problems that has occurred in past otolith collections is that the iki-jimi method of spiking the fish in the brain immediately after capture, though humane and good for product quality, damages the otoliths of a significant proportion of the fish. The time taken to collect 500 otoliths could be reduced by extracting otoliths on board the boats from fish that have not been spiked, or getting fishers to bring in 20 unspiked fish from a number of their catches each year.

Table 7. Costing (at 2003 prices) of various options for monitoring the Shark Bay Snapper Managed Fishery.

	Catch and Effort only	CE + factory grade data	CE + Length-sampling	Age-structured modelling
Salaries	4174	11482	29155	39370
Travel	1295	5123	15296	14850
Operating	2400	2400	1600	150
Total	7869	19005	46051	54370

Monitoring of pre-recruit year-class strength to give early warning of strong and weak recruitments which could require temporary management changes would be a significant advantage to management and to fishers in that measures such as temporary quota reductions could be spread over a number of years. This is an important component of the New Zealand snapper fisheries monitoring. Ongoing pre-recruit monitoring would need to be preceded by a research program to identify the best methods and locations to sample. An application to FRDC to begin such a research program in 2004 was unsuccessful (FRDC 2004/053).

7.8.4 Recommended fishery monitoring strategy

Until the estimate of spawning stock returns to 40% of the 1952 level, we recommend full on-board age and size monitoring. Although it is the most expensive of the options considered, it is important to know when the stock reaches this level so that a higher TAC can be implemented. After that, a re-evaluation of monitoring should occur. The recommended strategy is to sample otoliths of 500 snapper, 20 each from 25 catches per year for an age-length key, and 200 fish from at least 25 catches for length-frequency. The sampling intensity by season and area should match the seasonal and spatial distribution of the catches.

8.0 Benefits and adoption

8.1 Meetings with industry/working group

This project originally was intended to analyse data from the fishery up to 2000. When the cohort analysis for this period indicated that the spawning stock in 2000 was at a very low level compared with the 1980s, meetings were held with industry in mid 2003 to inform them of the assessment and obtain their feedback.

These meetings were followed by proposals to the Minister for Fisheries that, as an interim measure, the TACC for the managed fishery be reduced by 40%, which was supported by industry. The data for 2001-2003 would be worked up and included in an updated analysis and, if appropriate, the TACC for 2004 would be amended early in 2004. This updated analysis is the one presented in this report.

The Minister approved the interim management measures and asked that a working-group be formed to recommend short, medium and long-term management measures to address the problem of low spawning stock level. These recommendations were made to the Minister in late 2003 and the short-term measures proposed have been approved and are being implemented in 2004. The Minister has confirmed the interim decision on the 40% reduction to the TACC for the 2003-2004 season.

In addition to the reduction in TACC for the managed fishery, the issue of additional snapper mortality as a result of a bycatch of pink snapper by commercial fishers targeting other demersal species in the area of the fishery is being resolved by requiring all demersal fishers in the area to have snapper quota. All commercial catches of legal-sized snapper will in future be limited by the TACC.

From time to time, when an exceptionally strong year-class is approaching age of recruitment to the fishery, the abundance of undersized snapper increases in relation to the abundance of legal-sized snapper. This is particularly so in 2004 when the stock of mature snapper is estimated to be at its lowest since the start of the fishery. Industry is aware that a large proportion of undersized snapper returned to the water die and has proposed a reduction in minimum size so that these wasted smaller snapper can be kept for sale, accounted for within the TACC and hence result in an overall reduction in the fishing mortality. This proposal has implications for other commercial snapper fisheries and recreational fisheries in the state and is being examined.

A monitoring program is in place for 2004 whereby 25 catches will be sampled either in the factory or at sea, providing otoliths for 500 fish and lengths for 5,000. The catches to be sampled are selected according to the areas and months worked by the fishery to be representative of the total catch. Changes to the way catch and effort data are collected are being implemented for 2004 to take account of the development of a deep water fishery targeted at goldband snapper. It may no longer be appropriate to assume that during the peak snapper season of June and July, all effort by managed fishery boats will be targeted at pink snapper. Information from processors and the quota forms will be used in the peak season to determine whether or not each trip was targeted at pink snapper

Following the release of this report, there will be further meetings between industry, managers and researchers to discuss future management and monitoring for the fishery.

8.1.2 Meetings held to discuss the stock assessment and future management

June 6, 2003, Dr M Moran met with all snapper industry members present at the time in Carnarvon and Denham to advise them of the results of the stock assessment.

