

# Stock assessment of whaler and hammerhead sharks (Carcharhinidae and Sphyrnidae) in Queensland



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**Queensland**  
Government

This publication provides an assessment of the state of populations of tropical and subtropical sharks, some of Australia's most important marine predators, with recommendations for management, future research and data collection.

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## Executive summary

The majority of commercial shark product caught in Queensland comes from the East Coast Inshore Fin Fish Fishery (ECIFFF) and the Gulf of Carpentaria Inshore Fin Fish Fishery (GOCIFFF). The take of shark is managed through a variety of input and output controls such as maximum legal size limits, in possession limits and, in the case of the Queensland east coast, a total allowable commercial catch (TACC) limit. Data on shark catch sizes and catch rates are principally obtained through the commercial logbook system which has operated from 1988 to present, while data on the shark species composition have come mainly from the Fishery Observer Program (FOP) which operated only from 2006 to 2012. The logbook information has been built upon by ancillary projects such as the National Status of Australian Fish Stocks (SAFS) and Queensland Stock Status assessment processes. Shark species that interact with Queensland commercial and recreational fisheries have not been the subject of a formal stock assessment until now.

This stock assessment provides detailed results for the most common sharks encountered by Queensland commercial fishers. These sharks come from the whaler (Carcharhinidae) and hammerhead (Sphyrnidae) families and comprise sharpnose sharks (*Rhizoprionodon taylori* and *R. oligolinx*), the milk shark (*R. acutus*), the creek whaler (*Carcharhinus fitzroyensis*), the hardnose shark (*C. macloiti*), the spot-tail shark (*C. sorrah*), the Australian blacktip shark (*C. tilstoni*), the common blacktip shark (*C. limbatus*), the spinner shark (*C. brevipinna*), bull and pigeye sharks (*C. leucas* and *C. amboinensis*), the winghead shark (*Eusphyra blochii*), the scalloped hammerhead (*Sphyrna lewini*) and the great hammerhead (*S. mokarran*). Reef sharks were excluded because fishery observer data indicated that they were largely spatially segregated from sharks caught in the inshore net fisheries. The three common species of reef sharks in Queensland, which are all whaler sharks, are the grey reef shark *Carcharhinus amblyrhynchos*, the blacktip reef shark *C. melanopterus* and the whitetip reef shark *Triaenodon obesus*.

The assessment includes a new demographic analysis to estimate shark populations' natural mortality rates and productivity parameters. Compared to previously published demographic analyses of sharks, the new one offers consistent methodology over all the species assessed, uses up-to-date data specific to Australia where possible, corrects some errors and converts the demographic parameters into parameters commonly used in fishery stock assessment models (most notably in the stock–recruitment relationship).

The population dynamic model used in the assessment was tailored to the quality of the available data, especially the lack of shark species identification by fishers in the logbook data. The model analysed all shark species simultaneously and used population parameters from the new demographic analysis which in turn made use of the wealth of biological data available for sharks. Input data on species composition came only from the Fishery Observer Program. Species compositions before and after the time of the FOP were inferred indirectly by the model.

The model divided Queensland waters into three broad “Management regions”: the Gulf of Carpentaria, the northern east coast and the southern east coast. As shark populations can display strong regional differences, the Management regions were further divided into a total of ten Subregions, based on sampling regions used in the Queensland Long Term Monitoring Program (LTMP). Population parameter estimates were calculated for each species present in each Subregion.

The FOP data used for species identification in the assessment were compared to the frequency of species encountered in a major shark tagging experiment (James Cook University, FRDC, project no. 2010/006). The comparison showed close agreement between the two data sets, thereby providing verification of the accuracy of the FOP data on species composition, except for a discrepancy in the proportions of sharpnose sharks recorded. The

tagging program recorded more sharpnose sharks while the FOP recorded more of other species of small sharks.

Fishery logbook data were not used for species composition due to the inaccuracy of shark species identification by fishers. Logbook data were used only to calculate annual harvest sizes and standardised catch rates for the aggregate of all shark species. These model inputs were still subject to substantial statistical error and potentially to biases from sources including frequent catches of sharks by fishers targeting various species of bony fish such as mackerel and barramundi, consequent discarding of sharks, market preference for small sharks, and political sensitivities that may affect fishers' reporting of shark catches. Discards usually were not recorded in logbooks. Other sources of error include possible inconsistencies in how characteristics such as net length are reported in the logbooks, absence of data on net depth, and absence of detail on precise locations in which nets were set, e.g., distance from shore and depth of water.

Fishery catch rates were considered reliable enough to use in the assessment only from the year 1991 onwards, i.e., three years after the beginning of the logbook system. Standardised catch rates, due to the difficulty of species identification by fishers, could be defined only for all shark species combined and were not species-specific. The catch rates showed no meaningful trends in most Subregions but trended downward in the Whitsunday (covering Bowen and Mackay) and Stanage Subregions, and upward in the Rockhampton, Sunshine Coast and Moreton Subregions.

Biological data, in contrast to fisheries data, are of high quality for some species of sharks. Growth parameters, life cycles and reproductive rates are known with some precision. These data supported the stock assessment by providing reliable estimates of length at age, age at maturity, litter size and maximum age attained.

Use of data from the Shark Control Program (SCP) protecting popular Queensland east coast bathing beaches was explored. On the advice of the assessment's Project Team, these data were not used in the assessment, mainly due to concerns about numerous changes in both gear and gear-setting techniques over time. SCP data were available from the beginning of the SCP in 1962. A major feature was a long (roughly 15-year) initial period of depletion of local shark populations after shark control gear was introduced, followed by much lower catch rates after this period. As with fishery data, SCP data suffered from lack of reliable species identification.

Estimates of population parameters in the assessment are presented from model simulations by Markov chain Monte Carlo (MCMC). The study ran a total of 500,000 MCMC iterations with every 50th simulation being saved. The limitations of the input data were reflected in the population model outputs with population size estimates subject to large statistical errors. The input data failed to provide realistic upper limits for the population size estimates, due to standardised catch-rates remaining stable or increasing in the majority of Subregions. However, minimum values of population size were determined with greater certainty. The primary reasons for this were that (a) values had to be consistent with the catch-size history and (b) none of the catch-rate time series for the different Subregions displayed large declines.

As a consequence of the data limitations, the assessment adopted a conservative approach to the estimation of maximum sustainable yield (MSY) for sharks. Species-specific MSY calculations assumed a multi-species fishery in which no species was allowed to be fished beyond the fishing mortality rate corresponding to its individual MSY: hence the rate of fishing for all species present in a Subregion was limited to that which produced MSY for the most sensitive species in that Subregion. In addition, the maximum-likelihood MSY estimate was not used and the scope of the study was restricted to the lowest 25% of the saved simulations. The study selected two representative parameter vectors for further analysis. The first vector was termed the *Substitute Maximum Likelihood Estimate* vector and came from the low-end of a cluster of highly likely MSY simulations. The second vector was

termed the *Minimum-MSY Estimate* and represented one of the lowest MSY values produced by the population model. The *Minimum-MSY Estimate*, by design, is highly conservative and is situated within the lowest 0.5% of the total-MSY values. The use of these two vectors, although nominally conservative, still carries an implication that the input data, especially the catch rate time series, are not heavily biased and that upward trends in catch rates in some Subregions are not due to large increases in fishing efficiency.

The *Substitute Maximum Likelihood Estimate* indicates MSY of 4903 tonnes per year (all regions and species combined), comprising 1111 t in the Gulf of Carpentaria, 2121 t in the northern east coast management region and 1670 t in the southern east coast management region. The breakdown of the indicative MSY in tonnes by species groups was as follows:

<b>Species</b>	<b>Gulf</b>	<b>Northern</b>	<b>Southern</b>	<b>Total</b>
Sharpnose and milk sharks, <i>Rhizoprionodon spp.</i>	34.7	117.2	266.6	418.5
Creek whaler, <i>Carcharhinus fitzroyensis</i>	9.1	29.6	–	38.6
Hardnose shark, <i>C. macroti</i>	–	62.0	–	62.0
Spot-tail shark, <i>C. sorrah</i>	121.5	280.7	47.2	449.5
Australian blacktip shark, <i>C. tilstoni</i>	512.5	670.4	–	1183.0
Common blacktip shark, <i>C. limbatus</i>	–	117.5	789.6	907.1
Spinner shark, <i>C. brevipinna</i>	–	68.0	329.5	397.5
Bull & pigeye sharks, <i>C. leucas</i> & <i>C. amboinensis</i>	258.8	438.2	191.6	888.7
Winghead shark, <i>Eusphyra blochii</i>	26.0	–	–	26.0
Scalloped hammerhead, <i>Sphyrna lewini</i>	69.0	163.0	45.8	277.8
Great hammerhead, <i>S. mokarran</i>	79.8	174.6	–	254.4
<b>Total</b>	<b>1111.4</b>	<b>2121.4</b>	<b>1670.3</b>	<b>4903.0</b>

Sharpnose sharks and the milk shark have been grouped together in this table because of the discrepancy in species identification between by the FOP and the JCU–FRDC tagging project mentioned above.

The *Minimum-MSY Estimate* vector produced a much lower total-MSY of 1273 t per year consisting of  $\geq 196$  t from the Gulf of Carpentaria,  $\geq 563$  t in the northern east coast management region and  $\geq 513$  t in the southern east coast management region. The species-specific breakdown was the following (in tonnes):

<b>Species</b>	<b>Gulf</b>	<b>Northern</b>	<b>Southern</b>	<b>Total</b>
Sharpnose and milk sharks	9.2	31.7	24.3	65.2
Creek whaler	5.0	9.7	–	14.8
Hardnose shark	–	14.1	–	14.1
Spot-tail shark	29.4	80.2	28.4	138.0
Australian blacktip shark	95.0	143.6	–	238.5
Common blacktip shark	–	34.0	213.3	247.3
Spinner shark	–	5.9	116.0	121.9
Bull & pigeye sharks	17.2	159.9	117.7	294.8
Winghead shark	4.3	–	–	4.3
Scalloped hammerhead	25.7	52.4	13.7	91.8
Great hammerhead	10.4	31.6	–	42.0
<b>Total</b>	<b><math>\geq 196.2</math></b>	<b><math>\geq 563.1</math></b>	<b><math>\geq 513.4</math></b>	<b><math>\geq 1272.8</math></b>

This simulation was less likely than the *Substitute Maximum Likelihood Estimate*: the negative log-likelihood was 13.0 units higher, corresponding to a value  $2 \times 13.0 = 26.0$  units higher in an approximate  $\chi^2$  statistic with 86 degrees of freedom (the number of parameters in the model).

Based on the data and this analysis, current commercial shark catches in Queensland are below MSY limits. Current TACCs are 480 t per year in the northern east coast management region and 120 t per year in the southern east coast management region. Annual harvest in the Gulf of Carpentaria has been around 300 t since 2008. There are, however, major concerns

about data quality, availability of data on discard rates of sharks, and lack of species composition data outside of the short period (2006–2012) over which the FOP operated. Reducing these uncertainties in future should increase confidence around MSY estimates, supporting the finding that catch levels for shark species covered by this assessment are currently sustainable.

The biggest potential improvement to future assessments of sharks in Queensland would come from better-quality input data. If resources can be made available, major benefits would arise from a survey of fishing gear and technology in the inshore net fisheries, some means of expert species identification of future commercial harvests and discarded catch, and accurate recording of net length, net depth and water depth in commercial logbooks.

## Acknowledgements

Many people other than the nominal author have contributed to this stock assessment. The assessment was overseen by a Project Team which met several times and provided very valuable advice. The Project Team comprised the following members:

- Dr Peter Baxter of the Centre for Applications in Natural Resource Mathematics (CARM), University of Queensland, mathematical ecologist
- Nadia Engstrom and Anna Garland, data coordinators for Fisheries Queensland (FQ, a Division of the Department of Agriculture and Fisheries, DAF) who provided the commercial logbook data and Fishery Observer Program data. Nadia also proved extremely knowledgeable about the observer data and the history and management of the fishery, and provided expert answers to many questions about these aspects.
- Dr Colin Simpfendorfer of James Cook University, expert on shark biology and shark fisheries
- Dr Andrew Tobin of James Cook University, expert on the Queensland shark fishery and on shark biology
- Dr Wayne Sumpton of Agri-Science Queensland (ASQ, another branch of DAF), expert on the Queensland Shark Control Program which protects swimmers from sharks at Queensland's popular bathing beaches, and more widely on shark biology
- Anthony Roelofs of FQ who initiated the Project Team and was the first chairman
- Dr Ian Jacobsen of FQ who took over as chairman after the first meeting and acted as the public contact for information about the shark stock assessment
- Michael Mikitis of FQ, contact for FQ's stock assessment requirements
- Dr Jonathan Staunton-Smith of FQ, leader of the southern Queensland Long Term Monitoring Program which undertakes scientific sampling and analysis of important species in Queensland's fisheries
- Tony Ham of FQ, fishery manager
- Andrew Thwaites of FQ, Director of regulatory reform
- Michael O'Neill of ASQ, leader of the fishery resource assessment group, who also provided valuable comments on drafts of this report.

The internal DAF members are especially grateful to Colin Simpfendorfer and Andrew Tobin for travelling from Townsville to provide their inputs to Project Team meetings.

Dr Peter Baxter made a substantial contribution to the assessment. He undertook the exploratory analysis of the Shark Control Program data presented in Appendix 1. It was later decided not to use this data source in the assessment, but it could be revisited in future assessments and could be used in ways other than provision of time series of catch rates which are assumed proportional to abundance. He advised on the demographic model in chapter 2 from his previous experience of demographic models which were a new field for me. He also made very beneficial comments on a previous draft of this report.

Dr Andrew Tobin, and all the staff involved in the shark tagging project that he led, generously provided data from that project, which was funded by the Australian Government's Fisheries Research and Development Corporation (FRDC project no. 2010/006). These data contributed valuable information on the species composition of the fishery and the mortality rates of sharks.

Dr Jenny Ovenden and Dr Jess Morgan of the University of Queensland ensured that I was as well informed as possible about the relative abundances of the two blacktip sharks (the Australian blacktip shark and the common blacktip shark) in different regions, and recommended that we separate them by latitude on the basis of results on mitochondrial DNA. These two species are visually indistinguishable and could be separated only by genetics or dissection followed by vertebral counts, although work is currently in progress to try to separate them by morphometrics.

The ADMB source code for the Cabezon stock assessment model, on which the model for this assessment was built, was kindly provided by Dr André Punt of CSIRO and the University of Washington.

Susan Theiss from FQ acted as data coordinator for the logbook and Fishery Observer Program data while Nadia Engstrom was on maternity leave.

Fisheries scientists from the New South Wales and Northern Territory fisheries jurisdictions helped with information about their shark fisheries, in which some of the species were common with Queensland.



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# 1. Introduction

## 1.1 Overview and data sources

Sharks are important members of marine ecosystems, often top-level predators, and are common in Queensland coastal waters. The concept of “fishing down the food web” (Pauly *et al.* 1998; Pauly and Palomares 2005), the low reproductive rate of sharks compared to most bony fish (see, e.g., Au *et al.* 2008) and the demand for shark products in Asia have all caused concerns about the sustainability of shark populations worldwide. Five species of sharks, including the scalloped hammerhead *Sphyrna lewini* and great hammerhead *S. mokarran*, were added to the *Convention on International Trade in Endangered Species of Wild Fauna and Flora* (CITES) in 2013 (Carrington 2013; CITES 1979, 2014) and this has affected the Australian Government’s obligations for accreditation of the Queensland shark fishery as a Wildlife Trade Operation under the *Environment Protection and Biodiversity Conservation (EPBC) Act 1999*. The validity of the concept of fishing down the food web, whereby a fishery begins by fishing down top-level predators and then proceeds to successively fish down species at lower levels in the food web, is disputed (Hilborn 2007) but is still widely believed in both scientific circles and the wider community.

This stock assessment has been undertaken to assess the status of exploitable shark populations in Queensland. It concentrates on the most common families of sharks encountered by Queensland commercial fishers: whaler sharks (family Carcharhinidae, known in many countries as “requiem sharks”) and hammerhead sharks (family Sphyrnidae). The tiger shark *Galeocerdo cuvier* is a member of Carcharhinidae and is very common in Queensland but was excluded from this assessment because it is caught in only very small numbers by fishers and adequate fishery data on it were not available.

The original target species for assessment are listed in Table 1. The “category” descriptor was defined for convenience in the stock assessment, but has no definite biological meaning. Roughly, a “small whaler” is a whaler species that grows to around one metre in length and is completely selected by the commercial gillnet fishery. A “medium whaler” is one that grows to a maximum length around 1.5–2.5 m and in which large adults are generally not caught by gillnets. A “large whaler” is a whaler species that grows over 2.5 m in which juveniles are caught by gillnets and most adults are not. The “hammerhead” category covers all the hammerhead sharks, which have very different net-selectivity characteristics to whalers.

Six additional species groups were added to the assessment due to lack of reliable species identification in the fishery data. The final twelve species groups used in the assessment are listed in Table 2. Many shark species are very difficult to distinguish, even for experts, especially during the juvenile stages of their life history. Consequently, much of the data available for stock assessment relates to multi-species aggregates. The twelve species groups cover the species commonly caught in the fisheries, and less common species were also allocated to these groups on the basis of similarity in biology (see section 1.2 and Tables 3 and 4).

The species of sharks encountered in Queensland are described in the next section “Shark taxonomy and biology”, but we draw attention here to the small whalers which are caught in substantial numbers in Queensland. The small whalers generally grow to a maximum total length of around one metre, and are themselves preyed upon by larger species of sharks. Their presence and position within broader food chains demonstrates that not all shark species can be considered top-level predators in their ecosystems.

Data that may allow the status of Queensland shark populations to be estimated come mainly from fisheries and comprise catch sizes, catch rates, species frequencies and length frequencies. The data sets are less informative than those for bony fish. This can be attributed to a number of factors, including the above-mentioned difficulty of distinguishing species, absence of data on discarded catch which do not appear in logbooks, possible non-

reporting of species considered to be of conservation interest, and the high proportion of shark harvest reported in generic categories such as “unidentified whaler” or “unspecified shark”.

Table 1: Original target species for assessment: “Category” is a convenient descriptor developed for use in this assessment of Queensland shark species, but has no biological meaning. Six other major species had to be added due to lack of species identification in the available data (see Table 5 in section 1.2).

Scientific name	Common name	Family	Category
<i>Rhizoprionodon acutus</i>	Milk shark	Carcharhinidae	Small whaler
<i>Carcharhinus sorrah</i>	Spot-tail shark	Carcharhinidae	Medium whaler
<i>Carcharhinus tilstoni</i>	Australian blacktip shark	Carcharhinidae	Medium whaler
<i>Carcharhinus limbatus</i>	Common blacktip shark	Carcharhinidae	Medium whaler
<i>Carcharhinus brevipinna</i>	Spinner shark	Carcharhinidae	Large whaler
<i>Sphyrna lewini</i>	Scalloped hammerhead	Sphyrnidae	Hammerhead

Table 2: The augmented list of shark species groups used in the assessment. Species from each family (whaler or hammerhead) are listed in roughly increasing order of size. Less common species are listed under the main species in each group and were allocated into the groups on the basis of similar biology.

No.	Group name	Common names	Scientific names
1	Sharpnose sharks	Aust. sharpnose shark Grey sharpnose shark	<i>Rhizoprionodon taylori</i> <i>Rhizoprionodon oligolinx</i>
2	Milk shark	Milk shark White-cheek shark Slit-eye shark	<i>Rhizoprionodon acutus</i> <i>Carcharhinus coatesi</i> <i>Loxodon macrorhinus</i>
3	Creek whaler	Creek whaler Nervous shark	<i>Carcharhinus fitzroyensis</i> <i>Carcharhinus cautus</i>
4	Hardnose shark	Hardnose shark	<i>Carcharhinus macloti</i>
5	Spot-tail shark	Spot-tail shark	<i>Carcharhinus sorrah</i>
6	Aust. blacktip shark	Aust. blacktip shark Graceful shark	<i>Carcharhinus tilstoni</i> <i>Carcharhinus amblyrhynchoides</i>
7	Common blacktip shark	Common blacktip shark	<i>Carcharhinus limbatus</i>
8	Spinner shark	Spinner shark	<i>Carcharhinus brevipinna</i>
9	Bull & pigeye sharks	Bull shark Pigeye shark Lemon shark Sandbar shark	<i>Carcharhinus leucas</i> <i>Carcharhinus amboinensis</i> <i>Negaprion acutidens</i> <i>Carcharhinus plumbeus</i>
10	Winghead shark	Winghead shark	<i>Eusphyra blochii</i>
11	Scalloped hammerhead	Scalloped hammerhead Smooth hammerhead	<i>Sphyrna lewini</i> <i>Sphyrna zygaena</i>
12	Great hammerhead	Great hammerhead	<i>Sphyrna mokarran</i>

Species composition and length frequencies of the shark fishery catch are provided by the Fishery Observer Program (FOP) which was conducted by Fisheries Queensland from 2006 to 2012. Due to the relatively short duration of the FOP program, data collated as part of the FOP provide only a “snapshot” of the species that interact with shark fishing operations. Species composition before and after that time has to be inferred indirectly through population modelling. The FOP data were the best available on species split. We acknowledge that they may still contain some errors due to the intrinsic difficulty of species identification, despite the extensive training undertaken by the observers. For example, it is difficult, although possible, to visually distinguish the graceful shark *Carcharhinus*

*amblyrhynchoides* from the blacktip sharks *C. limbatus* and *C. tilstoni*, and the bull shark *C. leucas* from the pignose shark *C. amboinensis*.

An additional problem to errors in species identification is that some species were known to be impossible to distinguish in the field, most notably the common blacktip shark *Carcharhinus limbatus* and the Australian blacktip *C. tilstoni*. Distinction of these species requires either dissection or genetic analysis, which field observers were not tasked to undertake. They were recorded as simply “blacktip sharks” in the FOP data. Scientific genetic studies, however, indicated that these two species could be fairly reliably separated by the latitudes at which they were caught, with *C. tilstoni* predominating in the north and *C. limbatus* in the south (Welch *et al.* 2011; J. R. Ovenden and J. A. T. Morgan, personal communication, 2013), and this is what was done for the stock assessment.

In contrast to fishery data, biological data for the species included in this assessment were of much higher quality. There is a dedicated community of biologists who study sharks, which has provided detail of life cycles and reproductive rates for many species. Biological data on ageing, age at maturity, pupping frequency and litter size allow demographic analysis of shark populations from which rates of natural mortality and recruitment compensation can be estimated.

Demographic analysis, in particular the “Leslie matrix” approach (called the Bernardelli-Lewis-Leslie matrix by Liu and Cohen 1987), uses biological data to examine the ability of a population to sustain itself, and can estimate a maximal annual rate of increase of the population (Bernadelli 1941; Lewis 1942; Leslie 1945). The first practical applications of this approach to fisheries science appear to be Vaughan and Saila (1976) for tuna, and Hoenig and Gruber (1990) and Hoff (1990) for sharks. The demographic analysis used for sharks in Queensland is covered in chapter 2 and improves on past analysis by using consistent methodology over all species and correcting some errors in methodology. The demographic analysis uses up-to-date information from Australian studies where possible, and converts the results into standard population productivity measures that are used in stock assessments of bony fish. To the best of our knowledge the last of these contributions has not previously been accomplished for sharks.

The Shark Control Program (SCP), which aims to protect swimmers from shark attack at popular Queensland East Coast bathing beaches, provided supplementary data, although these were not used in the assessment. Data on catch sizes and catch rates were available from the beginning of the SCP in 1962, twenty-six years before the start of the commercial logbook database. In common with the shark fishery data, the SCP data suffer from lack of reliable species identification.

Finally, tag release and recovery data on sharks were available from a tagging experiment funded by the Australian Government’s Fisheries Research and Development Corporation (FRDC, project no. 2010/006) and carried out by scientists from James Cook University. These data were kindly provided by Dr Andrew Tobin of James Cook University. That project recorded the species of each shark tagged, although it did not claim to be fully representative of commercial fishing operations. It was available as a check on which shark species were commonly encountered.

The tag-return data could also provide checks on the shark mortality rates estimated by demographic analysis in chapter 2. We were not able to devote the necessary time to undertake that in this assessment, but we hope to in future.

## **1.2 Shark taxonomy and biology**

Sharks are a diverse range of marine animals comprising nine taxonomic orders within the class Chondrichthyes (Heinicke *et al.* 2009). They differ from ray-finned fish (class or superclass Actinopterygii) in many ways, including having skeletons of cartilage rather than bone. For most of this report we refer to ray-finned fish by the more common term “bony

fish” which technically includes lobe-finned fish, from which land vertebrates descend. Well-known lobe-finned fish include coelacanths (order Coelacanthiformes) and lungfish (orders Ceratodontiformes and Lepidosireniformes), but nearly all living bony fish are ray-finned. The term “bony fish” also avoids confusion with the animals called rays which are close relatives of sharks and are not ray-finned fish.

A few diverse examples of sharks encountered in Queensland are the white shark (or great white shark) *Carcharodon carcharias* (order Lamniformes, mackerel sharks), the crested horn shark *Heterodontus galeatus* (order Heterodontiformes, bullhead sharks), and the tasselled wobbegong *Eucrossorhinus dasypogon* (order Orectolobiformes, carpet sharks) (Figure 1). The other six orders of sharks are Carcharhiniformes (ground sharks), Squaliformes (a diverse order including dogfish and gulper sharks), Squatiniformes (angel sharks), Echinorhiniformes (bramble sharks), Pristiophoriformes (sawsharks) and Hexanchiformes (frilled sharks and cow sharks).

The sharks of interest for stock assessment in Queensland all belong to the diverse order Carcharhiniformes and come from the families Carcharhinidae (whaler sharks) and Sphyrnidae (hammerhead sharks). Whaler sharks have a streamlined shape (Figures 2 and 3) and the different whaler species can be extremely difficult to distinguish. Also juveniles of one species can resemble adults of a different (smaller) species. Hammerheads are distinguished by their wide, hammer-shaped heads, called cephalofoils (Figure 4). Cephalofoils are not only visually striking but may greatly alter hammerheads’ vulnerability to fishing, as large hammerheads often get their heads entangled in gillnets designed for smaller animals (Sumpton *et al.* 2011). It is possible that cephalofoils may also reduce the vulnerability of juvenile hammerheads to fishing when the water flow is high, because when travelling front-on their heads may bounce off gillnets that would otherwise catch them around the body (W. D. Sumpton, personal communication, 2015).

Changes to the taxonomy of sharks are proposed frequently. Some current opinion places hammerhead sharks inside Carcharhinidae (Heinicke *et al.* 2009). Naylor *et al.* (2012) found that Carcharhinidae and Sphyrnidae were indeed very similar, but left them as separate families as they found that each of these groups was monophyletic, i.e., all members of Sphyrnidae descended from one single ancestral species and all members of Carcharhinidae descended from a different single ancestral species. They found, however, that the tiger shark *Galeocerdo cuvier* was more different from Carcharhinidae than Sphyrnidae was, and they proposed removing it from Carcharhinidae.

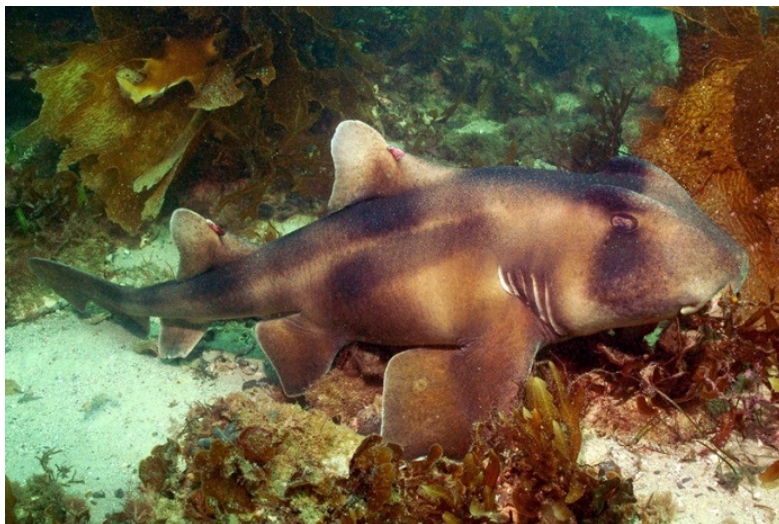
Most species of whaler shark can be distinguished visually by skilled observers, but two important species that cannot are the two blacktip species *Carcharhinus tilstoni* (the Australian blacktip) and *C. limbatus* (the common blacktip). For stock assessment these two species were separated on the basis of latitude, with *C. tilstoni* being more common north of about 24° S and *C. limbatus* being more common south of this latitude (Welch *et al.* 2011; J. R. Ovenden and J. A. T. Morgan, personal communication, 2013). The exact latitude at which this change takes place is subject to high uncertainty, as samples were collected only from widely separated locations.

We assigned all blacktip sharks to *C. tilstoni* in the Gulf of Carpentaria or on the Queensland East Coast as far south as Shoalwater Bay (approximately 22.7°S), the south-eastern side of which formed a natural geographic boundary between huge bays with abundant mud flats, and straighter coastline with direct access to the ocean. Waters in and around Shoalwater Bay also contained few blacktip sharks according to the Fishery Observer Program data, making it a logical division. All blacktip sharks south of Shoalwater Bay were assigned to *C. limbatus*.