July 1, 2003. Department of Fisheries senior staff, Drs Lindsay Joll, Program and Rick Fletcher, supervising scientist, Stock Assessment and Data Analysis Branch, invited all snapper industry members to a formal meeting to discuss the stock situation and appropriate interim measures. This meeting was preceded by an industry meeting without Department of Fisheries staff so that industry could come to a position on the issue.

A working group was set up at the request of the Minister for Fisheries to advise him on management responses to the current state of the fishery. The workgroup met three times and provided its report in early November 2003. The Minister has adopted the groups recommendations for short term management measures.

Working Group Membership

Sue Jones	independent chairman
Peter Glass	snapper fishery licensee
Mark Grove	snapper fishery licensee
Peter Jecks	snapper processing factory, snapper fishery licensee
Simon Little	snapper processing factory
Steve Lodge	snapper processing factory
Richard Patty	trawl industry
Steve Powell	commercial fisher
Lindsay Joll	Department of Fisheries. manager, Commercial Fisheries Management

Observers/advisors

Felicity Horn	WA Fishing Industry Council
Laurie Caporn	Department of Fisheries, Gascoyne regional manager
Tim Nicholas	Department of Fisheries, senior fisheries officer, Carnarvon
Mike Moran	Department of Fisheries, finfish research branch

9.0 Further Development

9.1 Cost-effective ageing

The cost of age-structured monitoring may be able to be reduced if innovative methods are developed of estimating age-structure. This will be evaluated for a range of finfish, including snapper in FRDC project 2004/042.

10.0 Planned outcomes

The major outcome of this project has been an assessment of what yields can be taken in the short term to rebuild the stock to the desired level and in the medium term to maintain it. Although the expectation was that the capacity of the stock for increased yields would be estimated, the occurrence of a series of years of low recruitments late in the time-series has enabled estimation of a more realistic sustainable yield, taking into account the natural variation in recruitment which now appears to occur in all snapper stocks.

The expectation that costs of monitoring the fishery could be reduced have also not been met in the short term, due to the current depleted state of the stock. Since the fishery is not as healthy or as stable as previously thought, it is advisable to continue age-structured monitoring until the stock returns to its target spawning biomass. Monitoring methods should be reviewed again at that time, with the additional benefit of FRDC project 2004/042.

11.0 Conclusion

***Objective 1**. Estimate annual recruitment and fishing mortalities in the snapper fishery throughout the 1980s and 1990s.*

Recruitment was found to be moderately variable, sufficiently so to cause occasional problems in the fishery when there is a run of years of low recruitment. The low year-class strengths in the late 1990s resulted in the low spawning biomasses in 2000-2003. Lack of forewarning of these low recruitments meant there could be no management response such as a moderate cut in TAC leading into the low stock years and required a severe quota cut to address the problem and rebuild the spawning stock.

Fishing mortality has been at a sustainable level throughout most of the recent history of the fishery, with the exception of the mid 1980s when there was a big influx of fishing effort, and in the recent years when fishing effort was maintained at a normal level but operating on a reduced stock. This study has found evidence that catchability increases as stock size decreases for snapper, as expected for a strongly aggregating species.

***Objective 2.** Assess the risks to the snapper stock of a range of annual commercial and recreational catches, taking into account the mortality of discarded fish and variability in recruitment.*

Various management scenarios were evaluated in relation to a 50% risk of the spawning stock falling below the reference point (40% of virgin biomass) and in relation to a 5% risk of spawning stock falling below 30% of virgin biomass. A scenario was considered acceptable if the risk of the stock falling below 40% of virgin biomass was less than 0.5 and the risk of falling below 30% of virgin biomass was less than 0.05. Assuming the same degree of variability in recruitment that was seen in the 1980s and 1990s, a catch limit (commercial plus recreational) of 250 tonnes per year from 2005 to 2009 would allow the stock to rebuild to 40% of virgin level in that time (probability 0.5). Thereafter an annual catch limit of 500 tonnes is estimated to have a probability of 0.5 of maintaining the stock at that level.

If significant amounts of undersize snapper are caught, the probabilities of achieving the stock level targets are reduced. The annual catches that have a probability of 0.5 of rebuilding and maintaining the stock at 40% of virgin biomass are 220 tonnes from 2005 to 2009 and 480 tonnes thereafter. With undersized snapper returned to the sea in deep water, post-capture mortality is likely to be in excess of 80%, so the effect on the stock is similar whether or not the fish are retained. It is worthwhile for managers to review the minimum legal length in this light.