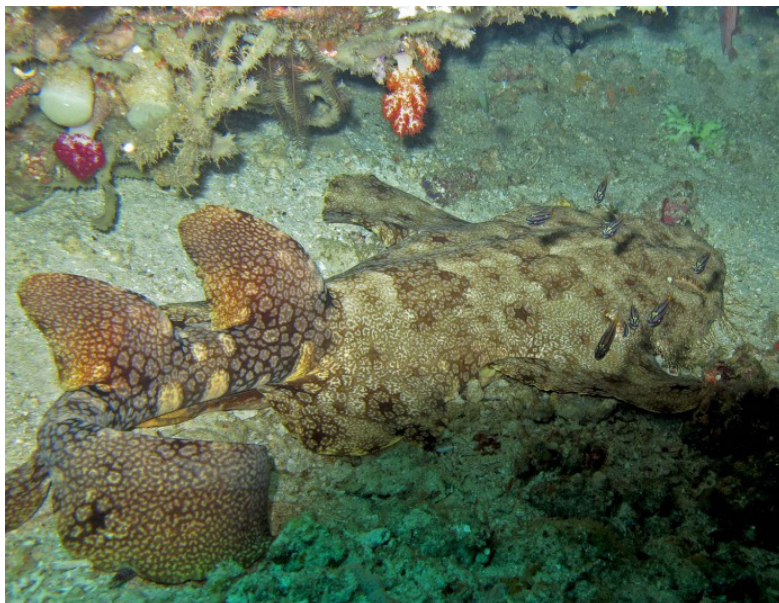
White shark  
*Carcharodon carcharias*  
order Lamniformes

Terry Goss  
Creative Commons by  
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Crested horn shark  
*Heterodontus galeatus*  
order Heterodontiformes

Ian Shaw, Reef Life Survey  
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Tasselled wobbegong  
*Eucrossorhinus dasypogon*  
order Orectolobiformes

Lakshmi Sawitri  
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*Figure 1: Some sharks from orders other than Carcharhiniformes that are encountered in Queensland; data on such sharks are insufficient to allow stock assessment.*





Common blacktip shark  
*Carcharhinus limbatus*

Rob Harcourt  
Used with permission



Lemon shark  
*Negaprion brevirostris*

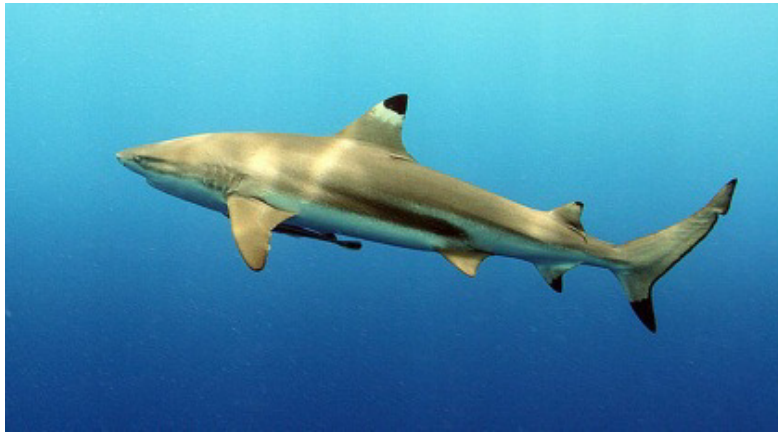
Albert Kok,  
Creative Commons by  
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Silky shark  
*Carcharhinus falciformis*

Alex Chernikh  
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*Figure 2: Some sharks from family Carcharhinidae commonly encountered in Queensland coastal waters, with which the stock assessment deals.*



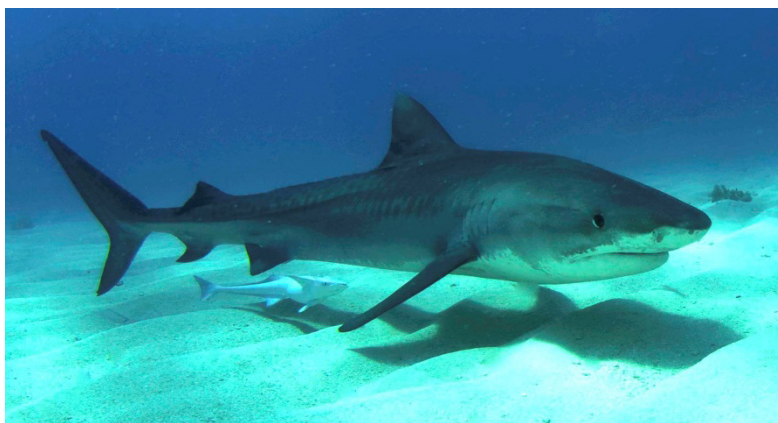
Blacktip reef shark  
*Carcharhinus melanopterus*

Klaus Stiefel  
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Use licence



Whitetip reef shark  
*Triaenodon obesus*

NOAA  
Public domain licence



Tiger shark  
*Galeocerdo cuvier*

Albert Kok  
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*Figure 3: Some sharks from family Carcharhinidae that are encountered in Queensland waters but can be largely excluded from the stock assessment due to their location, behaviour or body shape.*



Scalloped hammerhead  
*Sphyrna lewini*

Klaus Stiefel  
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Great hammerhead  
*Sphyrna mokarran*

Josh Hallett  
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*Figure 4: Two sharks from family Sphyrnidae commonly encountered in Queensland coastal waters, with which the stock assessment deals. The scalloped hammerhead is the most common hammerhead species and is distinguished from other hammerhead species found in Queensland by the marked scalloping on the front of its cephalofoil.*

Sharks are particularly interesting for stock assessment because their reproductive processes can be quantified to a much greater degree than those of ray-finned fish. Many sharks, including all those in the families Carcharhinidae and Sphyrnidae, give birth to live young (pups), either with or without (in the case of the tiger shark) a placental connection during gestation. This characteristic enables the pupping frequency and litter size to be measured from captured female sharks. Such information, combined with ageing from counts of rings on shark vertebrae, allows demographic analyses of shark populations to be conducted (see previous section).

Pups have a definite length at birth (age zero) which can be measured. Use of the birth length can reduce the number of parameters that need to be estimated in a growth function, from three to two in the case of the von Bertalanffy function (see, e.g., Harry *et al.* 2010, 2011). The von Bertalanffy growth function is (Bertalanffy 1938)

$$L = L_{\infty} \{1 - e^{-K(t-t_0)}\},$$

where  $L$  is the expected length of an animal at age  $t$ , and  $L_{\infty}$ ,  $K$  and  $t_0$  are model parameters. The parameter  $t_0$  is the theoretical age at which the expected length is zero, which for sharks will be negative, i.e., well before birth, due to growth *in utero* before they are born. If the

length at birth,  $L_0$ , is known, the growth function can be reparameterised to remove the parameter  $t_0$ :

$$L = L_\infty - (L_\infty - L_0)e^{-Kt}. \quad (1.1)$$

For sharks, separate growth functions usually have to be fitted to male and female sharks, as females usually grow bigger (see references in Table 5 and results in Table 6 below). Females are also often said to live longer than males (see, e.g., Harry *et al.* 2010); for reasons of complexity and lack of quantitative data for some species, this effect has not been included in the stock assessment. The resulting estimates of natural mortality rates are a rough average of male and female sharks, and so this simplification should have little effect on the results of the assessment.

In addition to having sex-specific growth functions, many shark populations segregate by sex (Sims 2005). Females of some species, notably hammerheads, are more inclined to move offshore than males. For example, Harry *et al.* (2011) found plenty of mature males but only one mature female out of 93 female scalloped hammerheads collected off the Australian east coast. On the other hand, females of many species, including the scalloped hammerhead, migrate into inshore nursery areas to give birth in locations in which pups will be relatively safe from predation (Castro 1993, 1996; Feldheim *et al.* 2002; Capapé *et al.* 2003; Hueter *et al.* 2005; Sims 2005; Harry *et al.* 2011). It does not seem to have been completely explained how female scalloped hammerheads move back inshore without being caught by fishers, but this is a worldwide phenomenon which has resulted in paucity of data on reproduction of the scalloped hammerhead (Stevens and Lyle 1989), and it is evident that the females' behaviour must be different during this period. The effect of this on stock assessment results is generally to make them err on the side of caution: the assessment will assume that roughly equal numbers of male and female sharks are caught by fishers. In reality it is likely that more males will be caught and females will be afforded partial protection from fishing activities. This factor is considered to be of particular importance to the ongoing health of regional shark populations.

While larger females tend to have larger litters, this could not be accounted for in the demographic analysis (chapter 2) due to a lack of quantitative data. The stock assessment population model, however, assumed that fecundity was proportional to weight, which is a fairly standard practice in stock assessment. We believe that the assumption in the population model is more accurate, but the assumption of constant litter size in the demographic model will roughly average the results over females of all sizes, so should have little effect on the results of the demographic analysis.

Many other subtle features of the biology of sharks were noted but were not feasible to take into account in this stock assessment due to the complexity of modelling that would be required. Examples include the following:

- Harry *et al.* (2011) found that scalloped hammerheads grow faster, but to a smaller maximum length, in north Queensland waters than in southern Queensland.
- Harry *et al.* (2011) also hypothesised split life cycles for male scalloped hammerheads, whereby some males stay inshore all their lives to better their chances of mating and consequently end up smaller than other males which travel offshore for a better diet.
- Some sharks, notably the milk shark, breed throughout the year (Stevens and McLoughlin 1991; Harry *et al.* 2010), whereas most sharks reproduce seasonally. This assessment assumes that all sharks reproduce seasonally. The effect on results should be negligible because the productivity of the whole population is much the same.
- Some sharks, notably the Australian blacktip, may mature earlier in the Gulf of Carpentaria than on the Queensland East Coast (Davenport and Stevens 1988; Harry *et al.* 2013). This assessment generally uses the most recent published data from

Queensland or the Northern Territory, irrespective of the exact location from which samples were collected.

- Sex ratios of sharks in the population are an open question, and are difficult to measure due to segregation of the sexes. The assessment assumed a 1:1 sex ratio at birth for all species and the same natural mortality rate for both sexes.

The forty shark species recorded by the Queensland Fishery Observer Program are listed in Table 3. They show that the catch is dominated by only a few major species, with the top four species by number making up 57% of the total. However, many other species needed to be taken into account to deal with deficiencies in fishery logbook data. Although species-specific harvests were required only for the species in Table 1 above, their estimation required all observed species to be considered. To produce a manageable list of major species to include in the population model, each observed species was, on the basis of similarity in biology, linked to one of the twelve species groups listed in Table 2: these links are shown in Table 4. Some minor non-hammerhead species did not have similar biology to any major species. These species were split between all nine whaler species groups, in the same proportions as those whaler groups were observed in that location and sector, in order to clearly separate non-hammerhead sharks from hammerheads whose fishery catchability characteristics were very different.

Key sources of biological information for the species groups are listed in Table 5. Parameter values for growth and lifespan derived from those sources and used in the assessment are listed in Table 6, and those for reproduction are listed in Table 7. When one or more values in Tables 6 and 7 were unavailable from the scientific literature, they were inferred from available data, e.g., age at maturity was derived from length at maturity in combination with the growth function. Von Bertalanffy growth functions were used for all species and both sexes. The length at birth, parameter  $L_0$  in equation (1.1), was set to the mean observed birth length; the  $L_0$  value from fitting the growth function was not used. The length used was total length, or more precisely “stretched total length” (STL) (see, e.g., Harry *et al.* 2011) which is the length measurement generally used for sharks in Australia. For reference, Stevens and McLoughlin (1991) provide the following equation relating fork length (FL) to STL, both measured in cm, for the pignose shark:

$$FL = 0.79 \times STL - 0.68.$$

Similar equations for the Australian blacktip shark from Stevens and Wiley (1986) are

$$FL = 0.803 \times STL - 0.075$$

and

$$STL = 1.235 \times FL + 0.913.$$

For the common blacktip shark, Wintner and Cliff (1996) provide an equation relating STL to pre-caudal length (PCL):

$$STL = 1.334 \times PCL + 4.27.$$

For the spot-tail shark *Carcharhinus sorrah* the asymptotic length parameter,  $L_\infty$  in equation (1.1), from Australian biological studies was much less than the reported maximum length of this species worldwide. The species is widely claimed to reach a length of 160 cm (Pillans *et al.* 2009; see, e.g., Last and Stevens 2009). For northern Australia, however, Stevens and Wiley (1986) state, “few females above 130 cm, and few males above 110 cm were caught”. The maximum lengths observed by Stevens and Wiley were 152 cm (female) and 131 cm (male), but both of these were on sharks that came from the Arafura and Timor Seas. The largest individuals observed by Harry *et al.* (2013) on the Queensland East Coast were 131 cm (female) and 114 cm (male). It seems likely that the few much larger sharks observed by Stevens and Wiley (1986) were migrants from Indonesia, and that the  $L_\infty$  values of 127 cm for female and 107 cm for male spot-tail sharks estimated by Harry *et al.* (2013) are appropriate for Australia.

Table 3: Shark species recorded by the Fishery Observer Program. Some of these species were not retained by fishers, and were returned to the water alive where possible.

<b>Common name</b>	<b>Scientific name</b>	<b>Frequency</b>
Blacktip shark	<i>Carcharhinus limbatus</i> & <i>C. tilstoni</i>	4394
Spot-tail shark	<i>Carcharhinus sorrah</i>	2080
Scalloped hammerhead	<i>Sphyrna lewini</i>	1654
Milk shark	<i>Rhizoprionodon acutus</i>	1231
Spinner shark	<i>Carcharhinus brevipinna</i>	989
Bull shark	<i>Carcharhinus leucas</i>	809
Australian sharpnose shark	<i>Rhizoprionodon taylori</i>	767
Winghead shark	<i>Eusphyra blochii</i>	710
White-cheek shark	<i>Carcharhinus coatesi</i>	662
Hardnose shark	<i>Carcharhinus macloti</i>	597
Weasel sharks	Family Hemigaleidae	373
Slit-eye shark	<i>Loxodon macrorhinus</i>	369
Creek whaler	<i>Carcharhinus fitzroyensis</i>	352
Pigeys shark	<i>Carcharhinus amboinensis</i>	266
Great hammerhead	<i>Sphyrna mokarran</i>	232
Grey sharpnose shark	<i>Rhizoprionodon oligolinx</i>	184
Carpet sharks	Order Orectolobiformes	157
Gummy sharks	Family Triakidae	108
Cat sharks	Family Scyliorhinidae	65
Nervous shark	<i>Carcharhinus cautus</i>	52
Grey reef shark	<i>Carcharhinus amblyrhynchos</i>	51
Dogfish & gulper sharks	Order Squaliformes	51
Lemon shark	<i>Negaprion acutidens</i>	49
Blacktip reef shark	<i>Carcharhinus melanopterus</i>	47
Silky shark	<i>Carcharhinus falciformis</i>	43
Graceful shark	<i>Carcharhinus amblyrhynchoides</i>	36
Sandbar shark	<i>Carcharhinus plumbeus</i>	36
Whitetip reef shark	<i>Triaenodon obesus</i>	35
Tiger shark	<i>Galeocerdo cuvier</i>	24
Wobbegongs	<i>Eucrossorhinus, Orectolobus, Sutorectus</i>	23
Silvertip shark	<i>Carcharhinus albimarginatus</i>	17
Crested hornshark	<i>Heterodontus galeatus</i>	8
Bronze whaler	<i>Carcharhinus brachyurus</i>	7
Tawny shark	<i>Nebrius ferrugineus</i>	5
Angel sharks	Family Squatinidae	5
Dusky whaler	<i>Carcharhinus obscurus</i>	4
Speartooth shark	<i>Glyphis glyphis</i>	4
Smooth hammerhead	<i>Sphyrna zygaena</i>	2
Galapagos shark	<i>Carcharhinus galapagensis</i>	2
Sawsharks	Order Pristiophoriformes	2

Table 4: Linking of shark species to major species that were modelled in the stock assessment and had similar biology. “Category” was defined for convenience, and has little biological meaning. The linked major species were intended to have similar biological parameters to the original species. Blacktip sharks were assigned to the Australian blacktip in the Gulf of Carpentaria and the northern east coast, and to the common blacktip in the southern east coast. “Whaler unspecified” signifies that no major species had similar biology, e.g., carpet sharks and cat sharks. In these cases the catch was divided between the whaler species in the proportions in which those whaler species were recorded, on the basis that they were much more similar to whaler sharks than hammerheads with regard to vulnerability to fishing.

<b>Common name</b>	<b>Category</b>	<b>Linked major species</b>
Blacktip shark	Medium whaler	Aust. blacktip GoC & NEC Common blacktip SEC
Spot-tail shark	Medium whaler	Spot-tail shark
Scalloped hammerhead	Hammerhead	Scalloped hammerhead
Milk shark	Small whaler	Milk shark
Spinner shark	Large whaler	Spinner shark
Bull shark	Large whaler	Bull shark
Australian sharpnose shark	Small whaler	Aust. sharpnose shark
Winghead shark	Hammerhead	Winghead shark
White-cheek shark	Small whaler	Milk shark
Hardnose shark	Small whaler	Hardnose shark
Weasel sharks	Weasel shark	Whaler unspecified
Slit-eye shark	Small whaler	Milk shark
Creek whaler	Small whaler	Creek whaler
Pigeye shark	Large whaler	Bull shark
Great hammerhead	Hammerhead	Great hammerhead
Grey sharpnose shark	Small whaler	Aust. sharpnose shark
Carpet sharks	Carpet shark	Whaler unspecified
Gummy sharks	Hound shark	Whaler unspecified
Cat sharks	Cat shark	Whaler unspecified
Nervous shark	Small whaler	Creek whaler
Grey reef shark	Medium whaler	Whaler unspecified
Dogfish & gulper sharks	Squaliformes	Whaler unspecified
Lemon shark	Large whaler	Bull shark
Blacktip reef shark	Medium whaler	Whaler unspecified
Silky shark	Large whaler	Whaler unspecified
Graceful shark	Medium whaler	Aust. blacktip shark
Sandbar shark	Large whaler	Bull shark
Whitetip reef shark	Medium whaler	Whaler unspecified
Tiger shark	Large whaler	Whaler unspecified
Wobbegongs	Carpet shark	Whaler unspecified
Silvertip shark	Large whaler	Whaler unspecified
Crested hornshark	Bullhead shark	Whaler unspecified
Bronze whaler	Large whaler	Whaler unspecified
Tawny shark	Carpet shark	Whaler unspecified
Angel sharks	Angel shark	Whaler unspecified
Dusky whaler	Large whaler	Whaler unspecified
Speartooth shark	Large whaler	Whaler unspecified
Smooth hammerhead	Hammerhead	Scalloped hammerhead
Galapagos shark	Large whaler	Whaler unspecified
Sawsharks	Sawshark	Whaler unspecified

Table 5: Sources of biological information used for the species groups in the assessment. Parameter values for the pigeye shark were used when those for the bull shark in Australia were not available. In all other cases the biological parameter values used were those of the most common species in each group; the groups were not treated as multi-species complexes. Other species were linked to these groups to reduce the number of species in the population model (see Table 4).

Group	Common name	Scientific name	Sources
1	Aust. sharpnose shark	<i>Rhizoprionodon taylori</i>	Stevens and McLoughlin (1991) Simpfendorfer (1992) Simpfendorfer (1993)
2	Milk shark	<i>Rhizoprionodon acutus</i>	Stevens and McLoughlin (1991) Harry et al. (2010)
3	Creek whaler	<i>Carcharhinus fitzroyensis</i>	Lyle (1987) Smart et al. (2013)
4	Hardnose shark	<i>Carcharhinus macloiti</i>	Stevens and McLoughlin (1991) Smart et al. (2013)
5	Spot-tail shark	<i>Carcharhinus sorrah</i>	Stevens and Wiley (1986) Davenport and Stevens (1988) Harry et al. (2013)
6	Aust. blacktip shark	<i>Carcharhinus tilstoni</i>	Stevens and Wiley (1986) Davenport and Stevens (1988) Harry et al. (2012) Harry et al. (2013)
7	Common blacktip shark	<i>Carcharhinus limbatus</i>	Stevens (1984) Wintner and Cliff (1996) Capapé et al. (2004) Carlson et al. (2006) Macbeth et al. (2009) Harry et al. (2012)
8	Spinner shark	<i>Carcharhinus brevipinna</i>	Branstetter (1981) Stevens (1984) Stevens and McLoughlin (1991) Joung et al. (2005) Macbeth et al. (2009)
9	Bull shark Pigeye shark	<i>Carcharhinus leucas</i> <i>Carcharhinus amboinensis</i>	Tillett et al. (2011) Stevens and McLoughlin (1991) Tillett et al. (2011)
10	Winghead shark	<i>Eusphyrna blochii</i>	Stevens and Lyle (1989) Smart et al. (2013)
11	Scalloped hammerhead	<i>Sphyrna lewini</i>	Stevens and Lyle (1989) Piercy et al. (2007) Harry et al. (2011)
12	Great hammerhead	<i>Sphyrna mokarran</i>	Stevens and Lyle (1989) Piercy et al. (2010) Harry et al. (2011)



Table 6: Growth parameters of the shark species included in the assessment. Parameters  $\alpha$  and  $\beta$  are for the length-weight relationship  $W = \alpha L^\beta$  where  $W$  is the weight of a shark (kg) and  $L$  is its stretched total length (cm);  $L_0$  is the average length at birth (cm);  $L_\infty$  (cm) and  $K$  ( $\text{yr}^{-1}$ ) are von Bertalanffy growth parameters from equation (1.1); and  $a_{\max}$  is the maximum age observed (yr). Maximum attainable lifespans are almost certainly greater than  $a_{\max}$ . Dashed lines separate the different categories of sharks (small, medium and large whalers, and hammerheads), but have no other meaning.

Common name	$\alpha$	$\beta$	$L_0$	Female		Male		$a_{\max}$
				$L_\infty$	$K$	$L_\infty$	$K$	
Aust. sharpnose shark	$2.17 \times 10^{-7}$	3.75	24	73.2	1.01	65.2	1.34	6
Milk shark	$3.74 \times 10^{-6}$	3.01	36	86.1	0.63	82.1	0.94	8
Creek whaler	$1.42 \times 10^{-6}$	3.292	51.5	125.8	0.21	99.6	0.37	13
Hardnose shark	$3.91 \times 10^{-7}$	3.55	42.5	87.9	0.26	87.9	0.26	12
Spot-tail shark	$5.45 \times 10^{-7}$	3.51	52	126.6	0.336	107.4	0.632	14
Aust. blacktip shark	$4.75 \times 10^{-6}$	3.06	61	194.2	0.14	165.4	0.19	15
Common blacktip shark	Use Aust. blacktip		72	262	0.21	262	0.21	16
Spinner shark	$1.13 \times 10^{-6}$	3.33	71	288.2	0.151	257.4	0.203	21
Bull shark	Use pigeye		68.5	340	0.09	340	0.09	29
Pigeye shark	$1.94 \times 10^{-6}$	3.27	62.5	288	0.088	282	0.087	26
Winghead shark	$2.71 \times 10^{-7}$	3.56	46	171	0.12	171	0.12	21
Scalloped hammerhead	$3.99 \times 10^{-6}$	3.03	47.5	330.5	0.077	319.9	0.093	31
Great hammerhead	$1.23 \times 10^{-6}$	3.24	65	402.7	0.079	402.7	0.079	39

Table 7: Reproductive parameters of the shark species included in the assessment. Parameters  $a_{50}$  and  $a_{95}$  are the ages at 50% and 95% maturity of females (yr); pupping interval is the average time interval between litters for an individual female shark (yr); and litter size is the average litter size to which a female shark gives birth. The age  $a_{95}$  in most cases was not available and was set equal to  $a_{50}$  when  $a_{50} \leq 2$ ,  $a_{50} + 1$  when  $a_{50} > 2$  and  $a_{50} < 10$ , and  $a_{50} + 2$  when  $a_{50} \geq 10$ ; when  $a_{95}$  was set equal to  $a_{50}$ , both were rounded up to the next whole year because the population model was annual. Ages  $a_{50}$  and  $a_{95}$  were inferred from published values of length at maturity when that was the only information available.

Common name	$a_{50}$	$a_{95}$	Pupping interval	Litter size
Aust. sharpnose shark	1	1	1	4.5
Milk shark	2	2	1	3
Creek whaler	4	5	1	3.7
Hardnose shark	3	4	2	2
Spot-tail shark	3	4	1	3.1
Aust. blacktip shark	5.65	6.65	1	3
Common blacktip shark	7	8	2	8
Spinner shark	8	9	2	10.9
Bull shark	9.5	10.5	2	Use pigeye
Pigeye shark	13.5	15.5	2	9
Winghead shark	7	8	1	11.8
Scalloped hammerhead	10	12	1	16.5
Great hammerhead	7	8	2	15.4

Data for the bull shark were taken where needed from the corresponding data for the pigeye shark, which has similar biology; e.g., length-weight relationship and mean litter size. The pigeye shark is less common in Queensland but has been studied more intensively than the bull shark. We believed that using data from the pigeye shark was more accurate than using foreign data on the bull shark. The bull shark in the Gulf of Mexico (Cruz-Martínez *et al.* 2005; Neer *et al.* 2005) and South Africa (Wintner *et al.* 2002) appears to grow to smaller lengths than in Australia, even after allowing for the use of length measurements other than STL (fork length in North America and pre-caudal length in South Africa).

Pupping intervals (time interval between litters for a female shark) for large whalers appear not to have been studied in Australia and were set to two years on the basis of foreign studies (see list of studies in Table 5).

The pupping interval for the scalloped hammerhead *Sphyrna lewini* is unknown, because very few mature females of this species have been caught and the proportion that are gravid (pregnant) at any one time is impossible to estimate. It was set to one year, the same as the winghead shark *Eusphyra blochii* but different to the great hammerhead *Sphyrna mokarran*. We considered that the lack of observation of mature female scalloped hammerheads was probably due to their lifestyle during gravidity, and hence that they were likely to be gravid most of the time. Also the male life-cycle strategy hypothesised by Harry *et al.* (2011), whereby some males live inshore in order to mate with females that have just given birth (see above), is not likely to be successful if females have a year of rest before becoming gravid again. For the demographic model in Chapter 2, female scalloped hammerheads were assumed to give birth every year. Because so few mature females of this species have been caught, it was not possible to verify this assumption from any published studies.

Due to absence of Australian studies, foreign data had to be used for some population parameters of the common blacktip shark (Senegal, South Africa and south-eastern USA), spinner shark (Taiwan) and scalloped hammerhead (maximum observed age from south-eastern USA) (see list of studies in Table 5). Growth parameters for the common blacktip shark come from Wintner and Cliff (1996) with PCL converted to STL. In eastern Australia this species as recorded by Macbeth *et al.* (2009) obviously grows larger than indicated by the ageing study by Carlson *et al.* (2006) in south-eastern USA.

### **1.3 Regional structure of the assessment**

This stock assessment of sharks is structured regionally, because the apparent abundance of sharks can change dramatically over quite a small area. The evidence from fishery data is that, for the shark species being assessed, individuals tend to cluster into particular preferred habitats (see, for example, the regional contrasts of species composition in Figure 10 on page 33 and the regional contrasts in catch rates in chapter 4). We note that the true spatial extent of regional populations may be even smaller than the Subregions defined below (Yates *et al.* 2012, 2015), but these Subregions are the smallest units on which standardised catch rates can be defined with reasonable accuracy from the available logbook data.

Apparent regional differences in species composition may be magnified by variation in the types of locations in which gillnets can profitably be set. Perceived differences in species composition between regions may be due partly to differences in fishing technique, but this does not remove the need to analyse the different regions separately. A clue to this phenomenon is that in many regions a shorter net has a higher average catch than a longer net, presumably because it can be set in a more suitable location (see chapter 4 below).

The regional structure of the assessment is based on the sampling regions used by Fisheries Queensland's Long Term Monitoring Program (LTMP). There are 22 of these regions, although only 19 of them had big enough shark catches to define meaningful catch-rate time series and species composition data from the Fishery Observer Program. These regions are called LTMP Regions in this assessment.

To reduce the statistical error in the standardised catch rates, we merged some LTMP regions into the final Subregions that were used in the population dynamic model in chapter 5 (see final column of Table 8). The regional structure of the assessment is listed in Table 8.

*Table 8: Regional structure of the stock assessment: LTMP Regions are listed clockwise around the coast from the southern Gulf of Carpentaria, north to Cape York and then south to the New South Wales border. LTMP Regions that fall within the Great Barrier Reef Marine Park are marked \*. The Torres Strait, Fraser Offshore and Brisbane Offshore Subregions were excluded from the assessment due to small catches, and are bracketed. Final Subregions which resulted from mergers of LTMP Regions are printed sideways in italics; the remaining Subregions comprised single LTMP Regions and retained their names.*

<b>Region</b>	<b>Region abbr.</b>	<b>LTMP Region</b>	<b>LTMP Region abbr.</b>	
Gulf of Carpentaria	Gulf	Karumba	Karumba	} Gulf
		Pormpuraaw	Pormpuraaw	
		Aurukun	Aurukun	
		Weipa	Weipa	
		Mapoon	Mapoon	
		(Torres Strait)	(TorresStrait)	
North East Coast	North	Lockhart*	Lockhart	} FarNorth
		Cooktown*	Cooktown	
		Cairns*	Cairns	
		Mission Beach*	Mission	
		Lucinda*	Lucinda	
		Bowen*	Bowen	
		Mackay*	Mackay	
		Stanage Bay*	Stanage	
		Rockhampton Estuarine*	RockEst	
		Rockhampton Offshore*	RockOff	
South East Coast	South	Fraser Inshore	FraserIn	} Moreton
		(Fraser Offshore)	(FraserOff)	
		Sunshine Coast Offshore	SunshineOff	
		Moreton Bay	MoretonBay	
		(Brisbane Offshore)	(Brisbane)	
		Gold Coast Offshore	GoldOff	

## 1.4 The fishery

### 1.4.1 Historical commercial fisheries in Northern Australia

Soviet and Taiwanese trawl and gillnet fisheries previously operated off Northern Australia, comprising the Gulf of Carpentaria, the Northern Territory and northern Western Australia. Records of Soviet trawl catches of tropical red snappers exist for the years 1966–1977, in a database maintained by CSIRO, but we are not aware of any records of Soviet shark catches. More is known about the Taiwanese fish-trawl and gillnet fishery, which operated from 1974 to 1990 (Harwood *et al.* 1984; O’Neill *et al.* 2011).

Data on red snapper catches indicate that most of the Soviet fishing took place in Western Australian and Northern Territory waters, and very little in Queensland. The Soviet fishery has not been included in this stock assessment.

Estimation of the size of the Taiwanese harvest of sharks is undertaken in chapter 3 (section 3.1). The main point made there is that the harvests of sharks taken in Queensland waters

appear to have been smaller than the levels that might be inferred from published literature, and may not have exceeded 1000 tonnes in any year.

A small Australian commercial gillnet fishery in Northern Australia began with the declaration of the Australian Fishing Zone in 1979, and by 1985 was catching 408 t of sharks per year over the whole of Northern Australia (Davenport and Stevens 1988, quoting an Australian Bureau of Statistics report).

Data from Queensland Fish Board reports (Halliday and Robins 2007) show a landing of 3 t of sharks from the GoC in financial year 1980–81, the final year before the Fish Board was disbanded, and no shark landings in any year prior to that.

#### *1.4.2 Historical fishery on the Queensland East Coast*

On the Queensland East Coast, the Queensland Fish Board (QFB) first recorded landings of sharks in 1974–75. The QFB was the government agency through which the harvest by law had to be marketed until 1981. It had various receiving stations along the Queensland coast, and data from its annual reports were collated by Halliday and Robins (2007). Some of the shark harvest levels were already stable by 1974–75 (i.e., did not increase much in the following years), especially from the reporting stations in the Fraser Inshore Subregion (Bundaberg and Tin Can Bay) and the Moreton Bay Subregion (Scarborough, Sandgate, Brisbane, Cleveland and Woongoolba). It is clear that the shark fishery had already been operating for some years on some parts of the East Coast, but the shark harvest was recorded as a separate category only from 1974–75 onwards.

Although marketing of fishery catches through the QFB was compulsory until 1980–81, it is probable that some of the shark catch was sold direct to local fish and chip shops without going through the Board, as fish and chips constituted a major use for shark meat at that time. Therefore the actual shark catch on the Queensland East Coast until 1980–81 was probably higher than the QFB data show.

There was also a major change in net technology in the 1970s, with the take-up of lightweight untarred nylon nets which allowed gillnet fishers to fish further from shore on the Queensland East Coast and actively target sharks. Therefore the catches of sharks may indeed have been very small prior to the mid-1970s, when many gillnet fishers using heavy nets were practically able to fish only rivers and estuaries (Dr Andrew Tobin, James Cook University, 2015, personal communication).

The classification of QFB data into the LTMP Regions from Table 8 is listed in Table 9, and the resulting annual catches of sharks are listed in Table 10. The QFB records used financial years (July to June). The largest QFB total recorded catch was 45 tonnes in 1980–81.

#### *1.4.3 The current commercial fishery*

Sharks in Queensland are fished primarily by commercial gillnet operators, with a smaller proportion of the catch taken in the line fishery. While prawn trawlers and fish trawlers catch some sharks, these species cannot be retained for commercial sale. Trawl fishers mostly do not record this catch in logbooks, so there is limited information on shark and ray catch rates in trawl fisheries. Sharks would, however, make up only a small proportion of the total trawl catch.

The gillnet fishery had by far the best coverage by fishery observers. The regional species composition for the other sectors is very uncertain.

On the Queensland East Coast, line fishers catch mainly reef sharks, the main species being the grey reef shark *Carcharhinus amblyrhynchos*, blacktip reef shark *C. melanopterus* and whitetip reef shark *Triaenodon obesus* (see Table 3 and Figure 3). These species are not on the list for stock assessment (Table 1). Therefore for the assessment the information relating to the Queensland east coast comes primarily from the net sector.

In the Gulf of Carpentaria the Fishery Observer Program data showed that the species mix caught by line is much the same as by gillnet. Given this, the line catch was combined with the net catch for this Region.

Table 9: Classification of Queensland Fish Board receiving stations into the LTMP Regions listed in Table 8.

QFB station	LTMP Region
Weipa	Weipa
Port Douglas	Cairns
Cairns	Cairns
Innisfail	Mission
Townsville	Lucinda
Bowen	Bowen
Mackay	Mackay
Yeppoon	Rockhampton Offshore (RockOff)
Rosslyn Bay	Rockhampton Offshore (RockOff)
Rockhampton	Rockhampton Offshore (RockOff)
Gladstone	Rockhampton Offshore (RockOff)
Bundaberg	Fraser Inshore (FraserIn)
Maryborough	Fraser Inshore (FraserIn)
Tin Can Bay	Fraser Inshore (FraserIn)
Tewantin	Sunshine Coast Offshore (SunshineOff)
Mooloolaba	Sunshine Coast Offshore (SunshineOff)
Bribie Island	Moreton Bay
Scarborough	Moreton Bay
Sandgate	Moreton Bay
Wynnum	Moreton Bay
Brisbane	Moreton Bay
Cleveland	Moreton Bay
Woongoolba	Moreton Bay
Southport	Gold Coast Offshore (GoldOff)
Northern Rivers	Gold Coast Offshore (GoldOff)

Table 10: Queensland Fish Board landings of sharks, classified into the LTMP Regions listed in Table 8. LTMP Regions that are not listed here were not assigned any catch. Data are catch weights in tonnes, converted to whole weight. Data may be subject to substantial under-reporting due to local marketing practices at the time. Source: Database provided by Halliday and Robins (2007); classification into Subregions from Table 9.

Year	Weipa	Cairns	Mission	Lucinda	Bowen	Mackay	RockOff	FraserIn	SunshineOff	MoretonBay	GoldOff	Total
1974/75	0.00	0.32	0.00	0.00	0.17	0.01	0.49	6.70	0.29	7.99	0.17	16.14
1975/76	0.00	0.06	0.00	0.00	0.00	0.04	0.59	4.48	0.05	5.93	0.14	11.29
1976/77	0.00	0.05	0.00	0.00	0.54	0.00	2.84	4.92	0.01	9.34	0.20	17.90
1977/78	0.00	0.03	0.00	0.07	0.21	0.00	1.91	3.25	0.12	5.35	0.22	11.16
1978/79	0.00	0.17	0.00	0.04	0.67	0.02	3.38	6.07	0.16	7.75	0.80	19.06
1979/80	0.00	0.31	0.00	0.08	0.26	0.30	8.78	15.32	0.55	12.42	1.64	39.66
1980/81	2.77	3.04	0.18	5.45	1.56	0.13	0.66	22.11	0.76	8.26	0.49	45.41

In the trawl fisheries we expected sizable sharks to be mostly excluded from trawl nets by the trawlers' turtle excluder devices (TEDs). In practice this happened to a lesser degree than anticipated and 13% of trawl-caught sharks measured in the Fishery Observer Program were over 80 cm in length. Some of these (23%) were released alive. We were not able to determine the overall size of the shark catches taken by trawling, as the available information came from a relatively small number of fishing trips on which fishery observers were on board. While Courtney et al. (2007, ch. 11) remark that whaler and hammerhead sharks are caught by trawlers in the inshore banana prawn trawl sector, their scientific research did not cover this sector.

Catches of sharks by trawlers were omitted from the stock assessment.

Gillnet fishing operations target sharks around one metre in length. They catch adults of the small species, but mainly only juveniles of the large species. Hammerheads are a special case because they can be caught by the head instead of around the body: hammerheads in the catch tend to be larger than whalers.

The gillnet fishery also targets many other species such as grey mackerel (*Scomberomorus semifasciatus*), barramundi (*Lates calcarifer*), school mackerel (*Scomberomorus queenslandicus*) and king threadfin salmon (*Polydactylus macrochir*). Sharks are often caught when fishing for these other species.

Harvest sizes of sharks recorded in logbooks are graphed in Figures 5 and 6. Figure 5 shows the catch by species. Fishers did not identify the majority of sharks caught by species until 2004, and even then the level of species resolution remained low and species could be misidentified. The blacktip category is particularly problematic, as there is a tendency to classify any shark with black tips on its fins as a "blacktip", which is often incorrect. Given this uncertainty, the stock assessment did not use species identifications made by fishers, and instead used only identifications made by trained fishery observers.

Figure 5 also includes the harvest of grey mackerel. At the beginning of the assessment this was believed to be the major target species other than sharks for net operators, but in the event that turned out to be largely untrue. Fishers target many species other than grey mackerel. In any case we found no evidence that catching grey mackerel reduced the catch rate of sharks (see chapter 4). Therefore the grey mackerel catch was not taken into consideration in the final analysis.

A notable feature of Figure 5 is that the ratio of scalloped hammerhead *Sphyrna lewini* to unspecified hammerhead falls after 2006, whereas the proportion of identified whaler species to unspecified whalers increases during this time. While it is difficult to quantify what caused the shift in hammerhead shark reporting, a change in fishers' perception of their own ability to differentiate between species is likely to be a significant factor. A high proportion of hammerhead sharks may have been identified as *S. lewini* in the belief that nearly all hammerheads caught were of this species. With the advent of the fishery observer program and widespread circulation of guidebooks, the situation may have become more complex as fishers picked up some information from observers and guides, but not enough to make them certain of their ability to distinguish species. Fishers with limited taxonomic experience may have identified more of their catch as unspecified hammerhead. We note that an alternative explanation is that fishers may have been reluctant to identify *S. lewini* once it became a major focus of worldwide conservation efforts.

Figure 6 shows time series of shark harvest by LTMP Region (as listed in Table 8). The reported total shark harvest rose steadily from 473 t in 1988 to 1966 t in 2003 and then fell again to 459 t in 2013. The Gulf of Carpentaria Region (red bars in Figure 6) peaked at 694 t in 2006, while the harvest from LTMP Regions between Lockhart and Stanage (green bars) peaked at 1104 t in 2003. The harvest from the Rockhampton and southern LTMP Regions (blue bars) was smaller, peaking at 489 t in 2004.

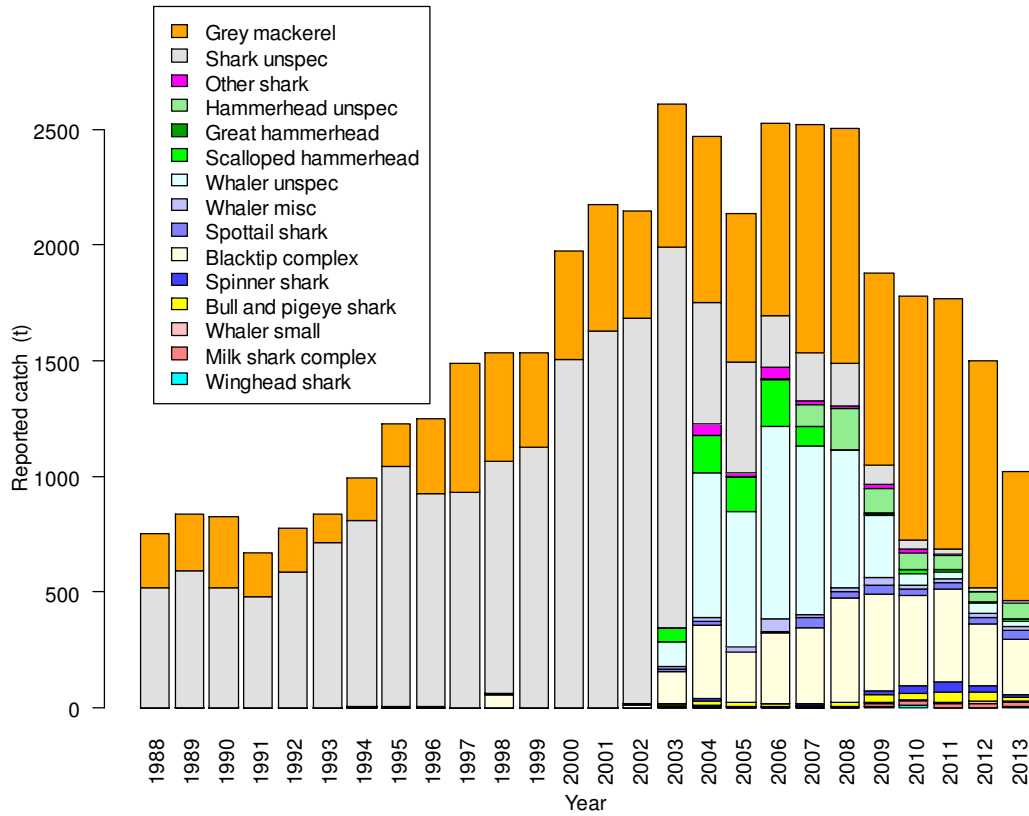


Figure 5: Commercial harvest of sharks and grey mackerel from Queensland logbooks, by species. Species identification of sharks by fishers began from 2003 onwards, but is considered unreliable. Source: Fisheries Queensland logbook database.

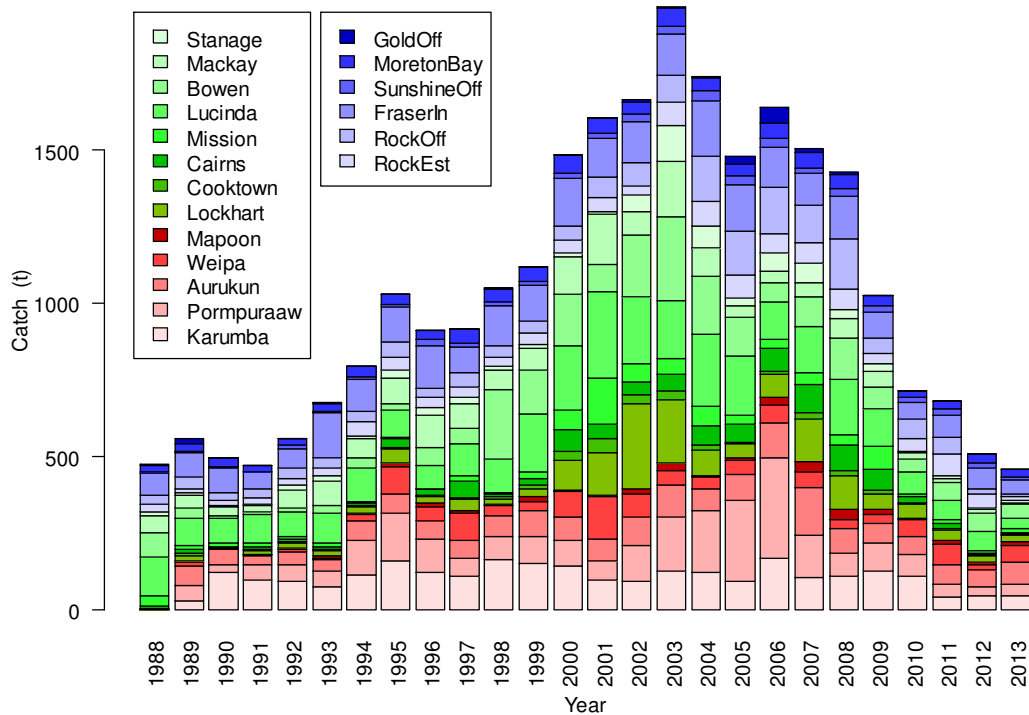


Figure 6: Reported harvest of sharks from Queensland commercial logbooks, by LTMP Region. Bars are coloured red for the Gulf of Carpentaria Region, green for regions from Lockhart to Stange, and blue for the Rockhampton and southern regions. Source: Logbook database maintained by Fisheries Queensland.

#### 1.4.4 Fishery Observer Program

Fisheries Queensland's Fishery Observer Program (FOP) operated from 2006 to 2012. Because its timespan is only narrow, in this assessment it is regarded as a "snapshot" of the fishery and no trends over time are derived from it. It is, nevertheless, extremely useful as a source of information on the species composition of the commercial catch. Participation by fishers in the observer program was voluntary. Differences in fishing characteristics between fishers who consented to take observers and those who did not are unknown.

The species compositions by number for the FOP (net fishery only) and the tag releases from the JCU–FRDC tagging experiment (described in section 1.1) are plotted in Figures 7 and 8. Not all LTMP Regions were sampled by the tagging program. The categories "Whaler small" and "Whaler misc" in these figures are aggregates of the less common species of small whalers and non-small whalers respectively. Sharks in these categories were still identified to species level.

The fishing gear types used to capture sharks differed between these two data sources. The FOP data came almost exclusively from gillnetting, whereas the tagging data came from a wide range of gear types which are listed in Table 11. Therefore the proportions of the different broad categories of sharks (e.g., large whalers versus small whalers) were expected to differ and such differences do not imply data problems. Close agreements in species ratios should, however, be expected for species that had similar biology.

Figures 7 and 8 show a major discrepancy in the proportions of sharpnose sharks (*Rhizoprionodon taylori* and *R. oligolinx* combined) relative to milk shark (*R. acutus*) and other small whalers. The tagging program reported a much greater proportion of sharpnose sharks than the FOP. This discrepancy probably stems from frequent species identification errors in one or both of the sources.

Comparison of Figures 7 and 8 shows no other obvious problems. The remaining differences in species composition could be explained by the different fishing gears used in the two sources.

In this assessment the FOP data are assumed to be correct, as they constitute the only data source that attempts to sample the commercial fishery. The tag-release data come mainly from scientific, fishery-independent and research-data sampling in which most of the catch is taken by different fishing methods to those used in the commercial fishery (see Table 11).

Figures 9 and 10 compare the commercial logbook harvest of sharks with the weight of sharks recorded by the fishery observers. It can be seen that the observer coverage was relatively high in the Karumba and Lucinda LTMP Regions, and was lower but still useful in the other LTMP Regions. The "Torres Strait" LTMP Region is defined only for the Queensland-managed fishery within three nautical miles of the coastline. It does not relate to catches in the Torres Strait fishery managed by the Australian Government. The variation in observer coverage between LTMP Regions was taken into account in the assessment. The major effect expected was that the assessment results would be subject to slightly higher random error than if the observer coverage had matched the regional shark catches.

The major shark taxa encountered by the fishery are, from Figure 10, the Australian blacktip shark *Carcharhinus tilstoni*, spot-tail shark *C. sorrah*, scalloped hammerhead *Sphyrna lewini* and great hammerhead *S. mokarran*. The great hammerhead was not on the original list for stock assessment, but we considered it necessary to include it due to its large contribution to the fishery when measured by weight. The great hammerheads that are encountered tend to be very large (see Figure 11). As mentioned earlier, hammerhead sharks are often caught by their heads in gillnets intended to catch fish or sharks around the body, so hammerheads caught in the nets can be much larger than other taxa.



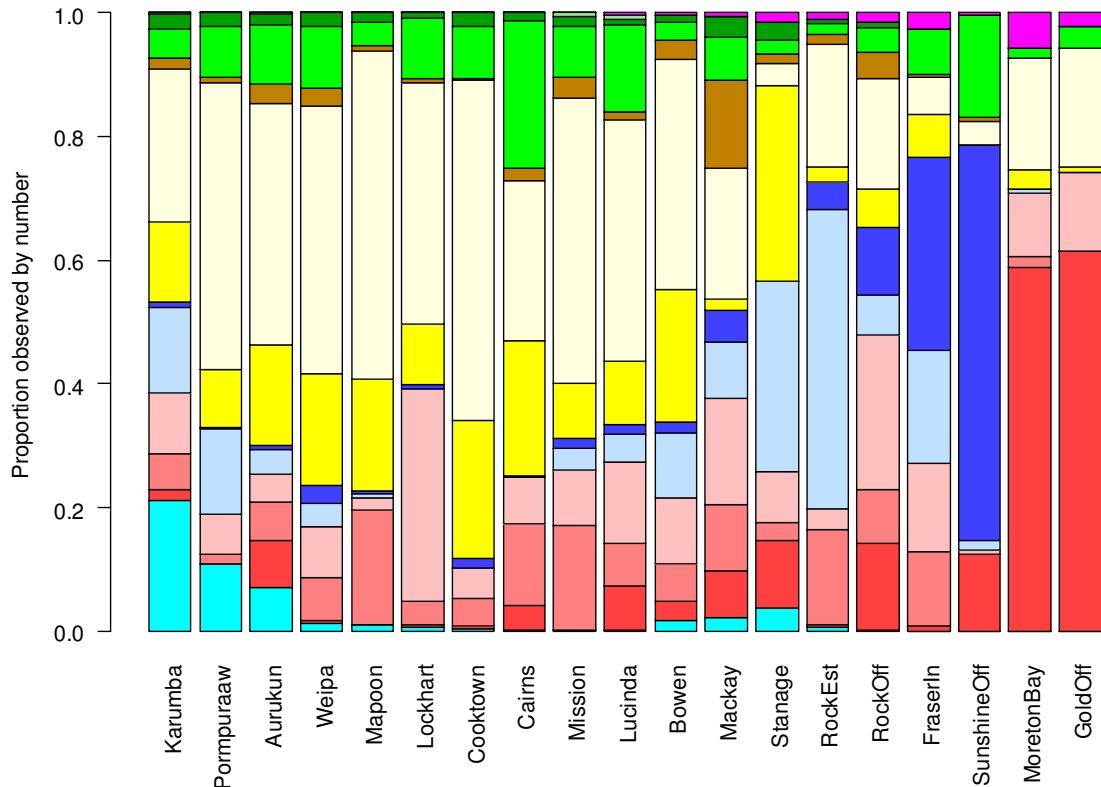


Figure 7: Species proportion by number for LTMP Regions from the Fishery Observer Program, net fishery. Fishing gear comprised mainly gillnets. Species legend is in Figure 8.

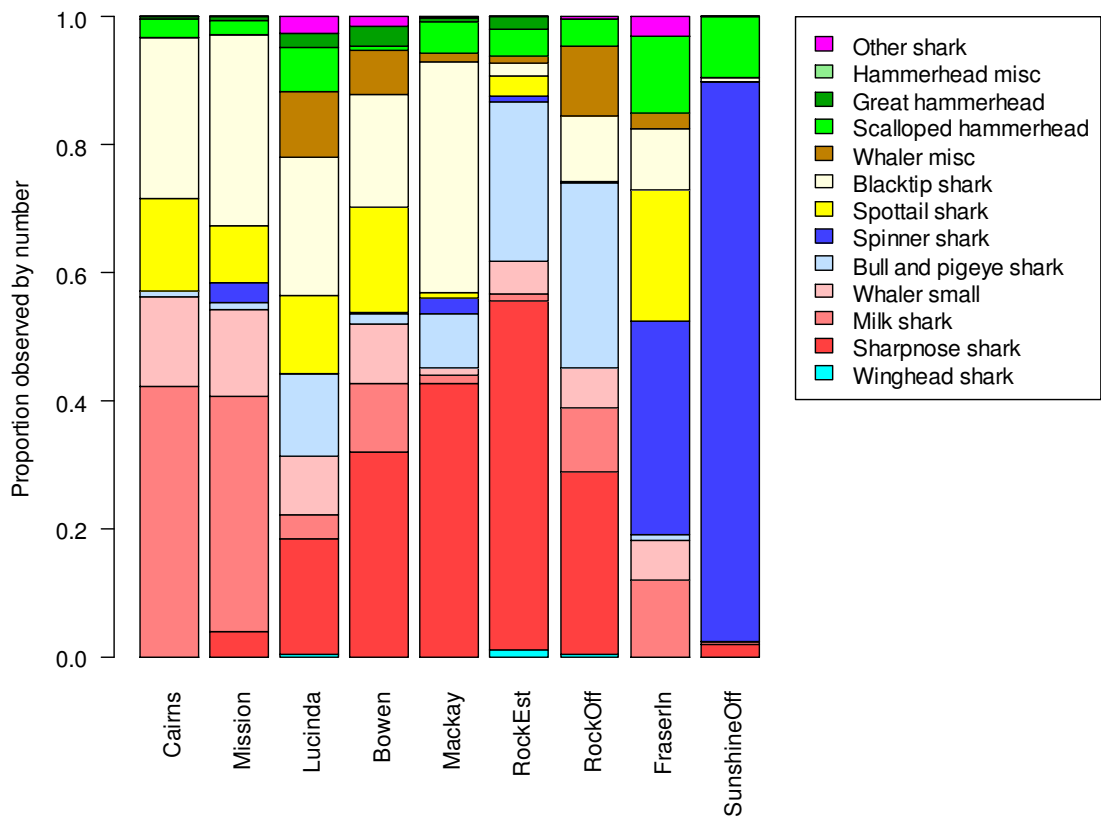


Figure 8: Species proportion by number for each sampled LTMP Region from tag releases in the JCU–FRDC tagging project, for verification of the species identification in Figure 7. A wide range of fishing gear types were used, as documented in Table 11, so the ratios of small to large whalers are not expected to be the same as in Figure 7.

It is notable that there is little relation between the size to which a shark species grows and the size at which it is taken in the fishery, especially in nets, which provide the major part of the catch (Figure 12). Each species has its own size-dependent vulnerability function. For example, the bull, pigeye and spinner sharks grow much larger than the Australian blacktip and spot-tail sharks (257–340 cm versus 107–165 cm; see Table 6, page 23), but in the fishery the typical sizes are the other way around (Figure 12). Also the winghead shark grows to about 170 cm (Table 6), but most individuals encountered in the fishery were only about 65 cm; this result is based on relatively few large hauls of small winghead sharks in the Gulf of Carpentaria.

*Table 11: Gear used to capture sharks for the JCU–FRDC tagging experiment.*

<b>Source</b>	<b>Gear</b>	<b>Number</b>
Fishery independent	Longline	1913
Research data	Net reel	1059
Fishery independent	NERP net 4/6.5'	588
Fishery independent	4.5' gillnet	249
Observer data	Net reel	199
Observer data	4.5' gillnet	197
Fishery independent	Rod & reel	180
Research data	Rod & reel	154
Research data	6' Gillnet	133
DEEDI observer tags	Net reel	98
Observer data	Offshore net	82
DEEDI observer tags	6.5' Gillnet	75
Observer data	6.5' Gillnet	75
Research data	6.5' Gillnet	75
Research data	Offshore net	57
Research data	4.5' Gill net	47
Research data	Line	45
Fishery independent	Line	41
Fishery independent	Foreshore net	40
DEEDI observer tags	Foreshore net	34
Observer data	SOCI breakaway panel	31
Research–fisher	4.5' Gillnet	30
Research data	Longline	26
Ross River flats	Foreshore net	25
DEEDI observer tags	River set net	20
Observer data	General purpose net	16
DEEDI observer tags	General purpose net	14
Observer data	SOCI control	14
Fishery independent	Offshore net	9
Observer data	SOCI Lay Down Sally fly	9
DEEDI observer tags	Line	8
Research–fisher	Foreshore net	6
Trawl survey	Trawl	4
Additional–misc.	Line	3
Ross River flats	Not specified	3
Fishery independent	Not specified	2
Research data	River set net	2
Research data	Not specified	1

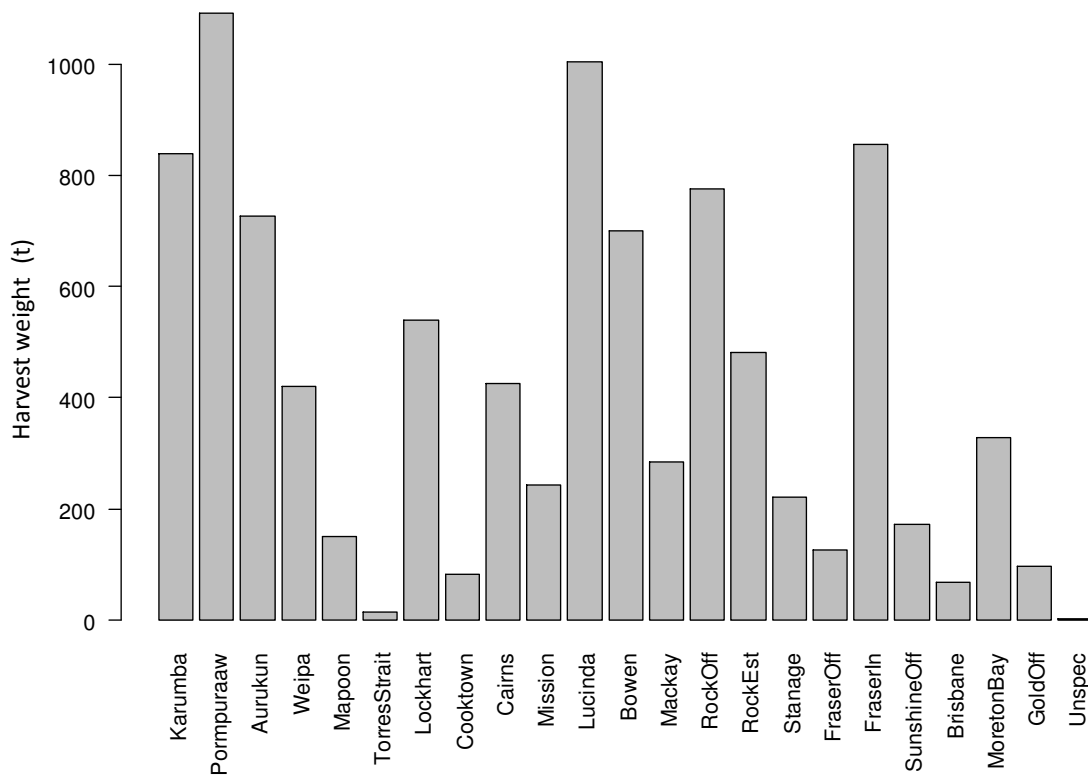


Figure 9: Reported commercial harvest of sharks by LTMP Region, totalled over the calendar years 2005–2013, for comparison to fishery observer data (Figure 10).

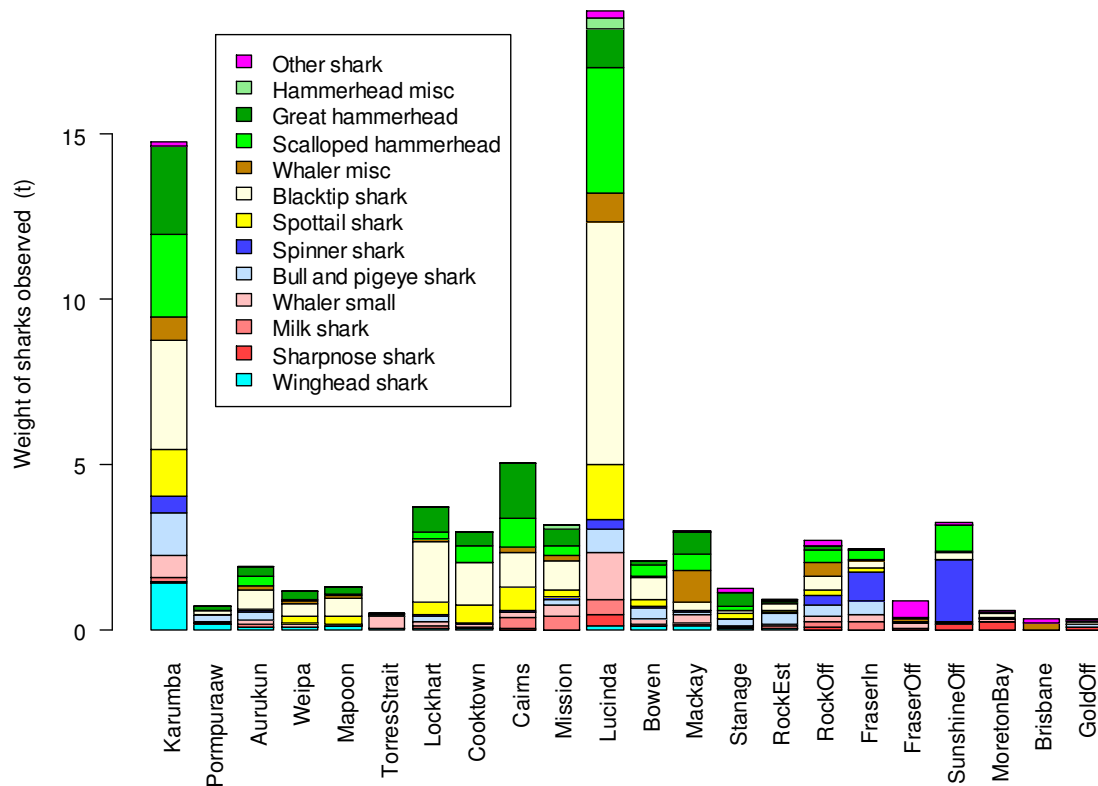


Figure 10: Total weight of sharks recorded by observers, by taxon and LTMP Region. The taxa are roughly ordered from smallest to largest size categories of sharks that are caught in the fishery. The category “Whaler small” was defined only for plotting and embraces several species of small whaler, including white-cheek shark, hardnose shark and creek whaler.

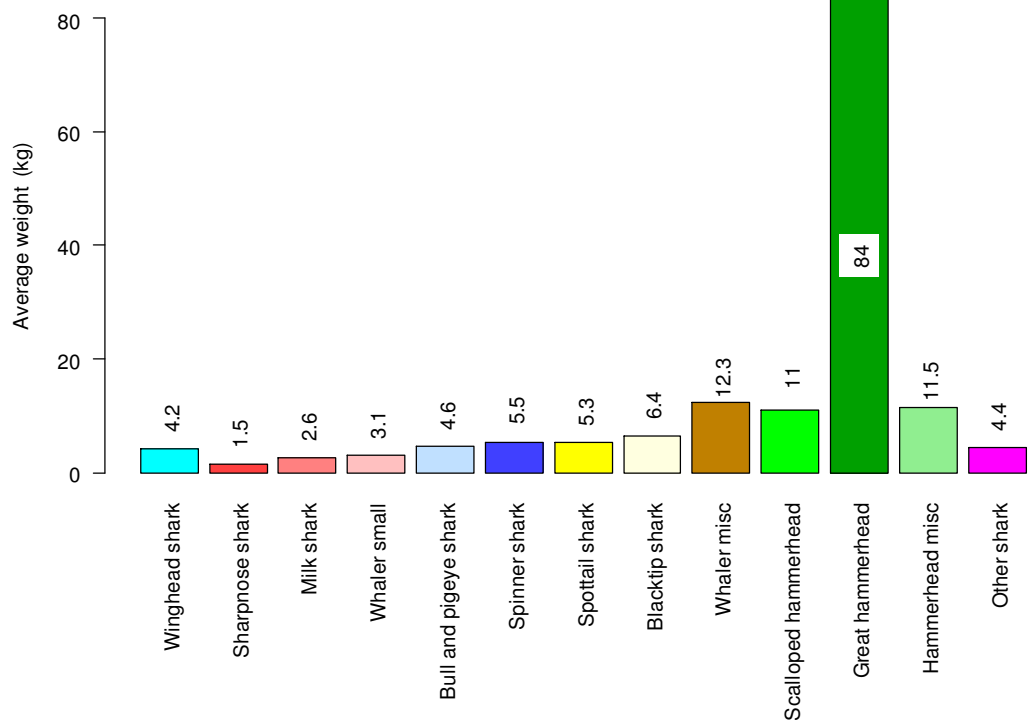


Figure 11: Average weight of sharks encountered in the commercial fishery: weights were converted from lengths observed in the Fishery Observer Program using published length-weight relationships (Table 6).