The proportion of the catch that is undersize varies, depending largely on whether a strong year-class of young snapper is just approaching minimum legal size. There are indications that a strong recruitment is occurring in 2004, so the problem of catching large numbers of undersize is worse than normal. The other aspect of a strong recruitment in 2004, provided it is followed by years of average or strong recruitment, is that rebuilding the stock to the target level is likely to be accelerated.

12.0 Management recommendations

1. That a catch limit of 220 tonnes per year be implemented for the years 2005 to 2009. This is combined recreational and commercial catch.
2. That the minimum legal size be reviewed to avoid wastage of the catch of undersize snapper which suffer high post-release mortality.
3. That the catch limit be reviewed annually using the risk assessment with the age-structured model to determine whether it can be safely increased.
4. That consideration be given to spatial closures, possibly limited to the peak fishing season, to minimize the catch of snapper smaller than 41 cm.

Objective 3. *Devise a minimal cost method for future monitoring of the snapper fishery.*

Until the estimate of spawning stock returns to 40% of the 1952 level, we recommend full on-board age and size monitoring. Although it is the most expensive of the options considered, it is important to know when the stock reaches this level so that a higher TAC can be implemented. After that a re-evaluation of monitoring should occur. The recommended strategy is to sample otoliths of 500 snapper, 20 each from 25 catches per year for an age-length key, and 200 fish from at least 25 catches for length-frequency. The sampling intensity by season and area should match the seasonal and spatial distribution of the catches.

Research recommendations:

1. That future monitoring include a component of on-board measuring of snapper, representative of the areas and seasons fished. This will allow description of the spatial distribution and abundance of fish of various sizes, possibly enabling spatial protection of small fish. It may also give advance warning of the occurrence of strong and weak year classes.
2. That consideration be given to surveys of abundance of 1-year old juveniles to give even more advance warning of extreme recruitment events.
3. That a representative sample of 500 snapper be sampled annually for age-determination, from at least 25 separate fishing trips, spread throughout the area of the fishery and the seasons in similar proportions as the catch.
4. That the age-structured model be updated annually, at least in the short term until mature biomass is estimated to be 40% or more of the virgin biomass.

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14.0 Appendices

Appendix 1: Intellectual Property

The results of this research are in the public domain, there are no intellectual property implications.

Appendix 2: Staff

Staff employed on the project were:

Dr M. Moran, Dr D. Gaughan, Mr P. Stephenson, Ms N. Tapp, Ms H. Mee and Mrs J. Moore.

Appendix 3: Equations for the age-structured model

The number of pink snapper in the fishery at the start of year *y* are determined by;

$$N^{s}_{a,y+1} = \begin{cases} R_{y+1} & \text{if } a = 0 \\ N^{s}_{a-1,y}\left[\left(1 - F_y V_{a-1}\right)e^{-M}\right] & \text{if } 0 < a < A \\ N^{s}_{A,y}\left[\left(1 - F_y V_A\right)e^{-M}\right] + N^{s}_{A-1,y}\left[\left(1 - F_{1,y} V_{A-1}\right)e^{-M}\right] & \text{if a} = A \end{cases} \qquad \text{Eq. 1}$$

where R_y is the recruitment to the fishery,

F_y is the harvest rate at the end of the year.

V_a is the proportion of vulnerable snapper of age *a*.

A is the maximum age

The number of 2 year old fish that recruit to the fishery at the start of each year is related to the biomass of spawning females (tonnes) at the end of the previous year according to:

$$N_{y+1,2}^{s=\text{female}} = \rho \frac{S_y}{\alpha + \beta S_y} \qquad \text{Eq. 2}$$

where S_y is the spawning biomass at the end of year *y*:

$$S_y = \rho \sum_{s=m,f} \sum_{a=1}^{A} N_{a,y}^{f} p_a W_a$$

α , β are parameters of the stock recruitment relationship steepness (*h*) and the virgin spawning biomass according to;

$$\alpha = \frac{S_1}{R_{init}} \left(1 - \frac{h-0.2}{0.8h}\right) \text{ and } \beta = \left(\frac{h-0.2}{0.8\,h\,R_{init}}\right)$$

p_a is the proportion of females mature at age a given by

$$p_a = \left(1 + e^{-\ln(19)\left(\frac{a-a_{0.5}}{a_{0.95}-a_{0.5}}\right)}\right)^{-1}$$

where $a_{0.5}$ and $a_{0.95}$ are the ages when 50% and 95% are mature.