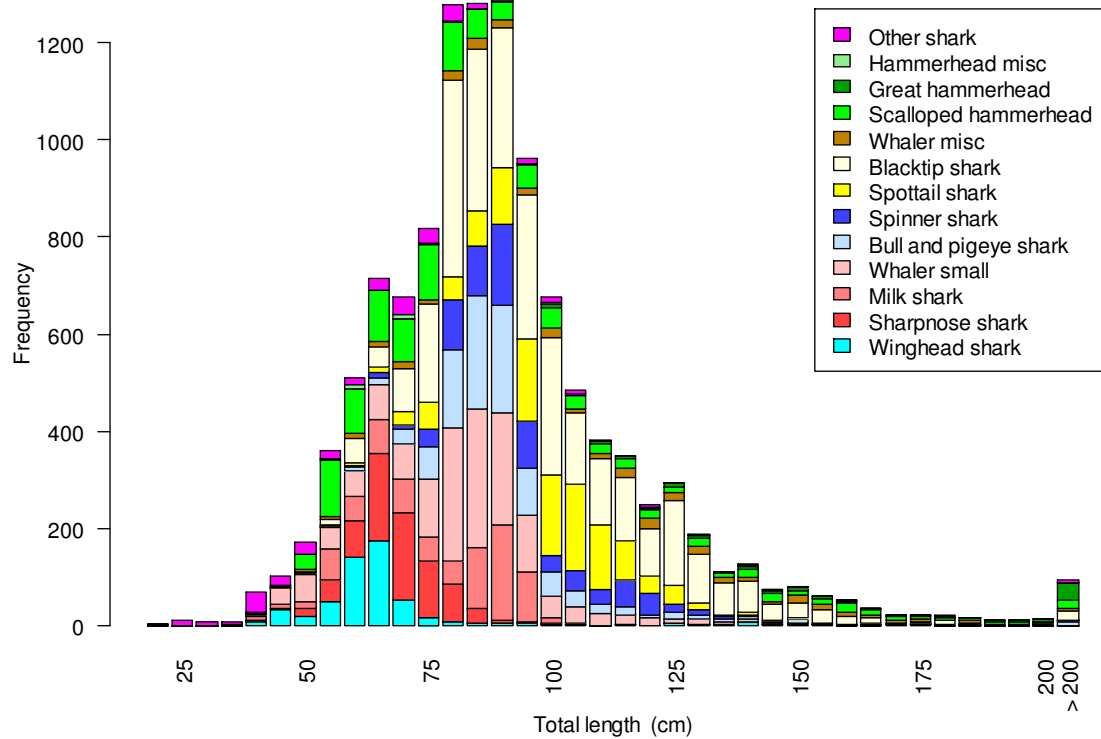


Figure 12: Length distribution (stretched total length, STL) of sharks encountered in the commercial fishery, from the Fishery Observer Program.

#### 1.4.5 Retention rates for the commercial fishery

Due to the multi-species nature of the fishing operations, not all sharks caught are retained for commercial sale, especially when an operator is targeting ray-finned fish. This stock assessment concentrates on net fishing, in which the discard rate may be affected by market price, demand from wholesale markets, and other operational and economic factors. As noted, the Fishery Observer Program data indicate that the line fishery on the east coast catches mainly reef sharks (blacktip reef shark, whitetip reef shark and grey reef shark), and trawl catch, although not quantified, was believed to be small. Therefore both of these sectors were excluded from this stock assessment.

The fate of sharks caught in the commercial gillnet fishery is graphed in Figure 13. It shows that most species have a high retention rate. The species with lower retention rates are the three hammerhead species (winghead shark, scalloped hammerhead and great hammerhead), bull shark and milk shark. Bull sharks have a much lower retention rate than pigeye sharks, presumably because pigeye sharks occur in waters where fishers target sharks, whereas bull sharks generally occur closer inshore and in estuaries where it appears that fishers target mainly bony fish. Milk sharks and other small whalers were found by inspection of the data to have lower retention rates for smaller individuals than for larger ones; the small individuals appear not to be desired by fishers.

For stock assessment purposes, sharks released alive from the net fishery are assumed to survive with no long-term ill effects from being caught. Then the effective harvest from the population is the sum of the retained sharks and the sharks released dead. We note that comparatively little research has been done into post-release mortality rates of sharks (Skomal 2007). Hueter and Manire (1994) found an overall discard mortality rate of 35% for a diverse range of small sharks released alive. Frick et al. (2010) found post-release mortality rates from gillnetting to be low for the Port Jackson shark (from order Heterodontiformes) but high for the gummy shark (family Triakidae, order Carcharhinidae). Braccini et al. (2012b) found similar results, with bottom-dwelling species having higher survival than pelagic species. Mandelman and Skomal (2008) found a wide range to the levels of physiological disturbance experienced by sharks from Carcharhinidae upon capture, with the tiger shark *Galeocerdo cuvier* and sandbar shark *Carcharhinus plumbeus* experiencing little disturbance but the dusky shark *C. obscurus*, Atlantic sharpnose shark *Rhizoprionodon terraenovae* and the common blacktip shark *C. limbatus* experiencing high levels of disturbance.

Little information was available on the trend in retention rates of sharks over time. Anecdotal information relayed by Project Team members indicated that retention rates may have decreased after the management restructure in 2009 when total allowable commercial catches (TACCs) were introduced. As part of this restructure, a net fisher must hold an “S” fishery symbol in order to retain sharks in excess of an allowed “incidental” catch of ten individual sharks, and additional reporting requirements were imposed in order to retain sharks.

Discarding of sharks can also be inferred from the proportion of catches in which fishers reported only grey mackerel but no shark. This was relatively high in the early years of the logbook system (e.g., 1988–1990), and in various other years which differed between Subregions. Catch rates in these Subregion–year combinations were excluded from input to the population dynamic model (see chapter 4 below).

In the population dynamic model it was assumed that the retention rate of sharks had remained constant over the history of the fishery. In this case discarding can usually be ignored because a TACC or an estimate of population size or maximum sustainable yield (MSY) can be applied to the animals that are retained. If the retention rate took a known low value, the population size could be scaled up appropriately but the important outputs from the stock assessment would not be affected.

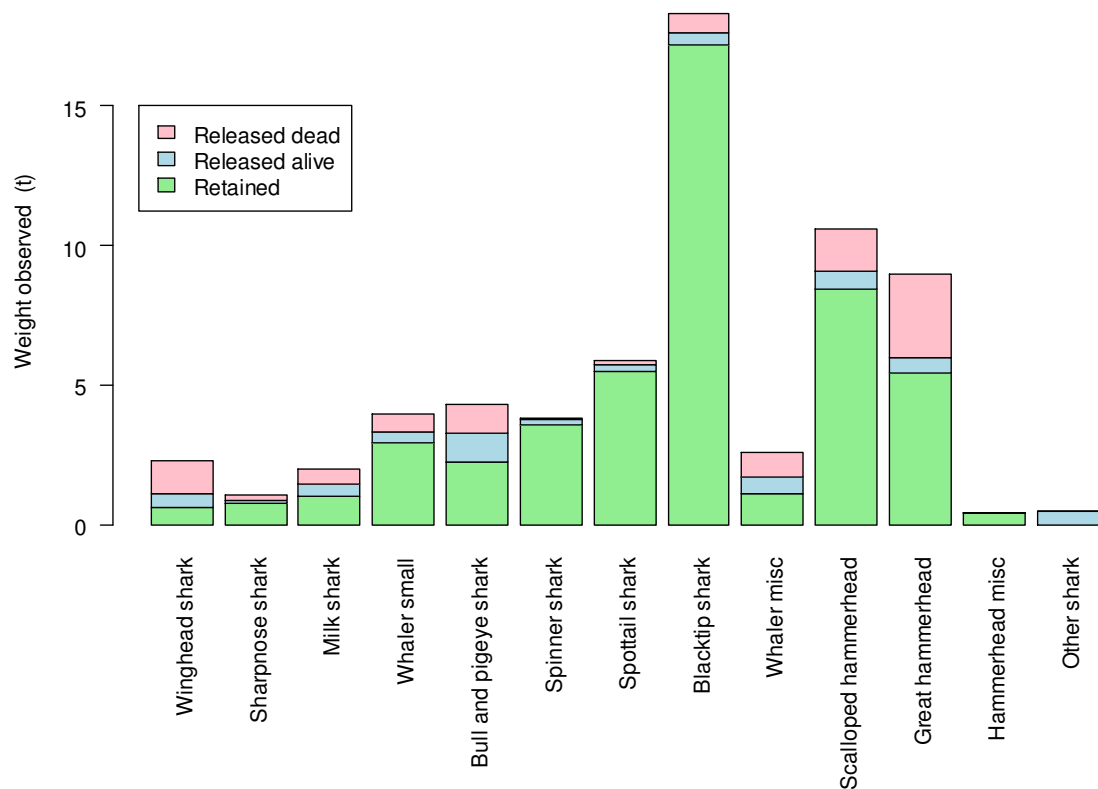


Figure 13: Retention of sharks encountered in the commercial gillnet fishery, from the Fishery Observer Program.

It should be noted that participation by fishers in the observer program was voluntary. Fishers who did not have observers on board may have had lower retention rates of sharks than fishers who had observers.

#### 1.4.6 Recreational fishery

Queensland has a large community of recreational fishers who target a wide range of fish species. Sharks are caught by recreational fishers but are not commonly targeted.

Recreational catches of fish in Queensland have been measured by State-wide diary surveys since 1997:

- Surveys conducted by Fisheries Queensland, known as RFISH, in 1997, 1999, 2002 and 2005 (Higgs 1999, 2001; Higgs *et al.* 2007; McInnes 2008).
- An Australian national survey (the National Recreational and Indigenous Fishing Survey, NRIFS) was conducted in 2000 and used different methodology. It was funded by the Australian Government's Fisheries Research and Development Corporation (FRDC, project number 99/158) (Henry and Lyle 2003).
- The NRIFS methodology was adopted by Fisheries Queensland for the State-wide survey in 2011, known as SWRFS (State-Wide Recreational Fishing Survey, pronounced "Swirfs") (Taylor *et al.* 2012).

The surveys consisted of two stages: a preliminary telephone survey to measure the participation rate of residents in each statistical area, followed by a year-long diary survey of telephone respondents who participated in recreational fishing. A further SWRFS survey was conducted in 2013 but results were not available at the time of this assessment.

Recreational fishing specialists in Fisheries Queensland prefer the NRIFS and SWRFS survey methodology, and those are the only surveys considered here. This methodology better handles fishers' recall bias by calling them more frequently and prompting them with a list of

species that they may have caught, and it is less susceptible to dropout bias whereby fishers who drop out during the course of a survey tend to be those who don't fish much.

The most notable aspect of recreational catches of sharks and rays is that most of them were released. The 2000–01 survey showed 288,000 sharks and rays released and only 37,000 (11.4%) retained (Henry and Lyle 2003; Department of Agriculture and Fisheries 2015). The 2011 survey showed 130,000 released and only 6,000 (4.4%) retained (with low confidence around the latter number) (Taylor *et al.* 2012; Department of Agriculture and Fisheries 2015). We assumed that most of the released sharks would survive, as they were caught by hook and line.

The average weight of sharks retained by recreational fishers is uncertain, but common fishing gear is designed to catch fish up to about one metre in length. Therefore we expect most of the sharks caught to be small, between 0.25 kg (the weight of a 40 cm milk shark) and 6 kg (the weight of a one-metre blacktip shark). Assuming an average of 2 kg provides a total retained recreational catch of about 75 t in 2000–01 and about 12 t in 2011.

We note that a small number of recreational fishers may target large sharks either for sport or for tag and release (W. D. Sumpton, personal communication, 2015). We assumed that most recreational fishers who caught sharks were not targeting them.

In view of the small size and downward trend of the recreational harvest, it was considered negligible for the purposes of this stock assessment, and was ignored.

#### 1.4.7 Commercial fishery management

The major event in management of the Queensland commercial shark fishery took place on 1 July 2009 when the following measures were imposed:

- Total allowable commercial catch (TACC) of 480 tonnes north of Baffle Creek (24.5°S) (which we term the “Northern Management Region”) and 120 t south of this latitude (the “Southern Management Region”).
- Introduction of an “S” licence symbol for net fishers to retain more than ten sharks, or line fishers to retain more than four sharks.
- Maximum legal size of 1.5 metres total length for sharks caught by recreational fishers or commercial line fishers.

Prior to 2009, management was conducted mainly by means of

- Limited entry to commercial fishers (new fishers have to buy an existing licence)
- Restrictions on net length, and
- Restrictions on mesh size of nets.

No minimum legal size has been applied to sharks in Queensland.

No maximum legal size of sharks has been applied to “S” (shark) symbol holders in the net fisheries. The net fisheries in any case retain few sharks over 1.5 m in length, due to market preferences and the multi-species nature of the fishery.

No TACC has been applied to the shark fishery in the Gulf of Carpentaria (the “Gulf Management Region”). The Southern Management Region comprises the Fraser Inshore, Sunshine Coast Offshore and Moreton Subregions. The Northern Management Region comprises all the other east coast Subregions.

## 1.5 The Shark Control Program

Since 1962 Queensland has had a Shark Control Program (SCP) to protect popular bathing beaches by catching large sharks that pose a danger to bathers. The gear used in the SCP consists of a combination of large-mesh gillnets and large fishing lines and hooks known as “drum lines”.

Upon review, the stock assessment Project Team decided that this data source contained too many complications for it to be included in the assessment. As such, it was excluded from the assessment. Some of the complications are listed below; we are indebted to Dr Wayne Sumpton of Agri-Science Queensland for most of this information:

- Over the years the SCP has changed in focus from an objective to catch as many sharks as possible to an operation more targeted towards large sharks only, and substantial efforts have been made to reduce bycatch of animals such as manta rays, turtles, dolphins and whales (DAF 2015).
- Self-baiting of SCP nets, whereby dead sharks previously caught effectively acted as bait to attract more sharks, was common in the early years of the SCP and would have produced higher catch rates than unbaited nets. In recent years more frequent servicing of the gear has resulted in all catch being removed relatively quickly.
- Various bait types have been used over the history of the SCP and it is not possible to standardise for the effectiveness of different baits over time. Currently mullet is generally used but shark flesh is also used at times.
- There have been many small-scale changes to the positioning and configuration of nets which have affected their effectiveness and patterns of selectivity. One example is that nets are currently set parallel to the beach but historically they were sometimes set at an angle.
- For some decades virtually all nets have been top-set, suspended by floats from above. In early years they were sometimes bottom-set, anchored closer to the sea bottom.
- The usage of nets has reduced over the years, in favour of drum lines.
- No nets have been used in the Woongarra Coast region (around Bundaberg) since 1978, due to unacceptable rates of bycatch of turtles.
- The traces (fishing lines) used on drum lines have changed over the years, from rope to chains or thin stainless steel traces.
- Contractors have sometimes had to raise gear from the water, e.g., for repair. Historically they may have preferred to do this on weekdays and during the winter when fewer swimmers are present in the water. Currently the turnaround to repair or replace gear is very short.
- There are many other fine details of the setting of gear that have considerable effects on catch rates but have not been recorded.
- Species identification of SCP catches is subject to similar difficulties to the commercial fishery. Sharks could generally be classified reliably only as whaler, hammerhead, tiger or white sharks, especially in earlier years.
- The lengths of sharks caught in the SCP are not reliable. SCP contractors received a bounty for sharks two metres long or more until about 1990, and it was in their interest to report sharks this big.

Features of the SCP data other than catch rates may offer possibilities for future stock assessment. These possibilities include the following:

- The initial population size of sharks prior to introduction of gear could be estimated from the depletion effect. Catch rates decline over some years after gear is introduced to a beach. The number of sharks caught over these years could be considered roughly equivalent to the size of the local population before the gear was introduced.
- The productivity of shark populations could be estimated from the ongoing catch rate after the above depletion has occurred. The number of sharks caught per year could be equated to the number of new sharks recruited to the local population per year. Such estimation may, however, be confounded with migration into the local area from other areas.
- The effective range (length of coastline) over which gear operates could be estimated from historical instances of the introduction of new gear on a neighbouring beach to



one that already had shark control gear for many years. If newly installed gear on a neighbouring beach to existing gear showed the same depletion pattern as for a beach far from any other gear, the effective range of the existing gear evidently did not extend to the new beach. On the other hand, if the depletion pattern was less clear or non-existent, it could be assumed that the existing gear had already affected the abundance of sharks of the new beach.

- A time series of the ratio of tiger-shark to whaler-shark catch rates could be used to infer the effect of fishing on the whaler-shark population. Tiger sharks are subject to only a very low level of fishing, and therefore their catch rates should be unaffected by fishing. Tiger shark populations may, however, have been significantly reduced by the Shark Control Program itself. Whaler sharks have much higher vulnerability to fishing. The ratio of catch rates could act as a standardised abundance measure for whaler sharks, and a decrease in the ratio could indicate high levels of fishing.

These avenues of analysis have not yet been intensively pursued. Analysis that we have undertaken of the SCP data is presented in Appendix 1.

## **1.6 Data used in the assessment**

The following data were used to generate inputs to the population dynamic model described in chapter 5:

- Growth parameters (Table 6)
- Reproductive parameters (Table 7)
- Population parameters from demographic analysis (chapter 2)
- Commercial harvest sizes (chapter 3)
- Standardised commercial catch rates (chapter 4)
- Fishery Observer Program data on
  - Species composition of the commercial catch by Subregion and
  - Species-specific length frequency of the commercial catch.

The tagging data described in section 1.1 were used as a check on the species composition recorded by the fishery observers and could also be used as a check on rates of fishing and natural mortality of sharks.

Shark Control Program data were studied separately (Appendix 1) and were not used to produce population model inputs, i.e., these data were not used in either the total or species-specific calculations of maximum sustainable yield.

## 2. Demographic analysis

### 2.1 Background

Demographic analysis is a tool that can be used to find a population's intrinsic rate of annual increase: this is the expected rate of population increase when the population has been reduced to a small fraction of its original size and then provided with very favourable conditions in which to recover. The intrinsic rate of increase is a theoretical quantity and its use does not imply that a particular population has either been greatly reduced or is currently experiencing favourable conditions. Demographic analysis was introduced briefly in section 1.1. Previous applications to sharks include the following:

- Hoenig and Gruber (1990) (lemon shark, *Negaprion brevirostris*)
- Hoff (1990) (sandbar shark, *Carcharhinus plumbeus*)
- Cailliet (1992) (leopard shark, *Triakis semifasciata*, family Triakidae)
- Cortés (1997) (sandbar shark)
- Simpfendorfer (1997) (dusky shark, *Carcharhinus obscurus*)
- Stevens (1997) (gummy shark, *Mustelus antarcticus*, family Triakidae; and school shark *Galeorhinus galeus*, also family Triakidae)
- Cortés (1998) (lemon shark; sandbar shark; dusky shark; common blacktip shark; Atlantic sharpnose shark, *Rhizoprionodon terraenovae*; and bonnethead shark, *Sphyrna tiburo*, a small hammerhead)
- Smith et al. (1998) (26 species including the bull shark, common blacktip shark, Atlantic sharpnose shark and scalloped hammerhead)
- Cortés (2002) (38 species including the Australian and Atlantic sharpnose sharks, spot-tail shark, Australian and common blacktip sharks, bull shark, spinner shark and scalloped hammerhead)
- Tsai et al. (2014) (shortfin mako shark, *Isurus oxyrinchus*, order Lamniformes).

This chapter will provide demographic analyses for the 12 major species of sharks in Queensland (listed in Tables 5–7), using updated Australian data where possible along with corrections to some aspects of the biology (e.g., lifespan, juvenile mortality rate, age at maturity, pupping interval). The methodology builds on that of Smith et al. (1998). A new aspect is that the methodology is extended to interpret the results in terms of parameters for stock-recruitment relationships that are commonly used in fishery stock assessment models.

### 2.2 Demographic model and assumptions

The demographic analysis presented here is somewhat different to most of the work reported above, and estimates natural mortality rates and stock-recruitment parameters. Our method is similar to that of Smith et al. (1998). We estimate rates of natural mortality by assuming that a population is in steady state, whereby a female shark produces an average of exactly one female shark over its lifetime (see equation (2.1) below). Firstly we estimate the virgin natural mortality rates by setting the fishing mortality to zero. Then we impose fishing mortality on adult sharks only, at the same level as natural mortality: the steady-state equation is still satisfied by means of a compensatory decrease in the natural mortality rate of juvenile sharks. This is the same framework as in Smith et al. (1998).

Finally, the demographic parameters are converted into recruitment compensation ratios as defined by Goodyear (1977). To the best of our knowledge this step has not been published previously and is new to fisheries science. It requires an additional assumption about the population size in the second (fished) steady state, which was not needed by Smith et al. (1998) (see equation (2.5) below).

It is important to note that the demographic assumptions do not relate directly to model outputs as described in Chapters 5 and 6. For example, the assumption, given by equation (2.5) below, that maximum recruitment compensation takes effect at a parental stock level of

20% of virgin, does not mean that the maximum sustainable yield that can be taken from the population also occurs at the 20% level. The relative stock size at maximum sustainable yield depends not only on demographic parameters but also on the vulnerability functions estimated by the model (see chapter 5), so it can only be estimated after the model has been run and estimates are available for both demographic parameters and model parameters.

This model follows the widely-held assumption in fisheries (Gulland 1970) that fishing an adult population of fish at a rate  $F$  equal to its instantaneous natural mortality rate  $M$  constitutes a reference point for sustainable fishing. According to this assumption, if only mature animals are fished, the population can become overfished only if  $F$  is routinely greater than  $M$  for some years.

The shark fishery in Queensland operates differently and does not focus on catching large individuals. Large whalers and hammerheads are targeted as juveniles, while lower fishing mortality is applied to the adults. Small whalers are targeted as both juveniles and adults. The model and its parameter values are still valid for these styles of target fishing. The model applies fishing only in order to estimate the maximum amount of compensation of which the population is capable: the same rate of compensation, in the form of reduced natural mortality of juvenile sharks, can be expected whether the population is reduced by fishing adults or juveniles. The model makes no direct assumption about what levels of fishing are sustainable for juvenile sharks: these have to be calculated using the parameter estimates from hypothetical fishing of adult sharks.

The steady-state population equation is

$$LX \sum_{a=0}^{\infty} S_a Y_a = 1, \quad (2.1)$$

where  $L$  is the average litter size,  $X$  is the proportion of newborn pups that are female,  $a$  denotes age in years,  $S_a$  is the probability that an animal survives to the end of year  $a$ , and  $Y_a$  is the probability that a female is mature at the beginning of year  $a$ . The left-hand side of (2.1) is the average number of female offspring produced by a female shark over its lifetime: setting it equal to 1 implies that the population is in steady state, i.e., neither increasing nor decreasing. The survival  $S_a$  is given by

$$S_a = \exp\left(-\sum_{i=0}^a Z_i\right),$$

where  $Z_i$  is the instantaneous total mortality rate at age  $i$ :  $Z_i = F_i + M_i$  where  $F_i$  and  $M_i$  are the instantaneous rates of fishing and natural mortality respectively. The maturity fraction  $Y_a$  is modelled as a logistic function (Haddon 2001 353):

$$Y_a = 1 / [1 + \exp\{-(\log 19)(a - a_{50}) / (a_{95} - a_{50})\}],$$

where  $a_{50}$  and  $a_{95}$  are the ages at 50% and 95% maturity of females, from Table 7 (page 23). The survival  $S_a$  is taken at the end of the year in order to account for the gestation period which is about one year. Even for sharks that give birth every two years, the gestation period is still roughly one year and is followed by a rest period of about one year (Branstetter 1981; Stevens and Lyle 1989; Stevens and McLoughlin 1991; Joung *et al.* 2005). Other studies including Smith *et al.* (1998) appear not to have taken gestation into account.

In our model, the total mortality rate  $Z_i$  takes one value  $Z_{\text{juv}}$  for ages less than the age at 5% maturity of females,  $a_5 = a_{50} - (a_{95} - a_{50})$ , and another value  $Z_{\text{adult}}$  for ages greater than or equal to  $a_5$ . In fact the model only needs the average juvenile mortality rate, and the results are unaffected by whether the mortality is greater at age zero than at the other juvenile ages. Values for females are used because the abundance of females is generally the limiting factor for animal populations' ability to breed and fishery stock assessment models commonly use female egg production as a measure of reproductive potential in preference to biomass summed over both sexes (Goodyear and Christensen 1984). The value  $Z_{\text{adult}}$  is the same for both females and males.

In a virgin population,  $Z_i = M_i$  and the two natural mortality rates are  $M_{\text{juv}}$  for juvenile sharks and  $M_{\text{adult}}$  for mature sharks. We fix a particular value for the ratio  $M_{\text{juv}}/M_{\text{adult}}$  and solve equation (2.1) for  $M_{\text{adult}}$ .

For the fished population we set  $Z_{\text{adult}} = 2M_{\text{adult}}$  and solve (2.1) for  $Z_{\text{juv}}$ . The solution is a new, productivity-adjusted value for the juvenile natural mortality rate, which we denote  $M_{\text{prod}}$ . Our setup is similar to that of Smith et al. (1998), except that they use  $S_{a_{50}}$  as the juvenile mortality parameter and don't check whether the ratio  $M_{\text{juv}}/M_{\text{adult}}$  is reasonable. For example, they allow  $M_{\text{juv}} < M_{\text{adult}}$  which is not biologically reasonable: biological theory holds that sharks are at higher risk when they are young, so  $M_{\text{juv}}$  should be greater than  $M_{\text{adult}}$ .

To quantify recruitment compensation, we remove the fishing but retain the lower juvenile natural mortality rate  $M_{\text{prod}}$ , thus simulating recovery from a depressed population size. Then the left-hand side of (2.1) is greater than 1 and is equal to the recruitment compensation limit, which we denote  $r_{\text{lim}}$ .

The standard Beverton-Holt stock recruitment relationship (Beverton and Holt 1957) can be written as

$$\frac{R}{R_0} = \frac{r B/B_0}{1 + (r-1)B/B_0}, \quad (2.2)$$

where  $r > 1$  is the recruitment compensation ratio (Goodyear 1977),  $R$  is the number of new recruits (newborn animals) to the population,  $B$  is a measure of the parental stock size (e.g., biomass of potential parents, or egg production by female animals), and the subscript 0 denotes values for a virgin (never fished) population. The recruitment compensation ratio  $r$  is the average number of number of animals produced by each animal during its lifetime at extremely low population sizes (i.e., as  $B/B_0 \rightarrow 0$ ).

For sharks and compatibility with the Smith et al. (1998) formulation of demographic analysis, we assume that the maximal recruitment compensation takes effect not only at extremely low population sizes but at some parental population size  $B_{\text{prod}}$  that results from fishing the adult population at a rate equal to the adult natural mortality rate (i.e.,  $Z_{\text{adult}} = 2M_{\text{adult}}$  as used above). Then the stock-recruitment relationship (2.2) changes to

$$\frac{R}{R_0} = \frac{B}{B_0} \min\left(\frac{r}{1 + (r-1)B/B_0}, r_{\text{lim}}\right). \quad (2.3)$$

For this to take effect at population size  $B_{\text{prod}}$ , we need the two arguments of the ‘‘min’’ function to be equal at that point, i.e.,

$$\frac{r}{1 + (r-1)B_{\text{prod}}/B_0} = r_{\text{lim}}.$$

This equation can be solved for  $r$ :

$$r = \frac{r_{\text{lim}}(1 - B_{\text{prod}}/B_0)}{1 - r_{\text{lim}}B_{\text{prod}}/B_0}. \quad (2.4)$$

The level  $B_{\text{prod}}$  for the fished population has to be assumed. It cannot be estimated from the population parameters alone. We assumed that

$$B_{\text{prod}}/B_0 = 0.2, \quad (2.5)$$

i.e., the maximal recruitment compensation takes effect when the parental population is reduced to 20% of its virgin level. Using higher values than this can be problematic, as it is clear from (2.4) that the denominator is positive only if  $B_{\text{prod}}/B_0 < 1/r_{\text{lim}}$ . Otherwise a fished population would produce more recruits than an unfished one, which is not biologically

sensible. We expect that stock assessment results will be much more sensitive to the value of  $r_{\text{lim}}$  than to the exact level of the ratio  $B_{\text{prod}}/B_0$ .

We did not put any upper limit on the ages of sharks in the population. The maximum ages that have been observed for the species analysed are listed in Table 6 (page 23), but these are not claimed to be the maximum ages possible. Indeed, the sample sizes on which these maximum ages are based were quite small compared to typical sample sizes of bony fish; they are listed in Table 12. Therefore the populations are very likely to contain some sharks older than the maximum ages observed. The maximum ages of shark species may be limited by senescence (i.e., much higher mortality for old sharks; see below), but no data on that were available. We believed that allowing sharks to keep ageing indefinitely was a more accurate model assumption than truncating the age distribution at the maximum observed age. This assumption could be revisited in the future; a middle ground whereby senescence sets in at some age older than the oldest observed age may turn out to be the best solution.

For each species, the ratio  $M_{\text{juv}}/M_{\text{adult}}$  was chosen to be the minimum value that made both of the following conditions hold:

- $M_{\text{prod}}/M_{\text{adult}} \geq 1.5$ , i.e., natural mortality on juveniles must be at least 1.5 times higher than on adults, even after the compensatory decrease in juvenile mortality that results from fishing. We note that it might be more logical to make this limiting ratio depend on the biology of the shark, e.g., make it lower for small whaler species and higher for large whaler and hammerhead species. We used the same limiting ratio for all species in order to have consistent methodology and due to lack of biological knowledge of this parameter. It certainly should be greater than 1 for all species.
- Proportion of sharks aged  $a_{\text{max}}$  or more in the fished population must be at least 0.002, i.e., at least one in 500 sharks must be at or above the maximum observed age from Table 6.

The above number of 500 sharks was chosen as an approximate upper limit to the number of sharks from any one species that had been aged in published studies (see Table 12). For some species, problems associated with low numbers of animals aged (relative to studies of bony fish) were compounded by lack of active targeting of old sharks by fisheries due to the fishing gear used, locations fished and behaviour of adult sharks (see chapter 1).

Table 12: Numbers of sharks aged in published biological studies, from which the data in Tables 6 and 7 (page 23) were drawn.

Species	Study	Numbers aged/collected
Aust. sharpnose shark	Simpfendorfer (1993)	138/465
Milk shark	Harry et al. (2010)	231/231
Creek whaler	Smart et al. (2013)	37/37
Hardnose shark	Smart et al. (2013)	37/37
Spot-tail shark	Davenport and Stevens (1988)	213/7748
	Harry et al. (2013)	297/659
Aust. blacktip shark	Davenport and Stevens (1988)	389/18201
	Harry et al. (2013)	449/512
Common blacktip shark	Wintner and Cliff (1996)	92/92
	Carlson et al. (2006)	608/628
Spinner shark	Joung et al. (2005)	208/383
Bull shark	Tillett et al. (2011)	94/94
Pigeys shark	Tillett et al. (2011)	199/199
Winghead shark	Smart et al. (2013)	14/14
Scalloped hammerhead	Piercy et al. (2007)	307/311
	Harry et al. (2011)	392/522
Great hammerhead	Piercy et al. (2010)	216/224
	Harry et al. (2011)	100/146

The assumptions underlying the demographic analysis are summarised in Table 13. The analysis was programmed in the software *R* (R Core Team 2015). The code is listed in Appendix 2.

Table 13: Assumptions of the demographic analysis.

Assumption	Explanation
$X = 1$	Sex ratio is 1:1, i.e., identical numbers of male and female pups born into the population.
Max. achievable age $> a_{\max}$	Sharks older than the maximum observed age are present in the population, due to relatively low sample size of sharks that have been aged and possible movement of old sharks out of the fished areas.
Prop. $a_{\max} \geq 0.002$	At least one in 500 sharks in the population is at or above the maximum observed age.
$F_{\text{prod}} = M_{\text{adult}}$	Fishing the adult part of a shark population at a fishing mortality rate equal to the adult natural mortality rate is a reference point for sustainable fishing and induces the maximum possible compensatory productivity response in the population.
$M_{\text{prod}} < M_{\text{juv}}$	A shark population responds to fishing through compensatory reduction in the natural mortality rate of juvenile sharks.
$M_{\text{prod}}/M_{\text{adult}} \geq 1.5$	Natural mortality of juveniles (age $< a_5$ ) is at least 1.5 times that of adults, even after the compensation induced by fishing.
$B_{\text{prod}}/B_0 = 0.2$	Maximum juvenile-mortality compensation from fishing takes effect at a female parental stock size 20% of virgin.

## 2.3 Results

Results of demographic analysis are listed in Table 14. The estimates of the ratio of juvenile to adult natural mortality in a virgin population are all greater than 2.7. This ratio has been limited for the first six species (smaller sharks) in the table by the condition  $M_{\text{prod}}/M_{\text{adult}} \geq 1.5$ , and for the last six species (larger sharks) by the condition that the proportion of sharks with ages greater than or equal to the maximum observed age must be at least one in 500.

Estimates of the adult natural mortality rate  $M_{\text{adult}}$  generally decrease as the size of the shark increases, ranging from  $0.401 \text{ yr}^{-1}$  for the Australian sharpnose shark which is small and short-lived ( $L_{\infty} \leq 73.2 \text{ cm}$ ,  $a_{\max} = 6 \text{ yr}$ ; see Table 6), down to  $0.052 \text{ yr}^{-1}$  for the great hammerhead which is very large and long-lived ( $L_{\infty} = 402.7 \text{ cm}$ ,  $a_{\max} = 39 \text{ yr}$ ).

The value of the limiting recruitment compensation ratio  $r_{\text{lim}}$  is similar for all the species, ranging from 2.22 for the great hammerhead up to 3.02 for the hardnose shark. The recruitment compensation ratio is the average number of offspring to which a newly-born shark will give birth over its lifetime under favourable conditions at low population size (which provides negligible intra-species competition); alternatively, it is also the average number of female sharks that will survive to maturity for each mature female under these conditions. A value of 1 equates to bare replacement with no capacity for population growth, a scenario that is not biologically feasible. Values of  $r_{\text{lim}}$  greater than 1 allow for population growth from a low base. The values of  $r_{\text{lim}}$  can be compared to values of the recruitment compensation ratio  $r$  for ray-finned (bony) fish, which typically range between about 5 and 25. Shark populations are intrinsically less productive than ray-finned fish, and take much longer to recover from population bottlenecks that may be caused by, for example, unfavourable environmental conditions or overfishing. The value of  $r$  in Table 14 is less

important, being merely a measure of how quickly the limiting value  $r_{\text{lim}}$  takes effect as the population size falls.

In terms of the alternative parameter known as “steepness” and defined as  $h = r/(4+r)$ , the above values of  $r_{\text{lim}}$  for sharks translate to a range of about 0.36 to 0.43, while the example values for ray-finned fish translate to a range of about 0.56 to 0.86.

*Table 14: Population parameter estimates from the demographic model: ratio of juvenile to adult natural mortality rates in a virgin population and in a fished population, instantaneous natural mortality rate for adults ( $\text{yr}^{-1}$ ), recruitment compensation ratios  $r_{\text{lim}}$  and  $r$  for use in equation (2.3), and the proportion of sharks aged  $a_{\text{max}}$  or more in the fished population, where  $a_{\text{max}}$  is the maximum observed age from Table 6. Dotted lines separate the different categories of sharks covered in the assessment (small whalers, medium whalers, large whalers and hammerheads respectively).*

Species	Virgin	Fished	$M_{\text{adult}}$	$r_{\text{lim}}$	$r$	Prop. $a_{\text{max}}$
	$M_{\text{juv}}/M_{\text{adult}}$	$M_{\text{prod}}/M_{\text{adult}}$				
Aust. sharpnose shark	3.78	1.503	0.401	2.494	3.980	0.0086
Milk shark	3.10	1.505	0.261	2.298	3.402	0.0169
Creek whaler	3.35	1.503	0.190	2.861	5.351	0.0080
Hardnose shark	4.01	1.505	0.221	3.023	6.117	0.0053
Spot-tail shark	4.19	1.504	0.199	2.908	5.558	0.0041
Aust. blacktip shark	2.74	1.504	0.150	2.529	4.095	0.0131
Common blacktip shark	2.84	1.935	0.195	2.890	5.481	0.0020
Spinner shark	4.77	3.711	0.126	2.549	4.161	0.0020
Bull shark	6.03	4.952	0.084	2.259	3.297	0.0020
Winghead shark	4.31	3.138	0.136	2.595	4.315	0.0020
Scalloped hammerhead	6.86	5.428	0.080	2.506	4.018	0.0020
Great hammerhead	17.92	15.365	0.052	2.216	3.183	0.0020

The estimated proportions of sharks at and above the maximum observed age are quite large (0.8% or more; final column of Table 14) for some of the small and medium whaler species. A more accurate demographic model might include senescence (high natural mortality of old animals) for these species. We have not imposed this due to lack of both data and evidence for this hypothesis.

We note that for the great hammerhead there is little difference in relative terms between  $M_{\text{juv}}$  and  $M_{\text{prod}}$  (final row of Table 14):  $M_{\text{juv}}$  is 17.9 times  $M_{\text{adult}}$  while  $M_{\text{prod}}$  is 15.4 times. This result may be unrealistic and introducing senescence might ameliorate it.

We note that acoustic tagging results from shark nursery grounds can show lower natural mortality rates than those estimated here (Knip *et al.* 2012), but those findings are applicable only for the first few weeks of life. Once pups move out of nursery areas they are no longer tracked acoustically and their natural mortality rates may be higher.

## 2.4 Data used in the assessment

The following parameter estimates from the demographic analysis (Table 14) were used in the age-structured population model (chapters 5 and 6):

- Estimates of natural mortality rates  $M_{\text{adult}}$  and  $M_{\text{prod}}$ : populations are assumed to be fished, so that  $M_{\text{juv}}$  is not required.
- Values of  $r_{\text{lim}}$  and  $r$  for equation (2.3).

These parameters were fixed in the model. If desired in future, alternative parameter values could be tested by re-running the model with different inputs.

### 3. Estimation of historical commercial harvests

#### 3.1 The Taiwanese fishery, 1974–1990

As discussed in the Introduction (section 1.4.1), a Taiwanese gillnet and fish-trawl fishery operated off Northern Australia from 1974 to 1990. There is disagreement in the literature about the magnitude of this fishery. In addition, if the historical shark catch was very large it would also imply large sustainable yield. Therefore it is important to clarify how large the fishery was, and make best estimates of the size of the shark catch.

Davenport and Stevens (1988, first paragraph of Introduction) state that sharks made up 78% of the catch of the Taiwanese fishery, a statement taken from Walter (1981). Stevens and Wiley (1986) state that 83% of the shark catch by number came from two species, the Australian blacktip shark *Carcharhinus tilstoni* and the spot-tail shark *C. sorrah*.

Published harvest sizes taken by this fishery are tabulated in Table 15. After the declaration of the Australian Fishing Zone (AFZ) on 1 November 1979, the Taiwanese fishery was restricted to the far northern part of the Gulf, but even this area received hardly any fishing effort from that time onwards (Harwood *et al.* 1984).

Effort from the Taiwanese gillnet fishery in Queensland waters was considered negligible from November 1979 onwards.

A map of the area fished by Taiwanese fishers up to 1979 is provided by Fig. 1 of Harwood *et al.* (1984). This figure indicates that the Taiwanese gillnet fishing grounds were situated mainly close to shore, with roughly 40% of the area on the Queensland (eastern) side of the Gulf of Carpentaria. If this figure were taken literally, it would imply that the catch in Queensland waters could have amounted to thousands of tonnes per year. Such a high level is not supported by available catch data, as described below.

Quantitative records of the Taiwanese harvest were available from a logbook database kept by the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES); these were used in a recent study of tropical red snappers in Northern Australia (O'Neill *et al.* 2011). These records are summarised in Table 16. They are of similar magnitude to Table 15 in the total harvest size of all species, although the logbook harvest appears to have been under-reported in most years.

The logbook data are incompatible with the statement by Walter (1981) that sharks made up 78% of the catch. In fact, in the logbook data about 80% of the catch was made up of bony fish.

We note that the values that could be reasonably inferred from Tables 15 and 16 are much smaller than the harvest sizes used in the 2013 Northern Territory (NT) stock assessment of sharks (Grubert *et al.* 2013, p. 25), in which, in some year, the harvest of black tip sharks exceeds 3500 t and that of spot-tail sharks exceeds 1500 t. The NT assessment must have assumed a larger proportion of sharks in the harvest than is implied by the logbook data.

The logbook catch of sharks taken on the Queensland (eastern) side of the Gulf of Carpentaria is tabulated in Table 17. From this we have made best estimates of the total Queensland Gulf harvest by scaling up the logbook harvest to match the unofficial processed weight of all species in from Table 15, in years in which the total logbook harvest was less than the published unofficial harvest quoted by Harwood *et al.* (1984). We also converted from processed weight to whole weight of sharks using the factor of 10:7 from Stevens and Wiley (1986).

The final Taiwanese harvest size estimates are listed in Table 18. The maximum estimated harvest of sharks from the Gulf is 812 t in 1977, and the second highest is 331 t in 1978. Any estimates of tens of thousands of tonnes of sharks caught in the Gulf, which may be indicated by previously published studies, are not supported by available data.



Table 15: Harvest sizes of the Taiwanese fishery in northern Australia, all shark and fish species combined and all regions combined. Subscript “a” denotes Jan to October 1979, and “b” November to December 1979. The sources say that the data up to October 1979 are very unreliable, and we have judged that the higher, unofficial figures are more accurate. Sources: Harwood et al. (1984) quoting earlier sources by D. G. Walter and P. J. Millington; Davenport and Stevens (1988) for the estimate that 78% of the catch comprises sharks; Stevens and Wiley (1986) for the scale factor of 10:7 to convert processed weight to whole weight.

Year	Processed weight (t)		Whole weight of sharks (t)	
	Official	Unofficial	Official	Unofficial
1974	618	618	689	689
1975	17303	17303	19280	19280
1976	12414	12414	13833	13833
1977	19174	26847	21365	29915
1978	20475	30523	22815	34011
1979 <sup>a</sup>	16490	16490	18375	18375
1979 <sup>b</sup>	716	716	798	798
1980	5611	5611	6252	6252
1981	7080	7080	7889	7889
1982	6904	6904	7693	7693

Table 16: Harvest sizes of the Taiwanese fishery in northern Australia, from Taiwanese fishers’ logbook data, prior to the declaration of the Australian Fishing Zone on 1 November 1979. Data are harvest weights in tonnes, presumed to be processed weight as in the left-hand side of Table 15. Nearly all of the recorded catch was taken by fish trawling. Source: Database retained by the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES).

Year	Sharks	Rays	Bony fish	Cephalopods	Crustacea	Total
1974	1412	168	12565	1274	588	16007
1975	285	76	6439	1331	59	8189
1976	382	146	6629	1081	75	8314
1977	552	138	11044	1263	66	13063
1978	1029	287	20894	3148	137	25497
1979	158	19	3007	216	7	3360

Table 17: Logbook harvest sizes of sharks in the Taiwanese fishery in Queensland Gulf of Carpentaria waters, prior to the declaration of the Australian Fishing Zone on 1 November 1979. Data are harvest weights in tonnes, presumed to be processed weight as in the left-hand side of Table 15. All of the recorded catch was taken by fish trawling. Source: Database retained by the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES).

Year	Karumba	Pompuraaw	Aurukun	Weipa	Mapoon	Torres Strait	Total
1974	0	0	0	0	0	0	0
1975	4	2	13	19	3	29	70
1976	2	2	26	4	11	38	82
1977	40	15	12	88	39	82	276
1978	31	17	25	9	58	55	194
1979	0	0	0	0	0	1	1

Table 18: Best estimates of harvest sizes of sharks in the Taiwanese fishery in Queensland Gulf of Carpentaria waters, by LTMP Region as used in Table 8. Data are harvest weights in tonnes, converted to whole weight. Sources: Database retained by the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES); published unofficial catch sizes from Harwood et al. (1984) quoting earlier sources by D. G. Walter and P. J. Millington; Stevens and Wiley (1986) for the scale factor of 10:7 to convert processed weight to whole weight.

Year	Karumba	Pompuraaw	Aurukun	Weipa	Mapoon	Torres Strait	Total
1974	0	0	0	0	0	0.2	0.2
1975	11.0	7.5	40.7	57.0	7.8	86.7	210.5
1976	3.7	3.4	55.5	7.6	23.8	81.4	175.4
1977	118.6	45.1	35.8	259.2	113.1	239.7	811.6
1978	52.3	28.6	42.5	14.9	99.2	93.9	331.4
1979	0	0	0	0	0	6.6	6.6

The result that the highest estimated Taiwanese catches do not exceed 1000t in any year is very important to the stock assessment in all regions of Queensland. Catches of tens of thousands of tonnes would have indicated very high carrying capacities of sharks on the continental shelf that surrounds Queensland, and would have demanded very high estimates of shark population sizes from the population dynamic model, along with corresponding higher estimates of sustainable yields. It is possible that carrying capacities are higher in deep, nutrient-rich water (e.g., the Arafura and Timor Seas) than on the continental shelf.

Most of the catch assigned to the Torres Strait LTMP Region was actually taken from the Arafura Sea. The Torres Strait Subregion was omitted from the stock assessment, due to small catches of sharks there since the inception of the logbook system (see Table 8 above).

### 3.2 The Australian fishery prior to 1988

There were conflicting indications about the size of the Australian fishery in Queensland prior to 1988 (see section 1.4.2). On the one hand, harvests on the east coast did not trend strongly upwards in the early years of the Queensland logbook database in the late 1980s and early 1990s, which indicated that they had been sustained for some years prior to that. Also the Queensland Fish Board data up until 1980–81 may have been underreported. On the other hand, net technology changed in the 1970s, allowing fishers to more efficiently target sharks. Hence catches prior to the mid-1970s were probably much lower than in the late 1980s.

We adopted a compromise and assumed that the Australian fishery began from zero in 1973 and increased linearly until the beginning of the logbook database in 1988. This assumption made the catch bigger than reported by the QFB, but zero before the advent of the new nets. For the purpose of the linear increase, to smooth out variation we took the 1988 catch to be the average of the 1988 and 1989 catches on the east coast. In the Gulf of Carpentaria no shark catches were recorded in 1988, and we used the 1989 catch. We also set the 1988 catch to the 1989 catch. We expect this assumption to have little effect on the results of the assessment, as the peak harvest size did not occur until the early 2000s (see below).

### 3.3 Harvest estimates input to the population dynamic model

The final harvest estimates by Subregion which were input to the population dynamic model (chapters 5 and 6) are plotted in Figure 14. They incorporate the data, estimates and assumptions discussed in this chapter and previously in section 1.4.

Harvest sizes are for all shark species combined, as species identification by fishers was not considered reliable enough to be used for assessment purposes.

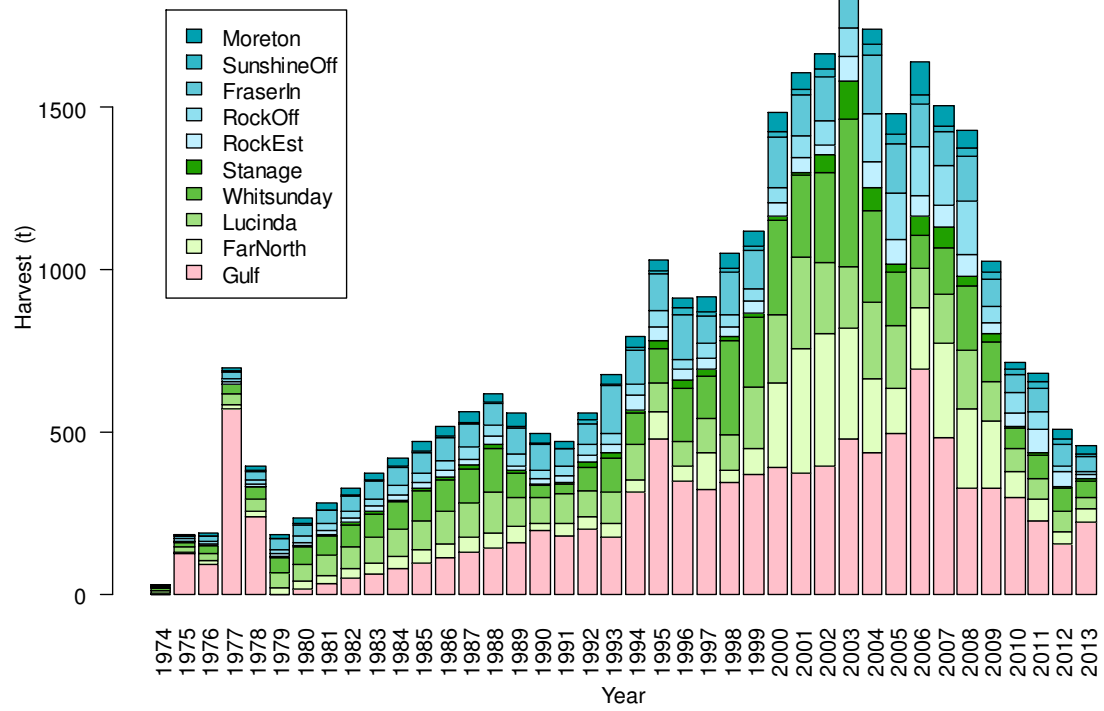


Figure 14: Final harvest estimates by Subregion that were input to the population dynamic model. Subregion names are listed in Table 8, page 25.

## 4. Commercial catch-rate analysis

### 4.1 Aims

Catch-rates are very important to fishery stock assessment. They provide a time series of relative abundance estimates.

It is desirable to calculate catch rates from the beginning of the fishery, so that the early years of the series represent abundance at close to virgin stock levels. In many fisheries, however, this is not possible, and the catch-rate series begins at a time when the harvest has already been commercially important for some years.

For the Queensland shark fishery, catch rates could be calculated from the beginning of the commercial logbook system in 1988. Data from the first few years of this system are not considered reliable, as it took a while for fishers to become accustomed to filling in daily logbook entries.

It can be seen from Figure 14 above that, although the logbook system began well after the start of the fishery, it fortunately covers the period of rapid expansion of the fishery from about 1990 to 2003. Therefore if the fishing during this period dramatically reduced the shark population, this should be apparent in the annual catch-rate time series.

In order for catch rates to accurately reflect abundance, it is highly desirable to standardise them to account for different fishing efficiencies of fishers and effects of location and time of year. Among other things, it is to be expected that for economic reasons inefficient fishers will tend to leave the fishery over time, while efficient fishers remain in it. Also this is a multi-species fishery, and the behaviour of fishers will probably vary with time of year, according to which species are seasonally abundant.

The methods used to do the standardisation are described below.

### 4.2 Methods

#### 4.2.1 Data limitations

Fishery data from which catch rates could be calculated were available from the beginning of the commercial logbook system in 1988. The logbook data were subject to many problems, including the following:

- Species identification by fishers was not reliable and could not be used.
- Sharks that were caught but discarded were not recorded.
- The precise nature of fishing locations was not recorded, e.g., distance from shore or depth of water.
- Net depth is usually not recorded and indeed most Queensland commercial logbooks have no space in which it could be recorded.
- Net length is sometimes recorded as the maximum net length that the fisher is licensed to use, instead of the length actually used (Dr Andrew Tobin, Project Team member, personal communication, 2015).
- Catch rates of sharks from neighbouring localities can show very different trends over time. Fishery observers also found that the species composition of the shark catch varied on quite a small spatial scale.

Problems with discards and precise fishing locations were evident in the following features of the data:

- Many fishing days were recorded with zero catches of sharks but nonzero catches of grey mackerel in the early years of the logbook system, especially 1988–1990. Zero reports of sharks were taken to be due to either discarding or non-reporting and were

not regarded as genuine zero catches, as there was no reason why the proportion of zero catches should be high in these years but not others.

- High incidences of zero catches of sharks were also notable in some year–Subregion combinations after 1990. Again we did not believe that these were genuine zero catches.
- Shorter nets often had higher catch rates of sharks than longer nets. We believed that this was due to the locations fished. It may not have been possible to set long nets at some desirable locations. Alternatively, it may simply be quicker and easier to transport a short net to a new location if nothing is being caught in the original fishing location; a long net will more often have to remain set in the same location even if it is not catching anything. Again we note in caution that net fishers may report the maximum net length that they are licensed to use, not the net length they actually use.
- Fishery observers found that the discard rate of bull sharks was higher than that of pignose sharks which had very similar biology (see section 1.4.5). We assumed that this was due to bull sharks' preference for inshore estuarine habitat, where fishers were more likely to target bony fish and hence more likely to discard sharks.

We investigated the effect of the “S” licence symbol on apparent shark discard rates. The S symbol was introduced in the 2009 fishery restructure and was needed for fishers to retain more than ten individual sharks in a catch.

Catch rates were defined using the finest feasible regional breakdown. As discussed in section 1.3 above, we based the stock assessment on the 22 Long Term Monitoring Program regions (LTMP Regions) that covered the shark fishery, but some LTMP Regions had to be merged due to lack of data to form the Subregions used for assessment (see Table 8).

We calculated catch rates using data from only the gillnetting method. The net fishery was the only sector for which the logbook data provided useful time series in each Subregion, and gillnetting was by far the most widely used method in this fishery.

We discarded catch rates for the years 1988–1990 in all Subregions, as it was clear that reporting of catches of sharks was inconsistent in those years. Some other Subregion–year combinations were also excluded due to apparent high discard rates of sharks (see below).

#### *4.2.2 Pre-processing of logbook data to produce fisher–day records*

The catch-rate analysis required daily catch records with no duplicate fisher–day combinations. The logbook database, on the other hand, contained multiple records when a fisher caught more than one species or fished in more than one location.

A large amount of pre-processing had to be done to collate catches down to one per fisher–day. The catch of each species was summed over multiple records and stored in a separate column in the new database. The assigned location for each collated record was the location with the maximum catch weight taken by that fisher on that day.

An input record for catch-rate analysis consisted of a daily catch by a single fishing operation, with the different species in separate columns. The nominal number of hours fished was not used, as it was not regarded as accurate.

Fishers were identified using the field “Authority Chain Number” in the logbook database maintained by Fisheries Queensland. The Fisheries Queensland data coordinators had recently corrected this field to allow for merging of licences in past years. Previously, multiple instances of the same Authority Chain Number could occur on the same day in locations hundreds of kilometres apart, and it was necessary to combine Authority Chain Number with the additional field “Boat Mark”.

Any catch record that was an aggregate over multiple fishing days, i.e., when the record's end date was greater than its beginning date, were omitted from catch-rate analysis, although they were included in the catch totals described in section 1.4 and chapter 3. Fishing trips of

duration greater than one day were still included in catch-rate analysis when each day's catch was recorded separately.

The software *R* (R Core Team 2015) was used for both data pre-processing and the catch-rate analysis presented below.

#### 4.2.3 Formulation of generalised linear models

Catch rates were standardised in each Subregion using a generalised linear model (GLM) (McCullagh and Nelder 1989) with Poisson error distribution. Whereas an ordinary linear model, given data  $y_j$ , would calculate the fitted daily catches  $\hat{\mu}_j$  by minimising the sum of squares

$$\sum_j (y_j - \hat{\mu}_j)^2,$$

the Poisson model instead minimises the *deviance*

$$2 \sum_j \{ \hat{\mu}_j - y_j + y_j \log(y_j / \hat{\mu}_j) \}.$$

The statistical software *R* (R Core Team 2015), which we used for the analysis, uses the term “quasi-Poisson” for this model in order to emphasise that it is more abstract: catches are not counts of units of one kilogram. The prefix “quasi” emphasises that the data are not treated as integers, as they would be under a strict Poisson model. The data in the application here are daily catches, measured in kilograms, and are mostly not integers. We have, however, followed the majority of sources, e.g., McCullagh and Nelder (1989), in calling this model simply a “Poisson model”.

In the strict Poisson model the data are counts of independent events (e.g., individual fish that don't school), which follow a Poisson distribution with probability function

$$p(y) = e^{-\mu} \mu^y / y!$$

for  $y = 0, 1, 2, \dots$ . In this case the dispersion parameter is assigned the value 1. The Poisson model can then be extended to allow for “over-dispersion”, in which the events are no longer independent but occur in clumps (e.g., schools of fish). Then the counts no longer follow a Poisson distribution. The dispersion parameter takes a value roughly equal to the average size of a clump (i.e., average number of fish in a school). Further theoretical allows non-integer data (e.g., weight measured in kg) that are not counts. In this case the concept of whether the data are ideally dispersed or over-dispersed has no meaning: the dispersion parameter has to be estimated and there is no special reason to assign it the value 1.

The major advantage of the Poisson model for catch rates is that it automatically weights the data correctly. For example, if one fisherman fishes for seven days, the standard deviation of his catch will be  $\sqrt{7}$  times that of another fisher who fishes for only one day, if all other things are equal. The Poisson model will produce much the same results whether the time unit over which catches are taken is a day, a week or a month. The same logic applies if for some unrecorded reason one fisher is seven times more efficient than another, due to superior skill or equipment. The Poisson model estimates an efficiency parameter for each fisher, and automatically downweights the fishers with lower efficiency.

The property of automatic correct weighting of fishers is not possessed by other models such as the ordinary linear model, loglinear model and gamma model. In the ordinary linear model all observations have the same standard deviation, and so the ratio of standard deviations in the above example would be 1 instead of  $\sqrt{7}$ . The ordinary linear model overweights fishers who take large catches, giving them undue influence on the results.

In both the loglinear and gamma models, the standard deviation of an observation is proportional to its mean; then in the above example the ratio of standard deviations would be 7 instead of  $\sqrt{7}$ . These models underweight fishers who take large catches, and allow undue influence from small fishers who in total contribute very little of the overall catch. In the loglinear and gamma models, the practitioner commonly has to subjectively decide on a catch threshold to exclude small-scale fishers: catches below this threshold are omitted from analysis. In the Poisson model this step is not necessary because small players are automatically down-weighted.

Standard errors of catch rates were calculated by re-running the GLM and including a year-month interaction for each Subregion. The year-month combinations became the experimental units between which standard errors were calculated. We regarded this as more accurate than using fisher-day combinations, due to potential extra variation that might result from, for example, year-to-year variation in seasonal movements of both sharks and the bony fish that might be targeted by fishers.

The explanatory variables that were used in the GLMs are listed in Table 19. They were all treated as factors (non-ordered categorical variables) with multiplicative effects on the catch rates. For example, as in the case above, if one fisher is seven times more efficient than another, this is true for the expected catch rates in all data records, irrespective of whether the expected catch is low or high in that year and month. Similarly, if the catch rate for one net length, year or month is greater than another by a certain ratio, this ratio will be the same for all fishers and not depend on whether the fisher is efficient or inefficient.

Levels of net length that were used in the GLMs were 200, 300, 400, 600, 800 and 1200 m. Net lengths were rounded (usually upwards) to the nearest of these levels, but lengths substantially less than 200 m or greater than 1200 m were excluded due to small numbers of records in these categories. As mentioned above, longer nets did not always catch more sharks, so we decided to make net length a factor instead of a continuous variable.

Only nonzero catches of sharks were analysed, as we believed that zero catches (in which fishers caught grey mackerel but not sharks) were more often cases in which sharks were discarded than genuine zero catches.

*Table 19: Explanatory variables included in the generalised linear model for catch rates. The response variable was the daily catch of sharks by a particular fisher. A separate analysis was run for each Subregion. The “factor” variable type is a non-ordered categorical variable, as opposed to a continuous variable with a well-defined numeric value.*

<b>Variable</b>	<b>Type</b>	<b>Meaning</b>
Boat	Factor	Fisher identifier
Net	Factor	Length of net
Year	Factor	Calendar year
Month	Factor	Calendar month

## 4.3 Results and discussion

### 4.3.1 Apparent retention rates

The proportion of nonzero catches of sharks, i.e., records fishers didn’t catch grey mackerel alone but caught some shark, was taken as an indicator of the retention rate of sharks in a particular Subregion-year combination. We took the view that sharks were present wherever fishers fished, and their absence in reported harvests was more an indicator of discarding or non-reporting than of genuine absence of sharks in the catch. The use of grey mackerel as the

major alternatively target species for net fishers stemmed from preconceptions at the start of the assessment process, which affected the logbook data requests. We recommend that future assessments should use all records of Queensland's East Coast Inshore Fin Fish Fishery and Gulf of Carpentaria Fin Fish Fishery, not only records in which either shark or grey mackerel were reported.

We found no correlation between discard rate and presence of an S symbol. Some S symbol holders had large discard rates of sharks after 2009, even though they had no strong impediment to retention of sharks. We concluded that discards were probably related to market demand rather than whether the fisher held an S symbol. The apparent retention rates by S-licensed fishers are graphed in Figure 15, which can be compared to Figure 16 which includes all fishers.

The apparent retention rates are plotted in Figure 16. On the basis of these results, catch rates from years 1988–1990 in all Subregions were excluded from input to the population dynamic model, as were other Subregion–year combinations with abnormally low apparent retention rates (see below).

The declining proportion of nonzero shark catches in the Gulf (first panel of Figure 16) is a cause for concern, and may indicate lack of targeting of sharks in the Gulf in response to lack of market demand. We left these catch rates in the model because there would otherwise have been no usable time series for the Gulf. We note that Gulf fishers tend to make longer fishing trips and have less opportunity to offload their catch at a close-by port than fishers on the east coast. Therefore it is reasonable that discard rates would be higher in the Gulf. We acknowledge that this is an additional source of error for catch rates in the Gulf.

#### *4.3.2 Annual catch rates*

Annual standardised catch rates are plotted for each Subregion in Figure 17. The units in these plots are arbitrary and have been scaled to an average of 1 in each case.

The plot for the Sunshine Coast Offshore Subregion shows a high catch rate in 2010. Evidence from fishers and scientists indicates that this was due to high recruitment of spinner sharks in that year.

These annual catch rates were used as abundance indicators in the population dynamic model (chapters 5 and 6). Points boxed in red or yellow in Figure 17 were excluded due to perceived high discard rates of sharks in that year and Subregion.

The standardised catch rates show no discernible trend in the Gulf, Far North and Lucinda Subregions. In view of the decline in the proportion of nonzero catches in the Gulf (Figure 16), which we assume to be an indicator of fishers' wish to target bony fish in preference to sharks, it is possible that shark catch rates in the Gulf would trend upwards if targeting behaviour had not changed.

Catch rates in the Whitsunday and Stanage Subregions trend downwards, but those in the Rockhampton Subregions trend upwards. We are unable to explain these trends, and regard it as very unlikely that populations in two adjacent Subregions could be falling while those in two adjacent neighbouring Subregions could be rising.