The number of snapper (millions), at start of 1952,the initial state, is

$$N_{a,1952}^{s} = \begin{cases} (1-\rho)R_{init}e^{-(a-1)M} & \text{if } s = male \text{ and } 2 \le a < A \\ \rho R_{init}^{\gamma} e^{-(a-1)M} & \text{if } s = female \text{ and } 2 \le a < A \\ (1-\rho)R_{init}\dfrac{e^{-(a-1)M}}{1-e^{-M}} & \text{if } s = male \text{ and } a = A \\ \rho R_{init}\dfrac{e^{-(a-1)M}}{1-e^{-M}} & \text{if } s = female \text{ and } a = A \end{cases} \qquad \text{Eq. 3}$$

where ρ is the proportion of each sex, R_{init}^{γ} is the estimated number of 2 year olds at unexploited equilibrium.

The number of recruits at the beginning of subsequent years is given by:

$$N_{y+1,0} = \begin{cases} R_y & y = 1952 \\ R_y\, e^{\varepsilon_y} & 1985 < y \le 2003 \\ R_y\, e^{N(0,\sigma_y{}^2)} & y > 2003 \end{cases} \qquad \text{Eq. 4}$$

where R_y the recruitment in the fishery from the stock recruitment relationship

ε_y is a random variable generating deviations in the recruitment for year *y*,

σ_y^2 is the variance of the random variables ε_y

$N(0,\sigma_y^2)$ is a random variable generating recruitment deviations

The estimated biomass of sexually mature fish D_y, in tonnes, at the end of year *y* for snapper of sex *s* was calculated as

$$D_y = \sum_{s=m,f} \sum_{a=2}^{A} N_{a,y}^{s} \, p_a \, W_a \qquad \text{Eq. 5}$$

The estimated biomass of sexually mature females S_y, in tonnes, at the end of year *y* for snapper of sex *s* was calculated as

$$S_y = \sum_{a=2}^{A} N_{a,y}^{f} \, p_a \, W_a \qquad \text{Eq. 6}$$

The estimated exploitable biomass B_y, in tonnes, at the end of year *y* for snapper of sex *s* was calculated as

$$B_y = \sum_{s=m,f} \sum_{a=2}^{A} N_{a,y}^{s} \, v_a \, W_a \qquad \text{Eq. 7}$$

where v_a is the vulnerability of fish of age a, estimated for $2 \le a \le 8$ and taken as 1 for $a > 8$

The catch by weight in year *y* is given by

$$C_y = C_y^C + C_y^R + C_y^F + C_y^C \qquad \text{Eq. 8}$$

where C_y^C is the commercial domestic catch, C_y^R is the recreational catch, C_y^H is the charter catch, and C_y^Q is the foreign catch

The fishing mortality F_y and is determined from

$$F_y = \begin{cases} \dfrac{C_y}{B_y} & 1952 \le y \le 1984 \\ q_y E_y & 1985 \le y \le 2003 \\ \dfrac{C_y}{B_y} & y \ge 2004 \end{cases} \qquad \text{Eq. 9}$$

where E_y is the effort in year, and the catchability is given by

$$q_y = \begin{cases} q & 1952 \le y \le 1984, \; y > 2003 \\ q + \alpha - B_y \times \beta & 1985 \le y \le 2003 \end{cases}$$

$\alpha = 9.443 \times 10^{-5}, \beta = 3.1777 \times 10^{-8}$

The logarithm of the likelihood function associated with the numbers at age from 1983 to 2003 was determined from

$$\lambda_2 = 0.5 \sum_{a=2}^{A} \left(A_{a,y} - \hat{A}_{a,y} \right)^2 \qquad \text{Eq. 10}$$

where $A_{a,y}$ is the observed numbers at age in year y

$\hat{A}_{a,y}$ is the model estimated numbers at age a, in year y determined from

$$\hat{A}_{a,y} = N_{a,y} \frac{\nu_a F_i \left(1 - e^{-(\nu_a F_i + M)}\right)}{\nu_a F_i + M}$$

$N_{a,y}$ is the number of fish in the age composition sample

K_2 is a weighting factor.

The recruitment residuals in each area are assumed to have mean zero and are log-normally distributed. Their contribution to the logarithm of the likelihood function is

$$\lambda_3 = K_3 \frac{1}{2\sigma_r^2} \sum_y \varepsilon_y^2 \qquad \text{Eq. 11}$$

where K_3 is a weighting factor.

The steepness, *h*, was assumed constant for all three stocks.

The objective function which is minimised in the model consists of the negative of the logarithm of the likelihood functions, together with the penalty functions as shown:

$$\lambda = -K_1\lambda_1 - K_2\lambda_2 - K_3\lambda_3 + P_1K_4 \qquad \text{Eq. 12}$$