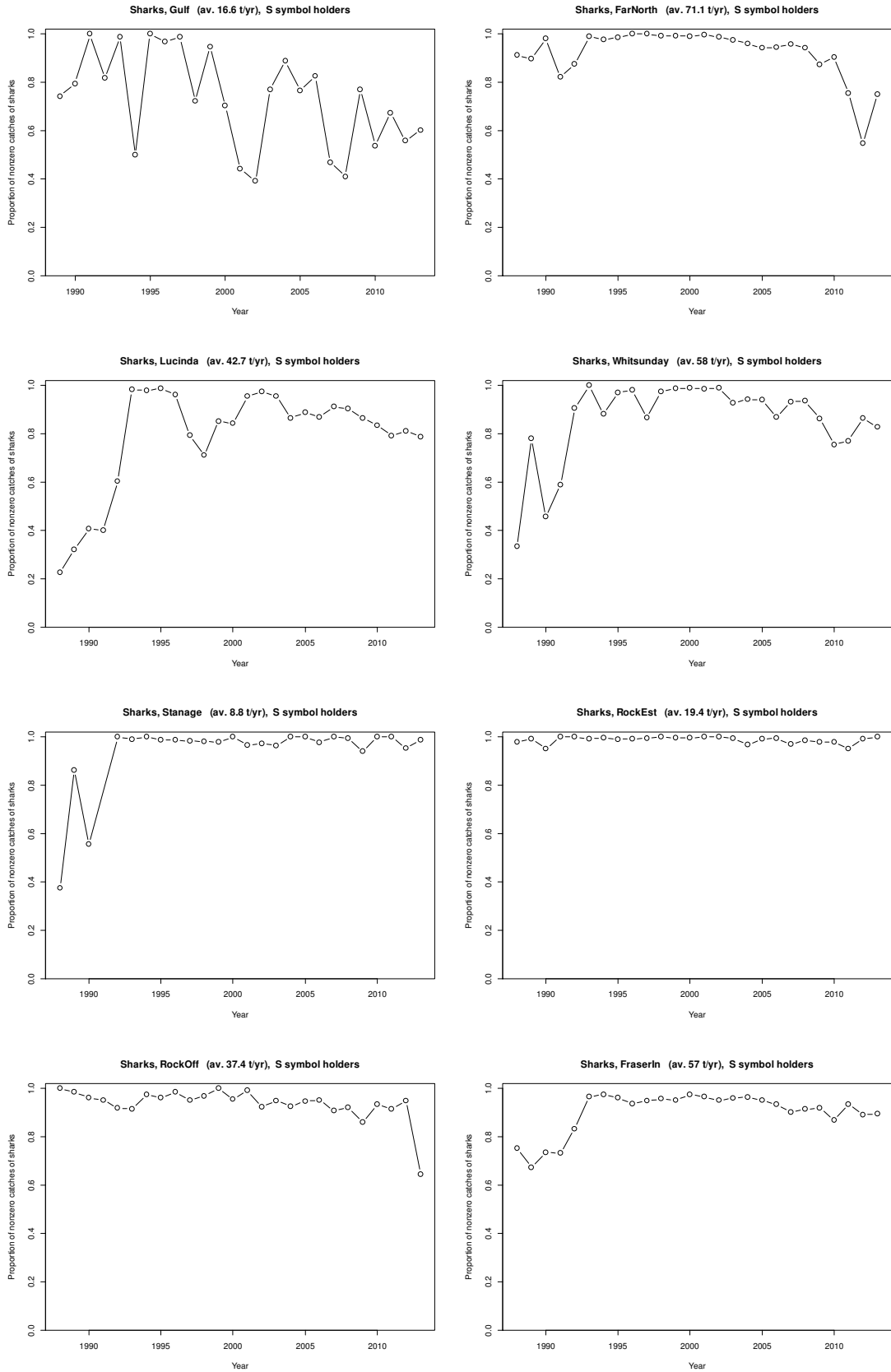


Figure 15: Proportion of nonzero catches of sharks by year in each Subregion, by S-licensed fishers only, which can be compared to the corresponding proportions by all fishers including non-S-licensed fishers in Figure 16 (continued overleaf).

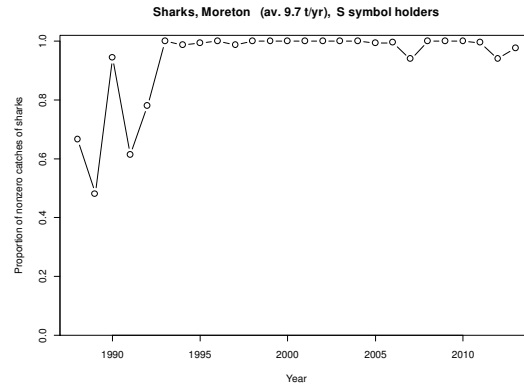
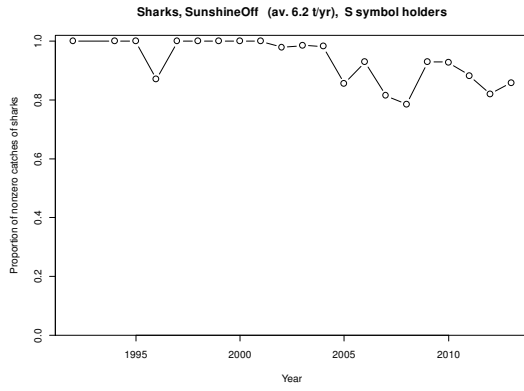


Figure 15, continued from previous page.

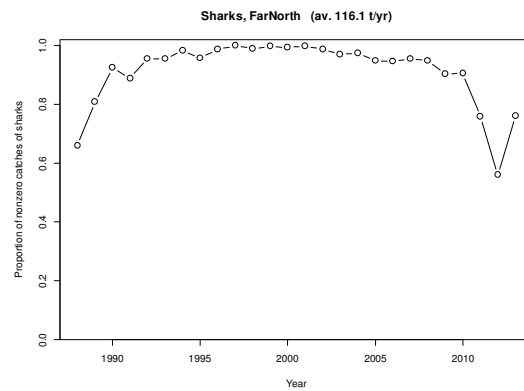


Figure 16: Proportion of nonzero catches of sharks by year in each Subregion, which we assumed to be an indicator of the retention rate (continued overleaf).

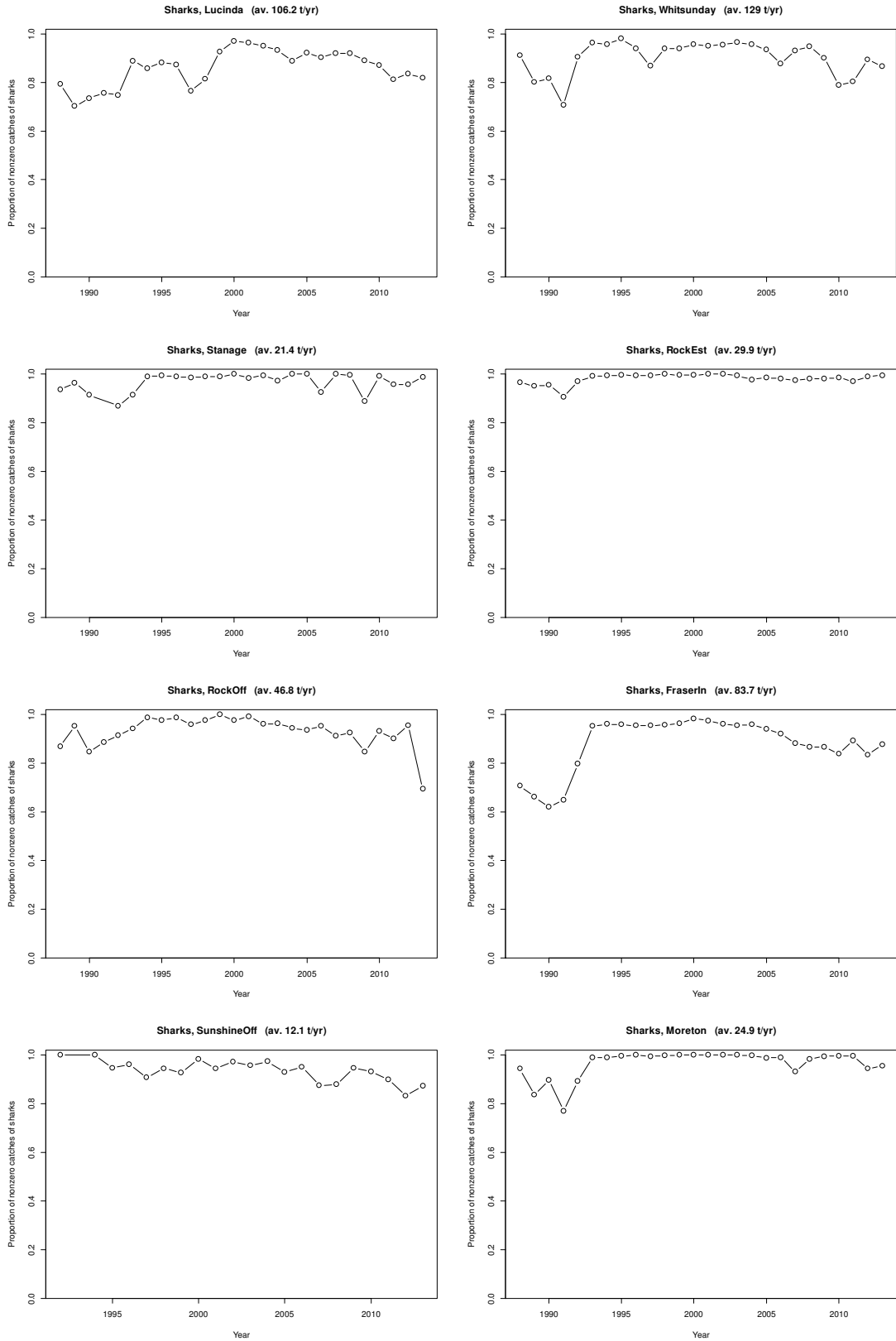
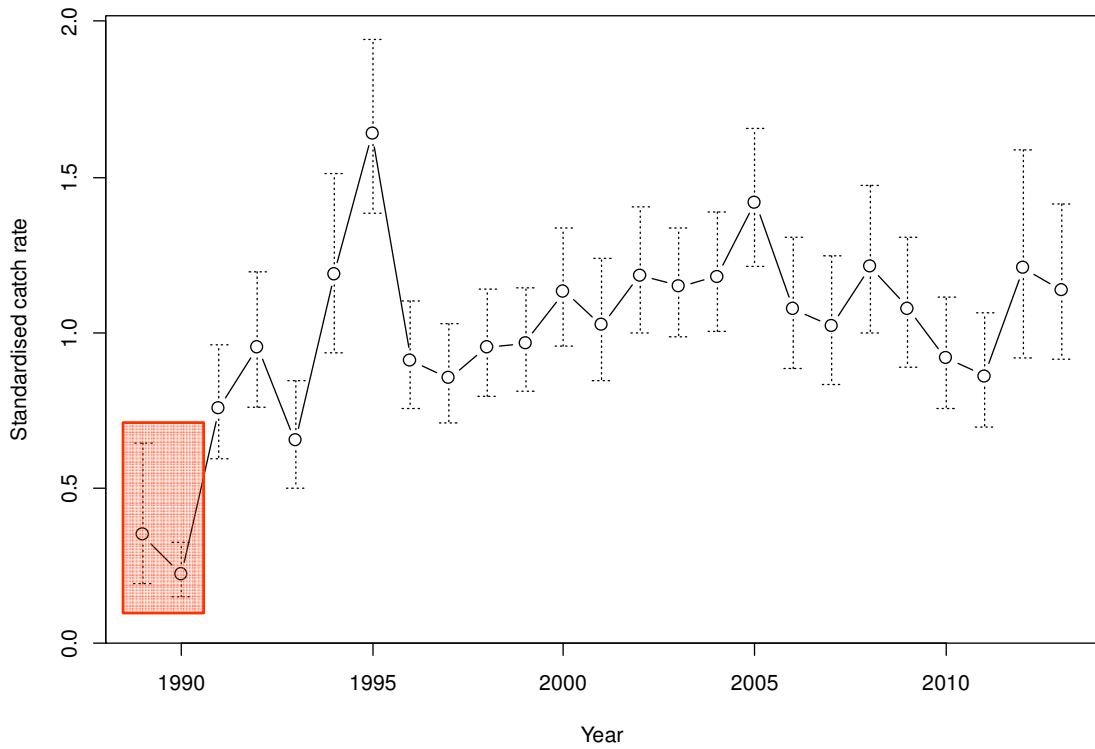


Figure 16, continued from previous page.

**Sharks, Gulf (av. 255.1 t/yr)**



**Sharks, FarNorth (av. 116.1 t/yr)**

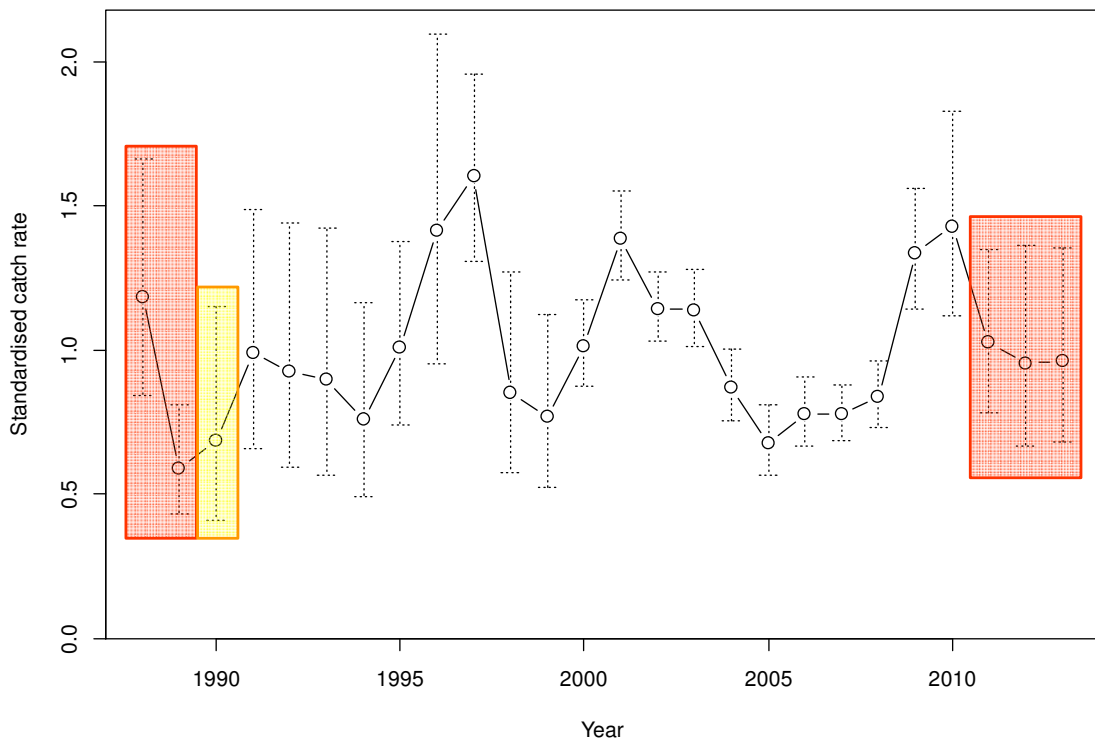
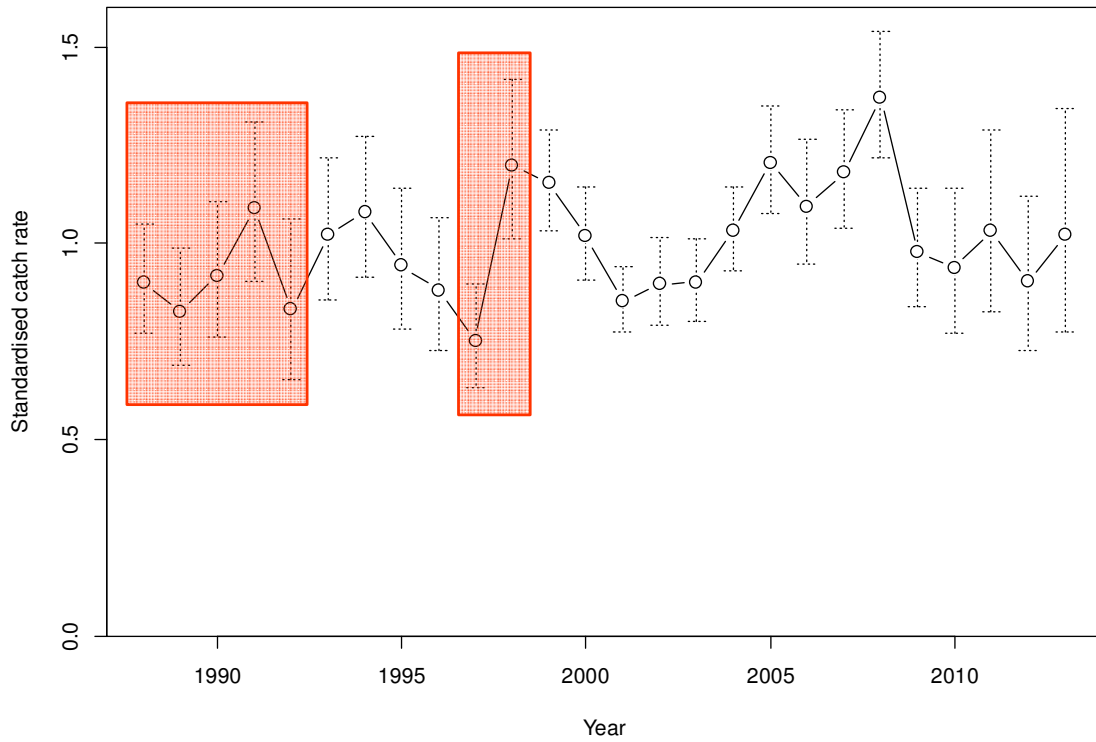


Figure 17: Standardised catch rates of sharks, used as input to the population model. Points boxed in red or yellow were excluded from input to the model due to apparent high rates of discarding of sharks: red for specific Subregion–year combinations, and yellow due to high rates in most Subregions in the years 1988–1990. Intervals shown are approximate 95% confidence limits (1.96 standard errors) on the log scale. (Continued on next four pages)

**Sharks, Lucinda (av. 106.1 t/yr)**



**Sharks, Whitsunday (av. 128.6 t/yr)**

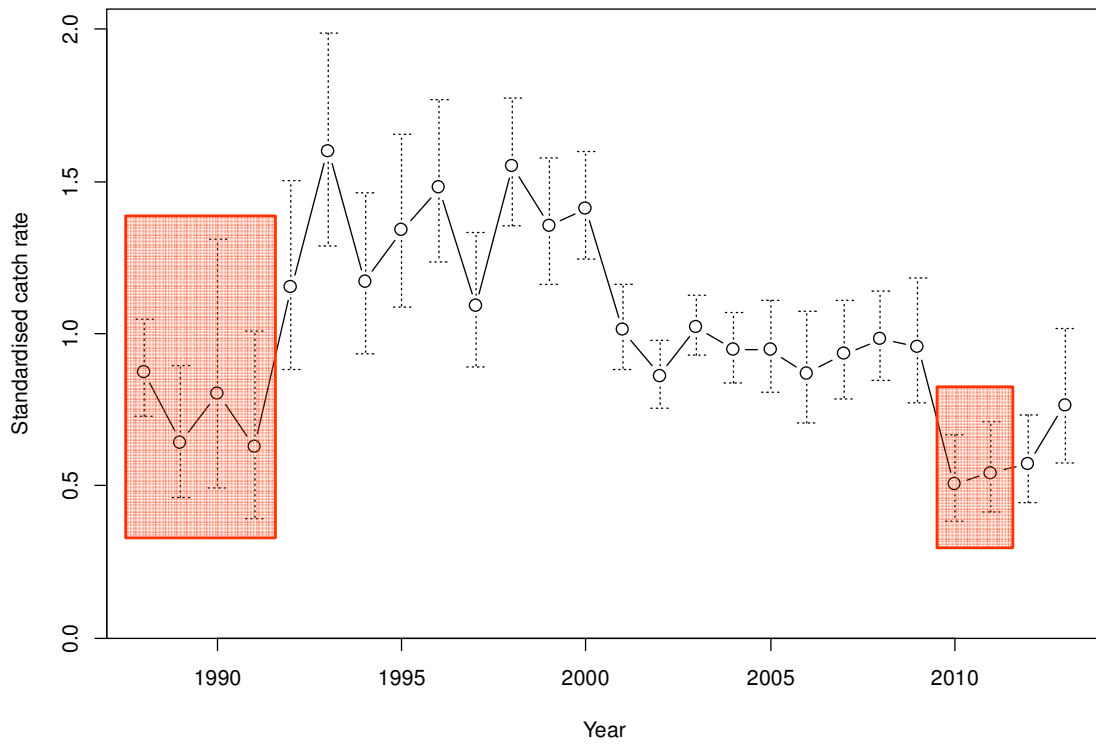
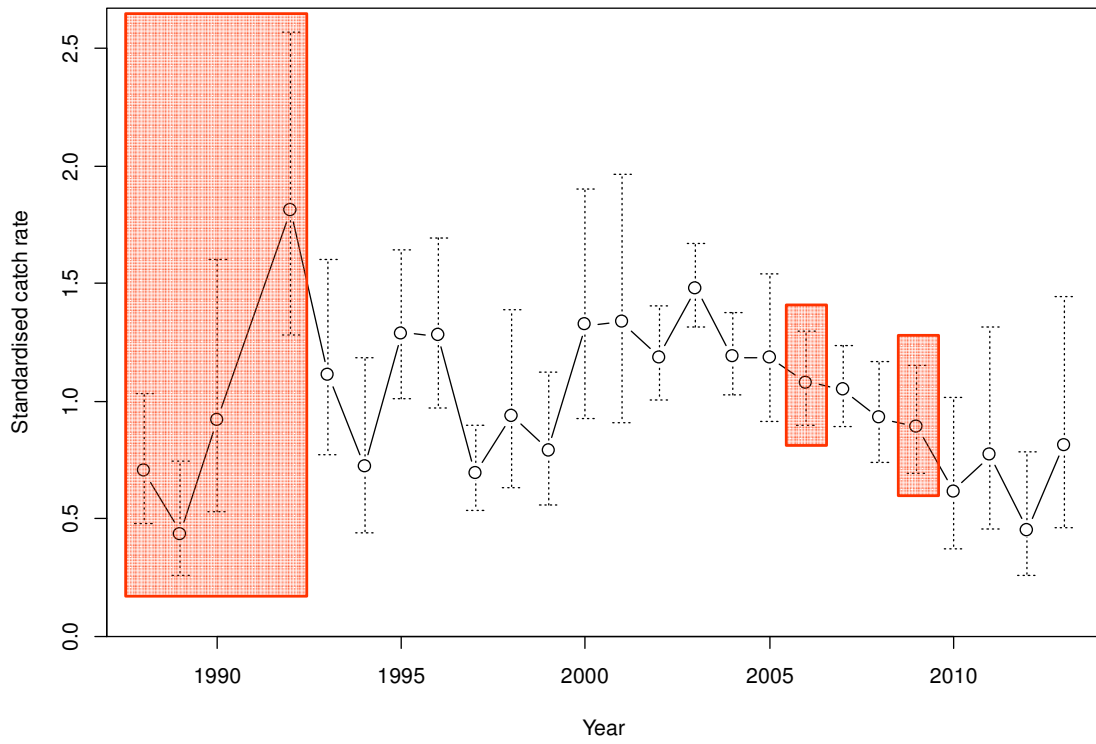


Figure 17, continued from previous page and on next three pages.

**Sharks, Stange (av. 21.4 t/yr)**



**Sharks, RockEst (av. 29.9 t/yr)**

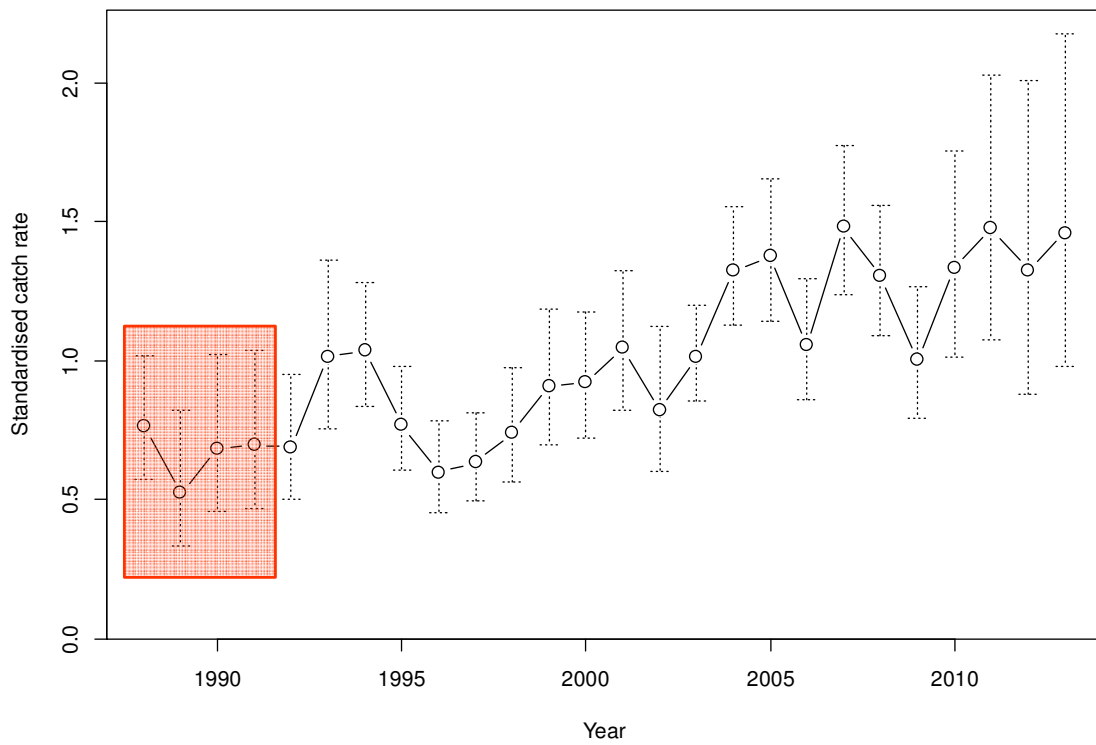
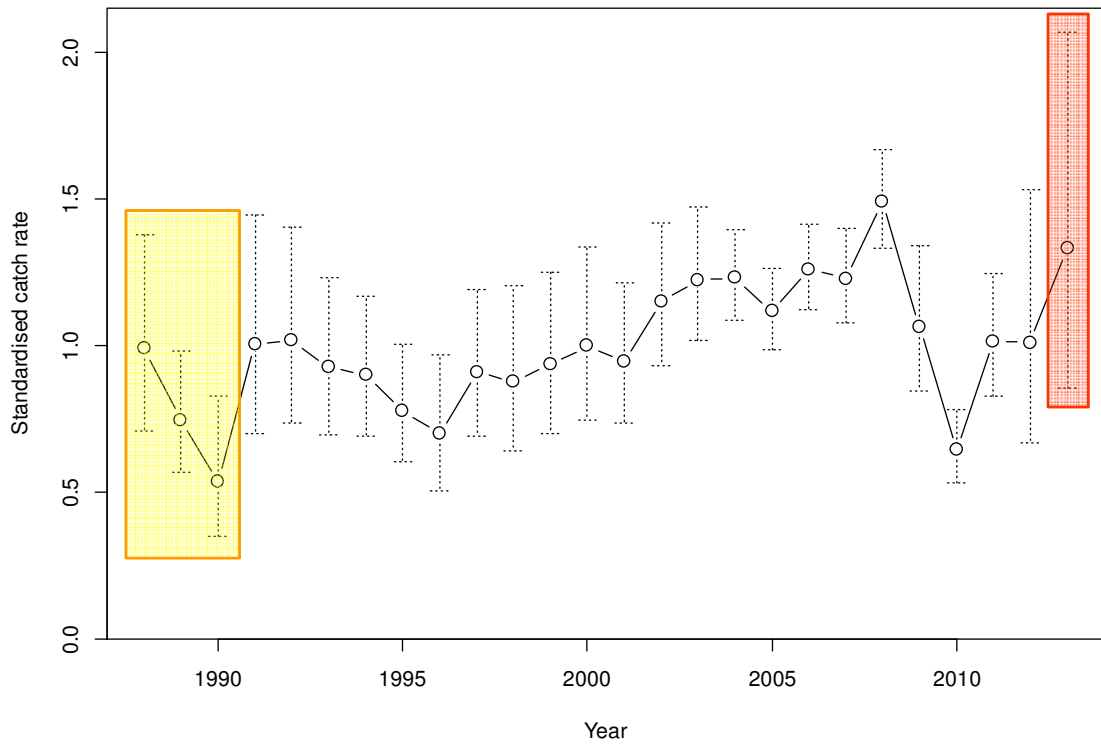


Figure 17, continued from previous two pages and on next two pages.

**Sharks, RockOff (av. 46.8 t/yr)**



**Sharks, FraserIn (av. 83.7 t/yr)**

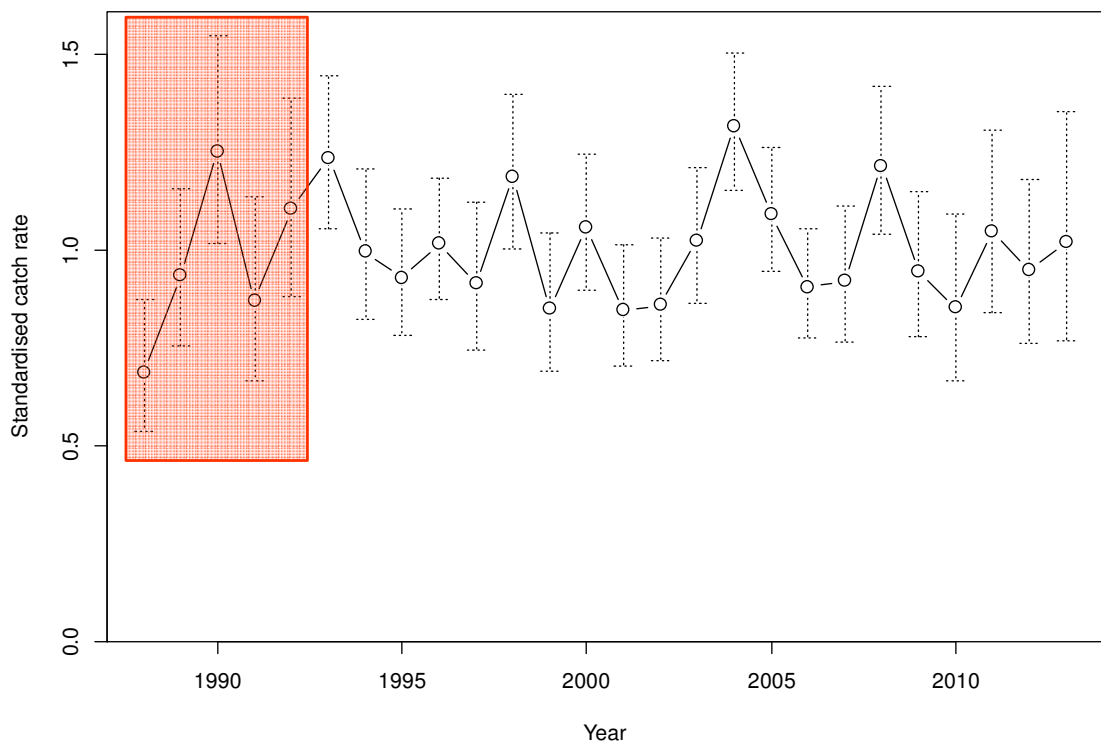
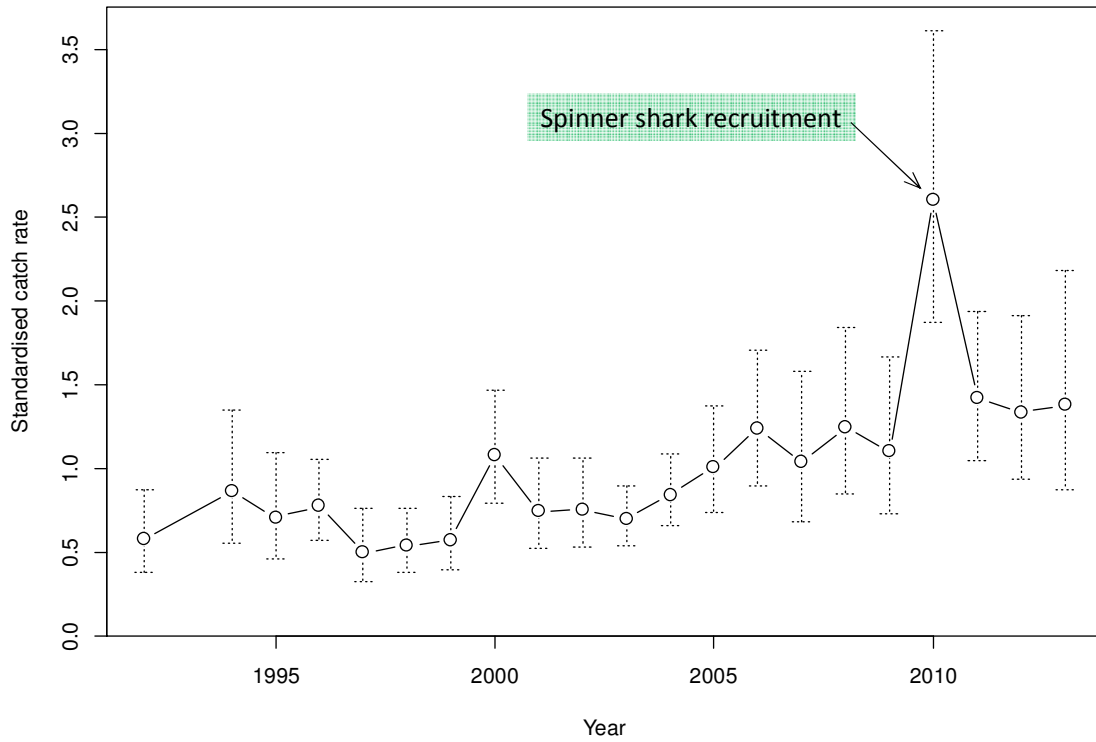


Figure 17, continued from previous three pages and on next page.

**Sharks, SunshineOff (av. 12.1 t/yr)**



**Sharks, Moreton (av. 24.9 t/yr)**

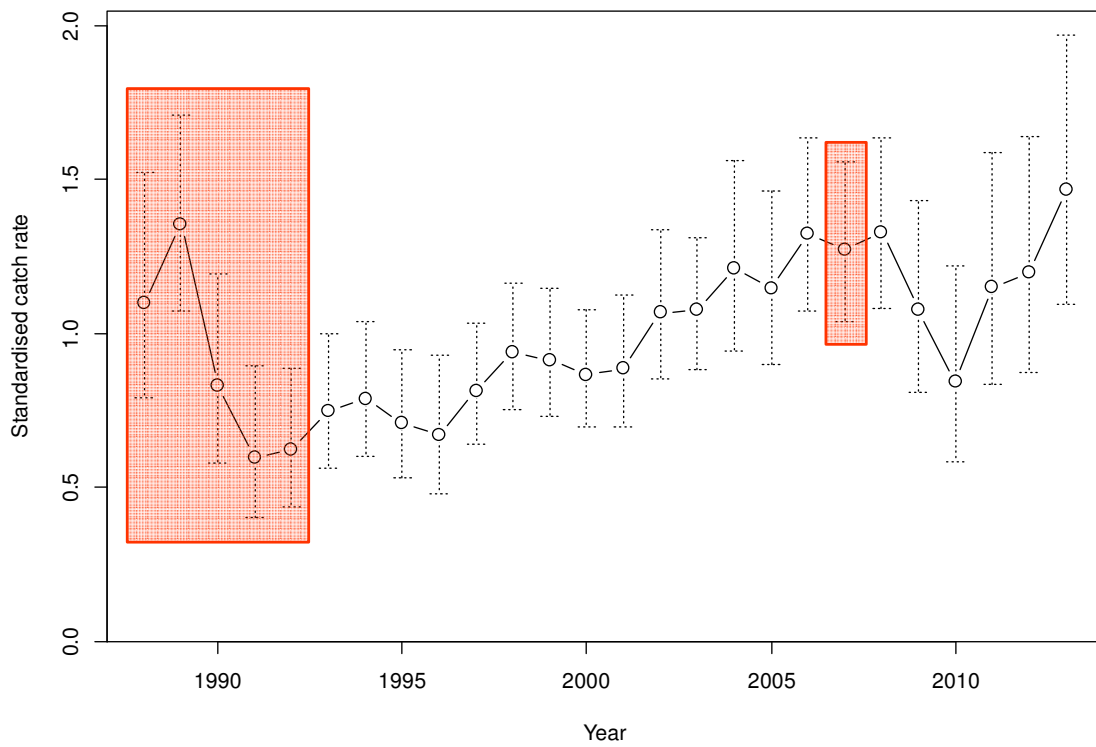


Figure 17, continued from previous four pages.



Catch rates in the Fraser Inshore Subregion have been steady for many years. This appears to be a productive Subregion for sharks and indeed for their bony fish prey which are often targeted by both commercial fishers and recreational anglers.

In the most southern Subregions, Sunshine Coast Offshore and Moreton, the standardised catch rates are rising. The reasons for this are unknown and may comprise several confounding environmental, social or economic factors, including the following. We acknowledge that these are highly speculative:

- Recreational fishing catches of sharks' prey species may have fallen to the extent that prey populations have rebounded with a flow-on effect to shark populations. Surveys show that recreational catches fell sharply between 2000 and 2011 (Henry and Lyle 2003; Taylor *et al.* 2012).
- Environmental standards around human population centres may have improved and resulted in increased abundances of both sharks and their prey.
- The Shark Control Program may have a substantial effect on shark populations throughout southern Queensland. Gradual replacement of nets by drum lines, together with various other measures to reduce bycatch, may have had a positive effect on shark populations.
- Conversely, the Shark Control Program may have had a big effect over many years on large sharks, thus allowing smaller sharks to thrive in the absence of large predators.

#### 4.4 Diagnostics

Analysis of deviance tables are presented in Table 20 for the GLM for each Subregion. In all Subregions, by far the most significant term is the fisher identifier. This probably reflects variation between fishers in both their targeting practices and their skill levels. The other terms vary in significance between Subregions. All the terms listed were left in the model, even if their *F*-statistics were on the low side. The *F*-statistics listed in the final column have been scaled by the deviance of the year-month interaction, not the model's residual deviance, which has reduced their magnitudes.

Scatter plots of residuals against fitted values from the GLMs are reproduced in Figure 18. The residuals used were deviance residuals, defined for an observation *y* and fitted value  $\mu$  as

$$r = \text{sgn}(y - \mu) \sqrt{2\{\mu - y + y \log(y/\mu)\}}.$$

They were standardised by dividing by the square-root of the residual mean deviance listed in Table 20.

The scatter plots show patterns typical of Poisson GLMs: the residuals are not meant to follow normal distributions. The curved envelopes at the bottom are usual and come about because the data are nonnegative. There are no strong relationships between the fitted values and the amounts of spread of the residuals in any of the plots, i.e., the residuals appear roughly homoscedastic, which establishes that the Poisson model has roughly the correct relationship between the mean and variance for these data (variance proportional to the mean).

Table 20: Analysis of deviance tables (generalised analysis of variance tables) for the Poisson GLMs used for catch-rate analysis. The quoted residual mean deviance, which was used to scale the mean deviances and produce F-statistics for each Subregion, came from the mean deviance of the year-month interaction, not from the model's residual mean deviance: this generally acted to reduce the F-statistics. All terms in the GLMs are factors (categorical variables), not continuous variables: Boat is the fisher identifier, fNet is net length, fYear is calendar year, fMonth is calendar month, and LookupRegion is the LTMP Region which was included when the Subregion consisted of more than one LTMP Region. The Null model includes none of these terms and assumes that mean catch rates are the same over all fishers, net lengths, years, months and regions.

<b>Gulf, residual mean deviance 768.086</b>						
Term	Df	Deviance	Resid. Df	Resid. Dev	Mean dev	F
NULL	-	-	2541	3975840.8	-	-
Boat	9	3534448.9	2532	441391.9	392716.5	511.292
fNet	4	21815.2	2528	419576.6	5453.8	7.100
fYear	24	75564.7	2504	344011.9	3148.5	4.099
fMonth	10	11720.7	2494	332291.1	1172.0	1.525
LookupRegion	4	3919.5	2490	328371.5	979.8	1.275
<b>FarNorth, residual mean deviance 804.336</b>						
Term	Df	Deviance	Resid. Df	Resid. Dev	Mean dev	F
NULL	-	-	9243	18898285	-	-
Boat	40	17237382.8	9203	1660902	430934.5	535.764
fNet	4	24977.5	9199	1635925	6244.3	7.763
fYear	25	130349.3	9174	1505576	5213.9	6.482
fMonth	11	23612.6	9163	1481963	2146.6	2.668
LookupRegion	3	60392.1	9160	1421571	20130.7	25.027
<b>Lucinda, residual mean deviance 354.710</b>						
Term	Df	Deviance	Resid. Df	Resid. Dev	Mean dev	F
NULL	-	-	8950	10140420.0	-	-
Boat	68	9239813.3	8882	900606.7	135879.6	383.072
fNet	4	38835.9	8878	861770.8	9708.9	27.371
fYear	25	33282.5	8853	828488.2	1331.3	3.753
fMonth	11	20594.7	8842	807893.4	1872.2	5.278
<b>Whitsunday, residual mean deviance 501.049</b>						
Term	Df	Deviance	Resid. Df	Resid. Dev	Mean dev	F
NULL	-	-	8558	14945852.1	-	-
Boat	65	13820658.3	8493	1125193.7	212625.5	424.360
fNet	5	25158.1	8488	1100035.5	5031.6	10.042
fYear	25	76577.4	8463	1023458.1	3063.0	6.113
fMonth	11	40963.4	8452	982494.7	3723.9	7.432
LookupRegion	1	1148.1	8451	981346.6	1148.1	2.291
<b>Stange, residual mean deviance 186.463</b>						
Term	Df	Deviance	Resid. Df	Resid. Dev	Mean dev	F
NULL	-	-	2739	1743693.9	-	-
Boat	53	1578772.4	2686	164921.4	29788.1	159.753
fNet	3	15184.8	2683	149736.6	5061.6	27.145
fYear	24	11476.4	2659	138260.2	478.1	2.564
fMonth	11	10768.2	2648	127491.9	978.9	5.250
<b>RockEst, residual mean deviance 215.377</b>						
Term	Df	Deviance	Resid. Df	Resid. Dev	Mean dev	F
NULL	-	-	6939	4016254.5	-	-
Boat	71	3579991.8	6868	436262.7	50422.4	234.111
fNet	3	10295.4	6865	425967.2	3431.8	15.933
fYear	25	25910.4	6840	400056.8	1036.4	4.812
fMonth	11	21320.9	6829	378735.8	1938.2	8.999
<b>RockOff, residual mean deviance 364.851</b>						
Term	Df	Deviance	Resid. Df	Resid. Dev	Mean dev	F
NULL	-	-	6937	8940769.0	-	-
Boat	70	8215748.1	6867	725020.8	117367.8	321.686
fNet	3	30460.6	6864	694560.2	10153.5	27.829
fYear	25	42600.9	6839	651959.3	1704.0	4.670
fMonth	11	43802.9	6828	608156.4	3982.0	10.914

<b>FraserIn, residual mean deviance 415.830</b>						
Term	Df	Deviance	Resid. Df	Resid. Dev	Mean dev	F
NULL	-	-	16046	12379295	-	-
Boat	62	10768540.8	15984	1610754	173686.1	417.684
fNet	3	17628.4	15981	1593126	5876.1	14.131
fYear	25	33587.8	15956	1559538	1343.5	3.230
fMonth	11	113502.2	15945	1446036	10318.3	24.813
<b>SunshineOff, residual mean deviance 146.117</b>						
Term	Df	Deviance	Resid. Df	Resid. Dev	Mean dev	F
NULL	-	-	1802	1018977.9	-	-
Boat	16	879677.6	1786	139300.3	54979.8	376.270
fNet	2	1260.6	1784	138039.6	630.3	4.313
fYear	20	11406.1	1764	126633.5	570.3	3.903
fMonth	11	7489.1	1753	119144.4	680.8	4.659
<b>Moreton, residual mean deviance 164.526</b>						
Term	Df	Deviance	Resid. Df	Resid. Dev	Mean dev	F
NULL	-	-	4822	1840921.4	-	-
Boat	37	1576859	4785	264062.1	42617.8	259.032
fNet	2	39	4783	264023.0	19.5	0.118
fYear	25	17088	4758	246935.0	683.5	4.154
fMonth	11	14194	4747	232740.2	1290.4	7.843
LookupRegion	1	4	4746	232736.4	3.8	0.023

Table 20, continued from previous page.

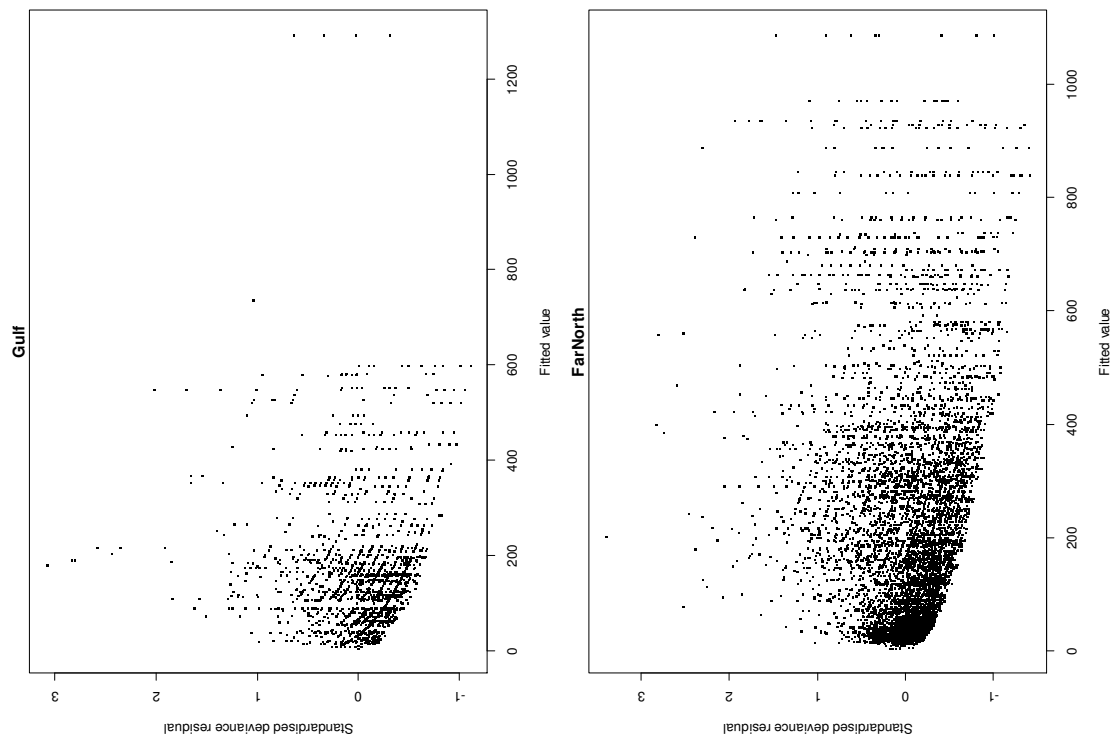


Figure 18: Plots of deviance residuals against fitted values for the Poisson GLMs used for catch-rate analysis. (Continued on next two pages)

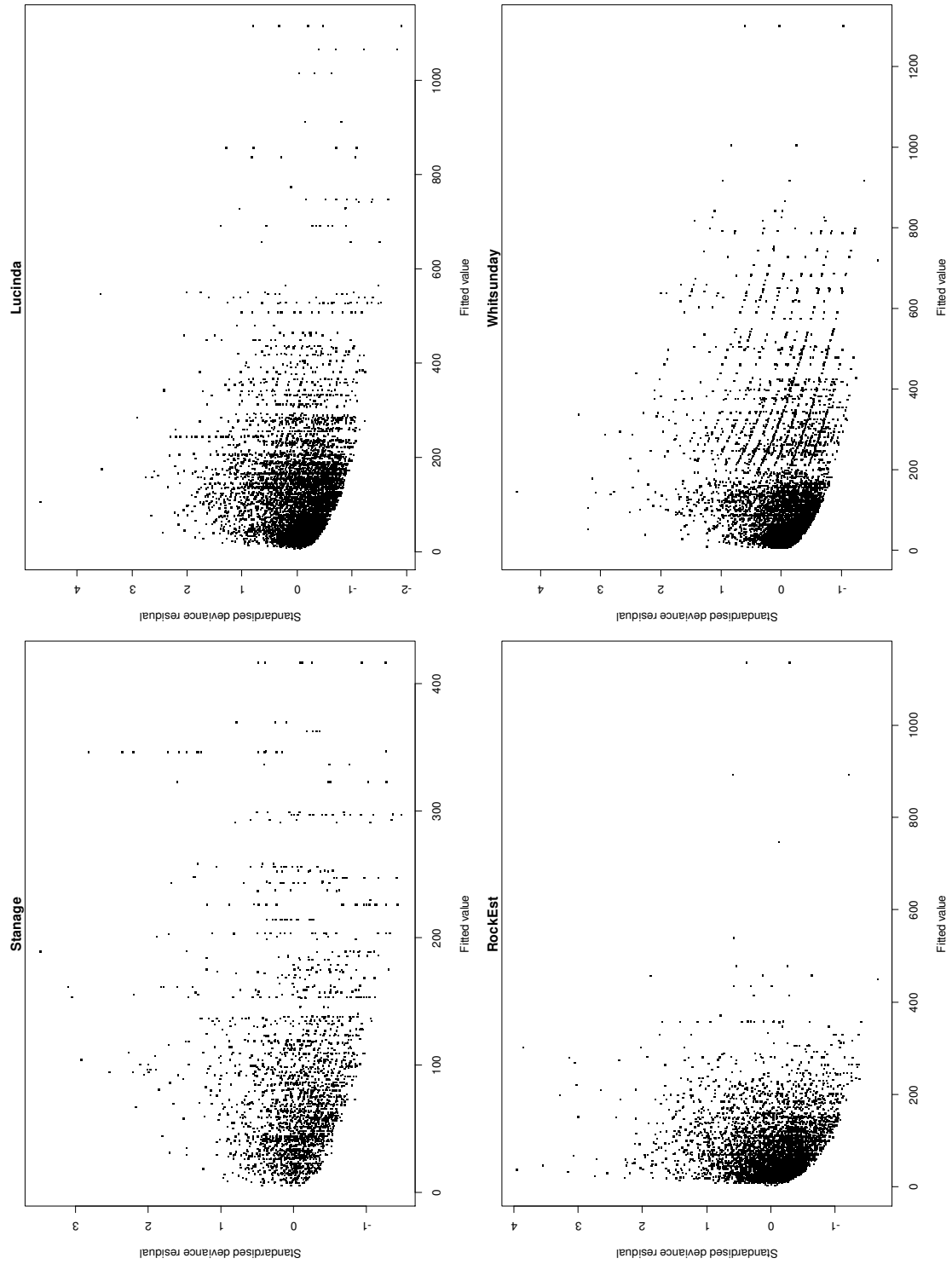


Figure 18, continued from previous page and on next page.

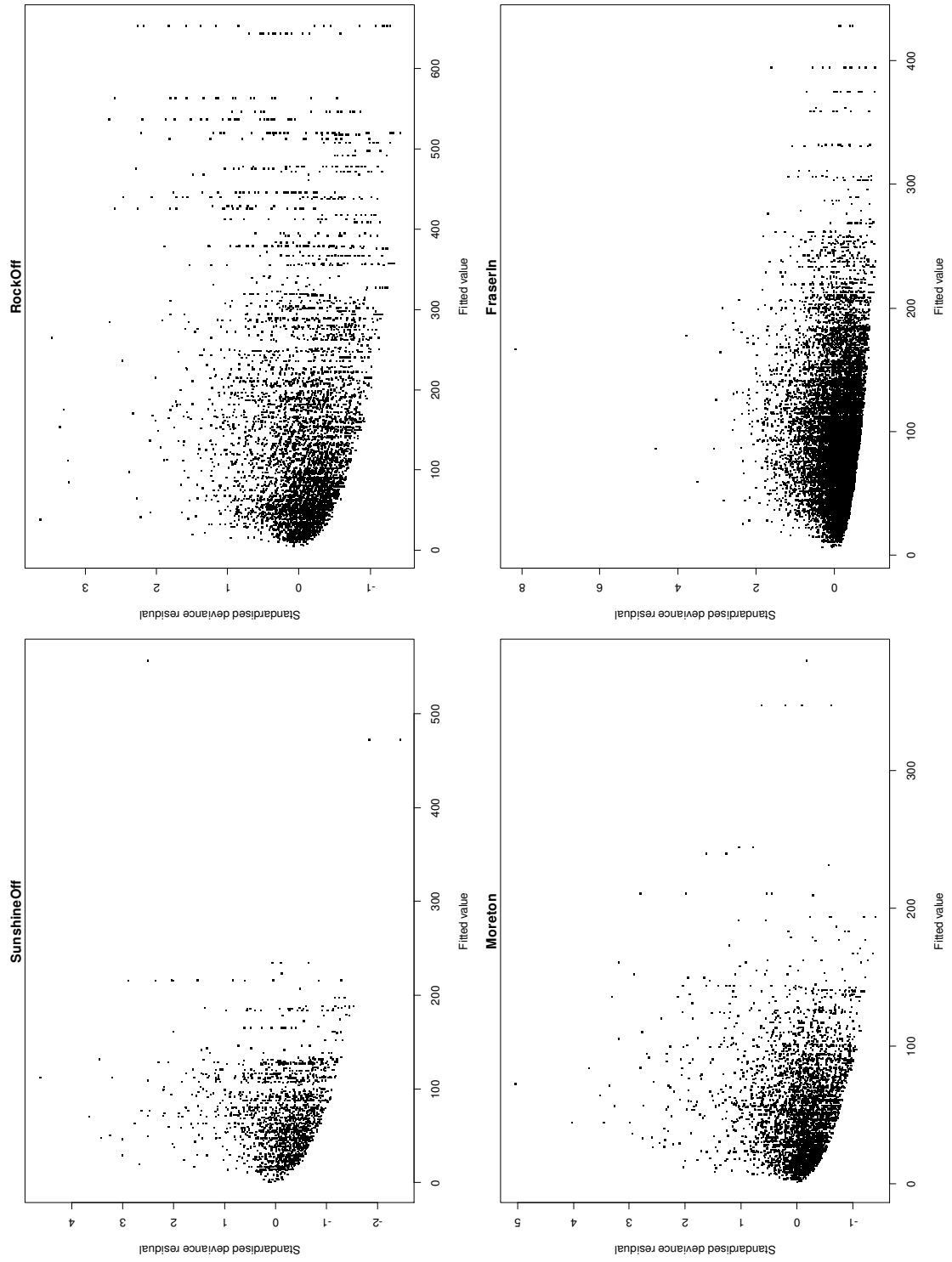


Figure 18, continued from previous two pages.

## 5. Population dynamic model

### 5.1 Overview

The population model used for shark stock assessment was tailored to the quality of the available data, and attempted to deal with the lack of species identification combined with high-quality biological data. It analysed all shark species simultaneously and used available estimates of reproductive rates and natural mortality rates. The model was also regional, to make use of the different time series of standardised catch rates and species compositions between Subregions.

It is important to note that, although this assessment concentrates on estimates of maximum sustainable yield (MSY), these quantities are not intrinsic to the model but are only derived from the model's estimates of population parameters. For a multi-species fishery there is no single "best" way to calculate MSY for the whole fishery. We use a precautionary method (see section 5.8.4 below) but whichever method is chosen uses the same model parameter estimates; the underlying model and its parameter estimates do not change.

The regional structure of the model is listed in Table 8 on page 25. The fundamental regional unit is the Subregion, of which ten cover the whole of Queensland. Each Subregion had its own time series of harvest size (chapter 3) and standardised catch rates (chapter 4), and its own species composition measured from the Fishery Observer Program (section 1.4.4, Figure 10).

The model was a regional, annual, age-structured, forward-prediction model. It was written in the software AD Model Builder (ADMB) (Fournier et al., 2012) and modified from the general-purpose stock assessment model Cabezón (specifically, the Original Cabezón or OC model) (Cope *et al.* 2003).

The Cabezón model calculates the number of animals of each age and sex in each year, and applies harvest rates (calculated from the recorded catch sizes) and the natural mortality rate to progress forward from one year to the next. It includes calculations of length-at-age and weight-at-age from a von Bertalanffy growth curve, and converts length-based fishing vulnerability functions to age-based ones. Fishing is assumed to take place as a short pulse in the middle of each year. This does not exactly match the shark fishery, in which fishing takes place all year round, but because sharks are quite long-lived we did not believe that the errors would be significant. Cabezón model projections can be matched against abundance indices, age-frequency data and length-frequency data.

The ADMB code from Cabezón was extensively modified to handle multiple regions, multiple species, differential natural mortality of juveniles and adults, and the additional data input stream of regional species composition. The species-composition data were handled the same way as length-frequency data. The final model included species-composition data and length-frequency data within each species. It did not include age-frequency data because no scientifically-sampled age-frequency data were available for catches of sharks by Queensland commercial fishers.

Demographic parameters were fixed to the values determined in chapter 2. The model did not have to estimate natural mortality rates or recruitment compensation ratios. Alternative values of these parameters could be tested only by re-running the model. Including these parameters as parameters that the model could estimate would greatly increase the complexity of the assessment. As it was, the number of parameters used in the model needed to be reduced to a minimum because of all the above-mentioned limitations in the input data.

The model did not include sharks that were caught but then discarded and hence not entered into logbooks. To this extent, this stock assessment assumes that the discard rate of sharks has not changed greatly over time. Some higher than normal discard rates were inferred in section 4.3.1 (Figure 16) but apart from the early years of the logbook system there was no

obvious trend. In those early years while fishers were becoming accustomed to the logbook system, sharks that were not reported may well have been retained. The observer data showed fairly low discard rates, although these were only from a snapshot over a period of a few years and from fishers who participated voluntarily in the Fishery Observer Program (section 1.4.4).

The software ADMB first estimates the model parameters by maximum likelihood, and can then run simulations using Markov chain Monte Carlo (MCMC) to provide a random sample of potential parameter values (Fournier *et al.* 2011). To first maximise the likelihood, the software uses automatic differentiation, which is an algorithmic way of generating derivatives of the objective function (negative log-likelihood or NLL). When the maximum-likelihood point has been found, it then calculates the matrix of second derivatives of the NLL at that point. It is a well-known result in statistics that this matrix is the inverse of the large-sample asymptotic variance matrix of the parameter estimators.

For the MCMC simulation the software starts from the maximum likelihood point and takes multivariate random “jumps” in the parameter space: a jump generates a new vector of parameter values which is equal to the existing vector plus the jump vector. The software applies the Metropolis-Hastings algorithm (Metropolis *et al.* 1953; Hastings 1970) to randomly either accept or reject each jump, according to how likely the new parameter values are. In the case of rejection, the algorithm retains the previous “jump-off” parameter values: importantly, these are repeated in the time series of simulated parameter values. The distribution of the jumps can be adjusted as the MCMC simulation proceeds, in order to maintain a reasonable frequency of acceptance of the newly-generated parameter values.

Confidence limits for parameters can be constructed from the MCMC simulations. We ran 500,000 MCMC iterations and saved every 50th one, for a total of 10,000 simulated values of the parameter vector.

A script in the software *R* (R Core Team 2015) collated the input data from various sources into text files for reading into the ADMB program. Another *R* script took parameter estimates output by ADMB and analysed them.

## 5.2 Basic population dynamics

The model operated on Populations, which were defined as Subregion–species combinations. There were ten Subregions (Table 8, page 25) and twelve species groups (Table 2, page 11), but not all species were present in substantial numbers in each Subregion. The Populations used are listed in Table 21. Species are denoted by their abbreviated common names except for the two blacktip species which were separated on the basis of latitude and are given their scientific species names in order to be precise about them: *Tilstoni* is the Australian blacktip, and *Limbatus* is the common blacktip.

Numbers of animals ( $N$ ) present in the model at the beginning of a year were indexed by Population ( $k$ ), year ( $t$ ), sex ( $g$ ) and age ( $a$ ). The model used calendar years, which were thought to suit the biological cycles of shark reproduction better than fishery quota years. Most shark species mate in the spring, which in the southern hemisphere is late in the year, and give birth to pups in spring the following year. Fishery management, on the other hand, generally operates on Australian financial years, July to June.

Ages ranged from zero to  $a_{\max} = 30$  years for all species, and length intervals were measured in 5 cm increments, the smallest interval being 15–20 cm and the largest 345–350 cm. Many age and length classes contained tiny numbers of animals for many species. We used a “plus group” whereby sharks in the final age class (30 years old) did not automatically die at the end of the year but remained alive in the same age class, having first had their numbers reduced by the appropriate fishing and natural mortality rates.

The number of animals of age zero was set to the recruitment  $R_{k,t}$  to Population  $k$  in year  $t$ :

Table 21: Populations in the model. Species groups are listed in Table 2 (page 11) and each is identified by its single most common species.

No.	Subregion	Species group	No.	Subregion	Species
1	Gulf	Milk shark	33	Stanage	Milk shark
2	Gulf	Creek whaler	34	Stanage	Spot-tail
3	Gulf	Spot-tail	35	Stanage	Bull
4	Gulf	Tilstoni	36	Stanage	Scalloped
5	Gulf	Bull	37	Stanage	Great hammerhead
6	Gulf	Winghead	38	RockEst	Milk shark
7	Gulf	Scalloped	39	RockEst	Limbatus
8	Gulf	Great hammerhead	40	RockEst	Bull
9	FarNorth	Milk shark	41	RockOff	Sharpnose
10	FarNorth	Creek whaler	42	RockOff	Milk shark
11	FarNorth	Hardnose	43	RockOff	Hardnose
12	FarNorth	Spot-tail	44	RockOff	Spot-tail
13	FarNorth	Tilstoni	45	RockOff	Limbatus
14	FarNorth	Scalloped	46	RockOff	Spinner
15	FarNorth	Great hammerhead	47	RockOff	Bull
16	Lucinda	Sharpnose	48	RockOff	Scalloped
17	Lucinda	Milk shark	49	RockOff	Great hammerhead
18	Lucinda	Creek whaler	50	FraserIn	Milk shark
19	Lucinda	Hardnose	51	FraserIn	Spot-tail
20	Lucinda	Spot-tail	52	FraserIn	Limbatus
21	Lucinda	Tilstoni	53	FraserIn	Spinner
22	Lucinda	Spinner	54	FraserIn	Bull
23	Lucinda	Bull	55	FraserIn	Scalloped
24	Lucinda	Scalloped	56	SunshineOff	Sharpnose
25	Lucinda	Great hammerhead	57	SunshineOff	Limbatus
26	Whitsunday	Milk shark	58	SunshineOff	Spinner
27	Whitsunday	Hardnose	59	SunshineOff	Scalloped
28	Whitsunday	Spot-tail	60	Moreton	Sharpnose
29	Whitsunday	Tilstoni	61	Moreton	Limbatus
30	Whitsunday	Bull			
31	Whitsunday	Scalloped			
32	Whitsunday	Great hammerhead			

$$N_{ktg0} = f_{kg} R_{kt}, \quad (5.1)$$

where  $f_{kg}$  is the proportion of recruits of sex  $g$ , which was set to 0.5 in all cases (i.e., equal numbers of female and male pups). Recruitment is discussed below (section 5.4).

For ages one year and upwards, population numbers are derived from those for the same year-class in the previous year (year  $t - 1$  and age  $a - 1$ ): for  $1 \leq a < a_{\max}$ ,

$$N_{ktga} = N_{kt-1ga-1} \exp(-M_{ka-1})(1 - V_{kga-1} U_{kt-1}), \quad (5.2)$$

where  $M_{ka}$  is the instantaneous natural mortality rate,  $V_{kga}$  is the vulnerability to fishing, and  $U_{kt}$  is the harvest rate which is the proportion of vulnerable sharks in Population  $k$  that are caught in year  $t$ . As described in Chapter 2, the natural mortality rate  $M_{\text{adult}}$  is used for ages at or above the age of 5% maturity of females, i.e., when females begin to mature. For the younger ages we used the value  $M_{\text{prod}}$  for a fished-down population in preference to  $M_{\text{juv}}$ , on the basis that the fished-down situation is the most important one for stock assessment. The vulnerability  $V_{kga}$  and harvest rate  $U_{kt}$  are described below and in the next section.

The oldest age-class  $a_{\max}$  was the “plus group”, holding all animals of age  $a_{\max}$  or older. The formula for it was slightly different to (5.2): for  $a = a_{\max}$ ,



$$N_{k t g a} = N_{k t-1 g a-1} \exp(-M_{k a-1})(1-V_{k g a-1} U_{k t-1}) + N_{k t-1 g a} \exp(-M_{k a})(1-V_{k g a} U_{k t-1}). \quad (5.3)$$

The model started from the equilibrium virgin (never fished) state at the beginning of year 1, which for the purposes of this study was defined as calendar year 1974. Both fishing and the Shark Control Program were considered to have had a negligible effect on state-wide shark populations before that time. The population structure in year 1 was given by, for  $1 \leq a < a_{\max}$ ,

$$N_{k 1 g a} = f_{k g} R_{k 0} \exp\left(-\sum_{i=0}^{a-1} M_{k i}\right),$$

where  $R_{k 0}$  is the deterministic number of recruits to population  $k$  in the virgin state (see section 5.4 below). For the plus group the formula took account of older animals: for  $a = a_{\max}$ ,

$$N_{k 1 g a} = f_{k g} R_{k 0} \exp\left(-\sum_{i=0}^{a-1} M_{k i}\right) / \{1 - \exp(-M_{k a})\}.$$

The vulnerability  $V_{k g a}$  is estimated in the model and represents the relative chance that a shark of sex  $g$  and age  $a$  in Population  $k$  will be caught by fishing. In this model vulnerability is a parametric function of an animal's length, although the Cabezon code converts it so that it depends on sex and age instead. Vulnerability is defined to equal 1 at some length, and to lie between 0 and 1 at other lengths. It is less than 1 if animals at some length are either

- Too small, too large or too powerful to be caught in a gillnet, i.e., they are not selected by the fishing gear, or
- Not present in the area being fished, e.g., they may be in nursery areas not targeted by fishers or they may have migrated offshore.

Sharks are subject to both of the above factors. Many newly-born sharks, although they can be quite long, are too thin to be caught in gillnets of the mesh size used in the fishery. Over the history of the gillnet logbook database, 71% of the harvest came from mesh sizes between 150 and 165 mm; another 17% was taken between 100 and 149 mm, 3% less than 100 mm and 8% greater than 165 mm. Large sharks, especially whalers, are too big to be caught around the gills by commonly-used mesh and are able to escape by damaging the net if they are caught around their noses. Also many sharks are born in inshore nursery areas from which they migrate as they become older or approach sexual maturity (Castro 1993, 1996; Feldheim *et al.* 2002; Capapé *et al.* 2003; Hueter *et al.* 2005; Sims 2005; Harry *et al.* 2011), making it unlikely that both juveniles and adults will be present in full numbers at any specific location preferred by a gillnet fishery.

In the model,  $M_{k a}$  and  $V_{k g a}$  depended on species, age and (in the case of vulnerability) sex, and not on location; whereas  $U_{k t}$  depended on Subregion and year, and not on species. The formulation of  $U_{k t}$  embodied an additional assumption to the standard ones, which was that every species has 100% vulnerability at some length and that the same harvest rate applies to all species in that Subregion and year. This assumption was needed because the catch-size and catch-rate data were not species-specific but were aggregates over all species.

The harvest rate  $U_{k t}$  is the proportion of vulnerable animals in Population  $k$  that are caught in year  $t$ . Because catch sizes were specified only as aggregates over all species within a Subregion,  $U_{k t}$  depended only on the Subregion  $s$  that contained Population  $k$ :

$$U_{k t} = U_{s t}^*.$$

The Subregion harvest rate  $U_{s t}^*$  was calculated as the ratio of catch weight from Subregion  $s$  in year  $t$ , to the mid-year vulnerable biomass in Subregion  $s$  just before the start of the fishing pulse (which is described in section 5.1):

$$U_{s t}^* = C_{s t} / \sum_{k \in K(s)} \sum_{g=1}^2 \sum_{a=0}^{a_{\max}} N_{k t g a} \exp(-M_{k a}/2) W_{k g a} V_{k g a}, \quad (5.4)$$

where  $C_{s,t}$  is the harvest from Subregion  $s$  in year  $t$ ,  $W_{kga}$  is the average mid-year weight of a shark of sex  $g$  and age  $a$  in population  $k$ , and  $K(s)$  is the set of Populations that make up Subregion  $s$ . The weight at age  $W_{kga}$  was a data input to the model, derived from the growth curve, the coefficient of variation of length-at-age (see below) and the length–weight relationship for each species (see Table 6, page 23).

### 5.3 Vulnerability functions

One of the simplest and most widely used vulnerability functions is the logistic function. This function increases from very low vulnerability for small animals, to approach 1 for large animals:

$$V_L^* = 1/[1 + \exp\{-(\log 19)(L - L_{50})/(L_{95} - L_{50})\}], \quad (5.5)$$

where  $L_{50}$  is the length at 50% vulnerability and  $L_{95}$  is the length at 95% vulnerability (see Haddon 2001 353). This function has two parameters which are estimated in the model, and which we parameterised as  $L_{50}$  and the difference  $L_{\text{diff}} = L_{95} - L_{50}$ . The parameter  $L_{\text{diff}}$  was more convenient to which to apply bounds than  $L_{95}$  directly. The asterisk distinguishes length-dependent vulnerability  $V_L^*$  from age-and-sex-dependent vulnerability  $V_{ga}$ .

The logistic vulnerability function was used for most of the smaller sharks in the assessment: sharpnose, creek whaler, hardnose and spot-tail. These sharks were considered to still be fully selected by the fishery at their maximum lengths. For the milk shark the estimate of  $L_{\text{diff}}$  was unreasonably large, which made the vulnerability function very flat. Hence we made it flat for this species and used a constant vulnerability  $V_L^* = 1$  for all values of  $L$ , which did not involve any parameters. This parameter setting had no significant effect on the assessment and acted only to facilitate parameter estimation.

The larger sharks required a “dome-shaped” vulnerability function, whereby vulnerability peaks at some moderate size and then decreases for large animals, instead of continuing to increase like the logistic function.

To achieve dome-shaped vulnerability with as few parameters as possible, we developed a three-parameter generalisation of the logistic function that had an asymptote equal to some number  $p$  as  $L \rightarrow \infty$ , where  $0 \leq p \leq 1$ :

$$V_L \propto \frac{1}{1 + e_L} \left( p + \frac{1-p}{1 + e_R} \right), \quad (5.6)$$

where

$$e_L = \exp\{-(\log 19)(L - L_L)/L_{\text{diff}}\} \quad (5.7)$$

and

$$e_R = \exp\{(\log 19)(L - L_R)/L_{\text{diff}}\}. \quad (5.8)$$

The parameter  $L_L$  is the equivalent to  $L_{50}$  for a logistic function on the left-hand side (increasing), while  $L_R$  is the  $L_{50}$ -equivalent on the right-hand side (decreasing).

The parameters were arranged so that the maximum vulnerability occurred at  $L = L_R$ . By a substantial amount of algebra, it can be shown that this happens when

$$L_L = L_R - L_{\text{diff}} \left( \log \frac{1+3p}{1-p} \right) / \log 19. \quad (5.9)$$

Furthermore, the value of the right-hand side of (5.6) at  $L = L_R$  is then  $(1+3p)/4$ . Therefore, including the requirement that the maximum value of vulnerability must equal 1, the final formula for vulnerability is

$$V_L = \frac{4}{1+3p} \frac{1}{1 + e_L} \left( p + \frac{1-p}{1 + e_R} \right), \quad (5.10)$$

where  $e_L$  and  $e_R$  are given by (5.7) and (5.8),  $L_L$  is given by (5.9) and the three parameters to be estimated are  $L_R$ ,  $L_{\text{diff}}$  and  $p$ .

The formulation whereby the maximum vulnerability occurs at  $L = L_R$  is convenient for putting bounds on the model parameters. The maximum vulnerability is set at 1 and it is highly desirable that some animals in the population actually attain or come very close to this value; otherwise there will be a “phantom” group of animals that can produce recruits but are themselves never seen by the fishery. An example bound on  $L_R$  is to demand that  $L_R \leq L_\infty$ , the asymptotic length in the von Bertalanffy growth function (Table 6).

The form (5.10) was used for the remaining seven species of shark: Tilstoni, Limbatus, spinner, bull, winghead, scalloped and great hammerhead. In the event, the estimates of the parameter  $p$  hit the lower limit of zero for Limbatus, spinner, winghead and scalloped. For these four species this parameter was set to zero and the number of parameters in the vulnerability function was reduced from three to two. This setting had no effect on the assessment but facilitated parameter estimation.

Length-dependent vulnerability was converted to sex-and-age-dependent vulnerability using the distribution of length at age in the middle of the year; this functionality was provided by the original Cabezon model. The length distribution at a given age was assumed to be normal, with mean given by the von Bertalanffy growth curve (Table 6, page 23) and standard deviation by the estimated coefficient of variation which was another data input to the model: at a given sex  $g$  and age  $a$ , it produced the proportion of animals  $p_{g a}(L)$  in each length-class  $L$ , such that  $\sum_L p_{g a}(L) = 1$ . Then the age-dependent vulnerability was given by

$$V_{g a} = \sum_L p_{g a}(L) V_L^* \quad (5.11)$$

As noted above, the model used 5 cm length categories with midpoints ranging from 17.5 cm to 347.5 cm, and calculated the vulnerability in the middle of the year, at exact age  $a + \frac{1}{2}$ .

The coefficient of variation of length at age, which was needed to convert length-dependent to age-dependent vulnerability, was set to 0.07 for newly-born sharks (age 0) and 0.05 for sharks of age 30 or more, and was a linear function of age in between.

## 5.4 Recruitment

Recruitment in the model was deterministic. Standard stock assessment models include annual recruitment deviations that are not related to parental stock size and allow random high recruitment in some years and random low recruitment in other years. If recruitment deviations were included in a multiple-species model such as the shark model, it would be highly desirable to make them also depend on species and Subregion. This would add a very large number of parameters to the model. Considering the almost complete absence of data from which these parameters could be estimated (e.g., no age-frequency data), we did not consider their estimation achievable and hence we omitted them from the model.

The only place where recruitment deviations could have been useful was for spinner sharks in the Sunshine Coast Offshore Subregion (see section 4.3.2, Figure 17, page 62), and even then the evidence is largely anecdotal that the recruitment consisted of spinner sharks. We did not introduce any parameters to handle this one special case, which limited the model’s fit to the catch rates.

The stock–recruitment relationship was the modified Beverton–Holt one given by equation (2.3) in chapter 2, with fixed parameter values from Table 14. Because we especially wanted the model to work accurately for a heavily fished population, we used the parameter value  $M_{\text{prod}}$  from Table 14 for the juvenile natural mortality rate (ages less than the age of 5% maturity of females) in all years. This is only an approximation, and the value really should

lie somewhere between  $M_{\text{juv}}$  and  $M_{\text{prod}}$ , depending on the amount by which the population had been fished down.

For the biomass  $B$  in (2.3), we indeed used the parental stock biomass. For sharks this embodied the assumption that the litter size to which a female shark could give birth was assumed to be proportional to the weight of the shark. We believed that this was slightly preferable to assuming no dependence on the size of the mother. For ray-finned (bony) fish that are mass spawners,  $B$  can instead be defined as total egg production by females using fecundity measurements, but this concept does not extend easily to sharks which give birth to live young. We note that previous discussion of litter size in this report concerned only the demographic analysis in chapter 2, not the population dynamic model. The demographic analysis assumed no dependence of litter size on size of the mother, but that did not prevent us from assuming such dependence in the population model.

The concept of parental biomass, as opposed to the total number of potential parents in the population, is very common in fishery stock assessment and confers a reproductive advantage to a population containing old, large breeding animals.

Each Population gained its recruitment from only its own parental biomass: there was no source of recruitment from neighbouring Subregions. We acknowledge that sharks are capable of swimming long distances along coastlines, but we did not believe this to be especially common for the species in the assessment. In addition, sharks that swim long distances can still exhibit philopatry, i.e., return to a distinct “home” location (Hueter *et al.* 2005).

We do not claim that our Populations represent separate genetic stocks. Our model assumes only that genetic divergence between stocks takes place on time scales much longer than the time scale over which changes take place in the fishery.

Mating and recruitment were assumed to take place simultaneously at the beginning of each calendar year. The model allowed no time lag between mating and subsequent recruitment. This formulation matched that used by Cabezon, but differed from previous stock assessments of some other fisheries by DAF (see, e.g., Haddon 2001). Previous DAF assessments of fisheries have assumed spawning in the middle of the year, and subsequent recruitment at the beginning of the following year.

A more accurate recruitment formulation would allow for gestation of sharks by inserting a one-year time lag between mating and recruitment. In addition, such a formulation should allow for mortality (both fishing and natural) of the mother during the gestation period, which would also kill its pups. Time constraints did not allow this level of detail to be included in this assessment, but we recommend that it be considered when sharks are next assessed in Queensland. Its inclusion would have only a very small effect on the assessment because sharks are relatively long-lived and their population sizes change only slowly.

## 5.5 Habitat sizes

For convenience, virgin recruitment parameters in the model, denoted  $R_0$  in equation (2.3) on page 42, are expressed as densities per unit of habitat instead of as absolute population numbers. Habitat was calculated simply as the rough length of coastline in km in each Subregion, including sizable inshore islands. The coast provides nursery areas for the species of sharks assessed here, so we viewed coastline as a more appropriate measure than, for example, some area of water within which sharks are caught by any fishing method (including offshore line fishing and trawling).

The habitat lengths used in the assessment are listed in Table 22. The only effect that these measurements had on the results of the assessment were in the likelihood term that encouraged recruitment densities to be close together in neighbouring Subregions (see section 5.7.5).

Table 22: Habitat coastline length used in the model, for each Subregion.

Subregion	Length (km)
Gulf	883.7
FarNorth	920.7
Lucinda	445.0
Whitsunday	463.9
Stanage	305.9
RockEst	162.2
RockOff	147.7
FraserIn	461.7
SunshineOff	112.7
Moreton	389.2

## 5.6 List of model parameters

The parameters used in the model are listed in Table 23. They comprise only the virgin log-recruitment density for each population, denoted  $\ln\_R0[k]$ ,  $k = 1, \dots, 61$ ; and the parameters in the length-dependent vulnerability function for each species, denoted  $L50[i]$ ,  $L\_diff[i]$  and  $p[i]$ ,  $i = 1, \dots, 12$ , although not all of these parameters are defined for all species. Demographic parameters take their values from Table 14 on page 45 and are not estimated in the model. The total number of parameters in the model was 86 (61 for population size and 25 for vulnerability to fishing).

Table 23: Parameters estimated in the model. Milk shark (species 2) was assigned a vulnerability to fishing of 1 for all lengths, so has no vulnerability parameters. Vulnerability functions were either logistic (equation (5.5) for species 1, 3, 4 and 5) or dome-shaped (equation (5.10) for species 6–12).

No.	Symbol	Meaning
$k = 1, \dots, 61$	$\ln\_R0[k]$	Log-recruitment density for Population $k$ (Table 21)
$i = 1, 3, 4, 5$	$L50[i]$	Length at 50% fishing vulnerability for species $i$ (Table 2, p. 11)
	$L\_diff[i]$	Length at 95% minus length at 50% vulnerability for species $i$
$i = 6, 9, 12$	$L\_R[i]$	L50 for right-hand (decreasing) logistic vulnerability for species $i$
	$L\_diff[i]$	$L\_diff$ for both left-hand and right-hand functions for species $i$
	$p[i]$	Asymptotic vulnerability as $L \rightarrow \infty$ (see equation (5.10))
$i = 7, 8, 10, 11$	$L\_R[i]$ $L\_diff[i]$	} As above for species $i$ but with $p[i] = 0$

## 5.7 Data and likelihoods

### 5.7.1 Data

A summary of the data used in the assessment has been provided in section 1.6. Data used in the model are listed in Table 24. Mostly these were not raw data but had been derived from the raw data by methods presented in previous chapters.

The data listed above the bold line in Table 24 were used in the model's internal calculations. The data below the line were used to match the model's predictions, as described in the following sections.

Table 24: Data used in the model. The data listed above the bold line were used in the model's internal calculations, while those below the line were used to match the model's predictions. The species frequency and length frequency were considered to be only a snapshot in a single year in each Subregion, and were assigned the year in which the most sharks were observed in that Subregion.

Name	Description
$L_{\infty}, K, t_0$	Von Bertalanffy growth curve parameters, by species and sex (Table 6, p. 23)
$CVL_{\min}$	Coefficient of variation (CV) of length about the mean at age 1 (section 5.3)
$CVL_{\max}$	Coefficient of variation of length about the mean at age 30 (section 5.3)
$W_{i g a}$	Average mid-year weight of a shark of species $i$ , sex $g$ and age $a$ (section 5.2)
$x_{i a}$	Maturity proportion $\times$ female weight at age $a$ for species $i$ (Table 7, p. 23)
$H_s$	Habitat size (km of coastline) of Subregion $s$ (section 5.5)
$C_{s t}$	Commercial catch weight in Subregion $s$ and year $t$ (section 3.3)
$Y_{s t}$	Standardised commercial catch rate in Subregion $s$ and year $t$ (chapter 4)
$CVY_{s t}$	Coefficients of variation of $Y_{s t}$ , used in the model as lower bounds for CVs
$y_{k t}$	Species frequency for Population $k$ , year $t$ in fishery observer data (section 1.4.4)
$y_{k t \ell}$	Length frequency for Population $k$ , year $t$ , length-class $\ell$ (section 1.4.4)

A coefficient of variation (CV) is usually defined as the ratios of the standard error to the mean value of a random variable. For the abundance data, however, the coefficient of variation CVY was defined as the standard error of the corresponding log-transformed parameter estimate in the generalised linear model in Chapter 4. The two definitions are very similar if the CV is not very big (e.g., around 0.2).

These CVs of abundance included only observation error, i.e., error that can be made arbitrarily small by collecting more data. They did not include process error caused by lack of fit of the model. Therefore, to account for possible process error, the CV estimates were used in the model only as lower bounds for the actual CVs.

The Fishery Observer Program ran only from 2006 to 2012. It was considered to provide only a snapshot of species frequency and length frequency. Therefore all the observer data for each Subregion were considered to have been collected in a single year, the year in which the program observed the most sharks in that Subregion.

### 5.7.2 Likelihood for relative abundance measures

The standardised commercial catch rate  $Y_{s t}$  is assumed to be proportional to the mid-year vulnerable biomass in Subregion  $s$  and year  $t$ , denoted  $B_{s t}$ :

$$B_{s t} = \sqrt{1 - U_{s t}^*} \sum_{k \in K(s)} \sum_{g=1}^2 \sum_{a=0}^{a_{\max}} N_{k t g a} \exp(-M_{k a}/2) W_{k a} V_{k a}$$

where  $U_{s t}^*$  is given by (5.4) and the square-root factor adjusts for the middle of the fishing pulse. It should be noted that this is different to the *parental* biomass denoted  $B$  (with no subscripts) in chapter 2, section 5.4 and section 5.8 below.

The catch rate  $Y_{s t}$  is assumed to follow a lognormal distribution. When the mean  $\mu$  and standard deviation  $\sigma_{s t}$  of  $\log Y_{s t} - \log B_{s t}$  are specified, the likelihood is

$$\prod_s \prod_t \left[ \exp\left\{-\frac{1}{2}(\log Y_{s t} - \log B_{s t} - \mu)^2 / \sigma_{s t}^2\right\} / (\sqrt{2\pi} \sigma_{s t}) \right],$$

where subscripts  $s$  and  $t$  denote Subregions and years respectively. It is convenient to use the negative log-likelihood (NLL), which, omitting the constant factors of  $\sqrt{2\pi}$  above, is

$$\ell_Y = \sum_s \sum_t \left\{ \log \sigma_{s t} + \frac{1}{2}(\log Y_{s t} - \log B_{s t} - \mu)^2 / \sigma_{s t}^2 \right\}. \quad (5.12)$$

The standard deviation  $\sigma_{st}$  is set to  $\text{CVY}_{st}$  (see Table 24) multiplied by a scale factor  $\sigma \geq 1$  which is intended to account for process error (see section 5.7.1). Then the NLL, omitting constant terms, is

$$\ell_Y = \sum_s \sum_t \left\{ \log \sigma - \frac{1}{2} \log w_{st} + \frac{1}{2} w_{st} (\log Y_{st} - \log B_{st} - \mu)^2 / \sigma^2 \right\}, \quad (5.13)$$

where  $w_{st} = 1/\text{CVY}_{st}^2$ .

Standard estimators of  $\mu$  and  $\sigma^2$  in Subregion  $s$  are:

$$\hat{\mu}_{Y_s} = \sum_t w_{st} (\log Y_{st} - \log B_{st}) / \sum_t w_{st}$$

and

$$\hat{\sigma}_{Y_s}^2 = \sum_t \left\{ w_{st} (\log Y_{st} - \log B_{st} - \hat{\mu}_{Y_s})^2 \right\} / (n_{Y_s} - 1), \quad (5.14)$$

where  $n_{Y_s}$  is the number of years of catch-rate data in Subregion  $s$ . Substituting these expressions into (5.13) provides a likelihood that depends only on data ( $Y_{st}$  and  $w_{st}$ ) and model predictions ( $B_{st}$ ):

$$\ell_Y = \sum_s (n_{Y_s} - 1) (\log \tilde{\sigma}_{Y_s} + \frac{1}{2} \hat{\sigma}_{Y_s}^2 / \tilde{\sigma}_{Y_s}^2), \quad (5.15)$$

where  $\tilde{\sigma}_{Y_s}$  is the estimate of  $\sigma$  taking account of its lower bound  $\sigma_{Y_{\min}} = 1$ :

$$\tilde{\sigma}_{Y_s} = \max(\hat{\sigma}_{Y_s}, \sigma_{Y_{\min}}). \quad (5.16)$$

The factor applied to  $\log \tilde{\sigma}_{Y_s}$  in (5.15) is  $n_{Y_s} - 1$  instead of  $n_{Y_s}$  as a correction for the need to estimate  $\mu$  by  $\hat{\mu}_{Y_s}$ . Formula (5.15) is similar to the negative log-likelihood derived by Haddon (2001 89) but includes the adjustment term for the lower bound on  $\sigma$ .

The ‘‘max’’ function is not suitable for ADMB, or indeed for any optimisation method that takes full advantage of derivatives, because its derivative is discontinuous. In fact, it is better not to calculate  $\hat{\sigma}_Y$  either, but to use  $\hat{\sigma}_Y^2$  directly from (5.14), because  $\hat{\sigma}_Y$  involves a square root which causes trouble if  $\hat{\sigma}_Y = 0$ . Therefore we used the following expression for  $\tilde{\sigma}_Y$ :

$$\tilde{\sigma}_Y = \sqrt{\frac{1}{2} (\hat{\sigma}_Y^2 + \sigma_{Y_{\min}}^2) + \sqrt{\frac{1}{4} (\hat{\sigma}_Y^2 - \sigma_{Y_{\min}}^2)^2 + 4\delta^2 \sigma_{Y_{\min}}^4}}, \quad (5.17)$$

where  $\delta > 0$  is a smoothness parameter that took the value 0.1. The value  $\delta = 0$  makes (5.17) the same as (5.16), which is the formula that has to be avoided. The smoothing has the side effect of shifting the value of  $\tilde{\sigma}_Y$  at  $\hat{\sigma}_Y = \sigma_{Y_{\min}}$  up to approximately  $(1 + \delta) \sigma_{Y_{\min}}$  instead of the desired value of  $\sigma_{Y_{\min}}$ . The value  $\delta = 0.1$  shifted it up 10%, which was held to be a reasonable compromise.

### 5.7.3 Likelihood for length frequencies

A length frequency consisted of a number of sharks  $y_{k t \ell}$  measured from each length class  $\ell$  in some Population  $k$  and year  $t$ . When each shark is considered to be independent of all other sharks, the likelihood of a length frequency is multinomial:

$$\binom{y_{\text{tot}}}{y_{k t 1}, \dots, y_{k t L}} \prod_{\ell=1}^L p_{\ell}^{y_{k t \ell}}, \quad (5.18)$$

where  $y_{\text{tot}}$  is the total number of sharks observed in that Subregion–year combination (sum of the  $y_{k t \ell}$ ),  $p_{\ell}$  is the model’s predicted proportion of sharks from length class  $\ell$ , the multinomial coefficient is defined as

$$\binom{y_{\text{tot}}}{y_{k t 1}, \dots, y_{k t L}} = y_{\text{tot}}! / \prod_{\ell=1}^L y_{k t \ell}!,$$

and the factorial function is defined as

$$y! = \prod_{j=1}^y j.$$

In practice, animals sampled from populations of fish or sharks are not independent, and instead of the total number  $y_{\text{tot}}$  the sample has an “effective sample size” that is usually much less than  $y_{\text{tot}}$  (Pennington and Vølstad 1994; McAllister and Ianelli 1997; Francis 2011).

We deal with the problem of effective sample size by adjusting the multinomial likelihood. The approach estimates the effective sample size from the “raggedness” of the length-frequency distribution: a smooth distribution gives a large effective sample size, and a very ragged one gives a small effective sample size. It does not use the actual sample size  $y_{\text{tot}}$ .

We accept the point made by Francis (2011) that this approach can overestimate the effective sample size if the sample distribution is smooth but randomly biased towards either big animals or small animals in particular years, e.g. if the fishing grounds are, by chance, frequented by schools of larger animals in one year but schools of smaller animals in another year. Our experience is that this is not a significant problem in sampling of Queensland fisheries, in which sample length distributions tend to be ragged and show little sign of smoothness. Raggedness results in effective sample sizes that are already small, from which any further decreases due to randomly biased sampling are likely to be negligible. The method proposed by Francis is extremely complex, and we have not managed to make it work in fisheries in which we have attempted it (O’Neill *et al.* 2014).

We believe that the method we use, although not perfect, is the best method currently available for adjusting length-frequency likelihoods for effective sample size. It differs from the one used by the original Cabezon model which abandoned the multinomial likelihood and replaced it by a sum of squares analogous to a chi-square statistic. We retain the multinomial likelihood as far as possible.

Firstly, we note that zero values of  $y_{k t \ell}$  in (5.18) make no contribution to the likelihood. Hence we restrict the likelihood to length classes  $\ell$  for which  $y_{k t \ell} > 0$ . We let  $q$  denote the number of such length classes and  $Q$  denote the set of these length classes. Then the likelihood (5.18) becomes

$$\left\{ y_{\text{tot}}! / \prod_{\ell \in Q} y_{\ell}! \right\} \prod_{\ell \in Q} p_{\ell}^{y_{k t \ell}}. \quad (5.19)$$

We introduce the effective sample size, denoted  $T$ , so that an observation of  $y_{k t \ell}$  sharks of age  $a$  in the sample of size  $y_{\text{tot}}$  is transformed to an effective observation of  $(T/y_{\text{tot}})y_{k t \ell}$  sharks from a sample of size  $T$ . We also treat likelihood (5.19) as a probability density function (p.d.f.) of the  $y_a$  in  $q-1$  dimensions; the number of dimensions is  $q-1$  rather than  $q$  because the  $y_{k t \ell}$  are not independent but are constrained to sum to  $y_{\text{tot}}$ . The transformed likelihood has to remain a p.d.f. of  $y_{k t \ell}$ , not of  $(T/y_{\text{tot}})y_{k t \ell}$ , which necessitates multiplying by the factor  $(T/y_{\text{tot}})^{q-1}$ . Therefore the likelihood (5.19) is transformed to

$$(T/y_{\text{tot}})^{q-1} \left\{ T! / \prod_{\ell \in Q} (T y_{k t \ell} / y_{\text{tot}})! \right\} \prod_{\ell \in Q} p_{\ell}^{T y_{k t \ell} / y_{\text{tot}}}. \quad (5.20)$$

When  $T y_{k t \ell} / y_{\text{tot}}$  is not an integer, the factorial function can be replaced by the gamma function, a mathematical special function which is defined for non-integer values and reproduces the factorial function at integer values.

We approximate the factorial function by Stirling’s formula which is a well-known formula in mathematics:

$$x! \sim \sqrt{2\pi x} x^x e^{-x}.$$



This approximation becomes extremely close as  $x \rightarrow \infty$ , but for practical purposes is also close for small  $x$ , e.g.,  $x \geq 1$ . Then, omitting constant factors and factors involving only the data  $y_{k t \ell}$ , the likelihood (5.20) becomes

$$T^{q-1} \left\{ T^{T+\frac{1}{2}} e^{-T} \left[ T^{q/2} \prod_{\ell \in Q} \left\{ (T y_{k t \ell} / y_{\text{tot}})^{T y_{k t \ell} / y_{\text{tot}}} e^{-T y_{k t \ell} / y_{\text{tot}}} \right\} \right] \right\} \prod_{\ell \in Q} p_{\ell}^{T y_{k t \ell} / y_{\text{tot}}},$$

which, with some algebraic manipulation, can be simplified to

$$T^{(q-1)/2} \prod_{\ell \in Q} (p_{\ell} / \hat{p}_{\ell})^{T \hat{p}_{\ell}},$$

where  $\hat{p}_{\ell} = y_{k t \ell} / y_{\text{tot}}$  is the observed proportion of sharks in length class  $\ell$  in the sample.

This produces the negative log-likelihood

$$\ell_L = -\frac{1}{2}(q-1) \log T + T \sum_{\ell \in Q} \hat{p}_{\ell} \log(\hat{p}_{\ell} / p_{\ell}). \quad (5.21)$$

(Note that  $p_{\ell} / \hat{p}_{\ell}$  has been replaced by  $\hat{p}_{\ell} / p_{\ell}$  to reverse the sign of the log factor.)

The effective sample size  $T$  is estimated by maximum likelihood, by minimising the negative log-likelihood (5.21):

$$\hat{T} = \frac{1}{2}(q-1) / \sum_{\ell \in Q} \hat{p}_{\ell} \log(\hat{p}_{\ell} / p_{\ell}). \quad (5.22)$$

In the theory of generalised linear models (see McCullagh and Nelder 1989 197), this is also the estimate produced by equating the deviance of the multinomial model,  $2T \sum \hat{p}_{\ell} \log(\hat{p}_{\ell} / p_{\ell})$  to its asymptotic, large-sample expectation  $q-1$ . Substituting the estimate (5.22) into the negative log-likelihood (5.21), and ignoring the resulting constant term, yields the final negative log-likelihood for the length-frequency sample:

$$\ell_L = -\frac{1}{2}(q-1) \log \hat{T}. \quad (5.23)$$

For every available age-frequency sample, the negative log-likelihood given by (5.23) and (5.22) is added into the overall negative log-likelihood for the model. Using this formulation it would be easy to impose a lower bound  $T_{\min}$  on the effective sample size  $T$  for each sample, e.g., to force  $T \geq 1$  or  $T \geq 2$ , but we did not consider it necessary to do that. The negative log-likelihood for such a case would be

$$-\frac{1}{2}(q-1) \log \tilde{T} + \frac{1}{2}(q-1) \tilde{T} / \hat{T},$$

where  $\tilde{T} = \max(\hat{T}, T_{\min})$ .

#### 5.7.4 Likelihood for length frequencies and species frequencies

A species frequency contained a number of sharks  $y_{k t}$  from each Population  $k \in K(s)$  in some Subregion  $s$  and year  $t$  (see sections 1.4.4 and 5.7.1 and Table 24). As defined earlier, the set  $K(s)$  is the collection of Populations present in Subregion  $s$ , and a Population is a combination of species and Subregion.

Species-frequency samples were handled in the same way as length-frequency samples. Each length-frequency or species-frequency produced a term of the form (5.23) that was added into overall negative log-likelihood for the model.

#### 5.7.5 Likelihood for recruitment parameters

An additional likelihood term or ‘‘penalty’’ term was included in the negative log-likelihood to encourage the log-recruitment densities  $\ln\_R0$  to be close together for the same species in neighbouring Subregions. This was needed because of the lack of data about population sizes of sharks. It was not possible to estimate the population size entirely separately in each Subregion, and neighbouring ones had to be tied together. This assumption does not affect the validity of summing regional biomass and yield estimates (chapter 6 below), but

confidence limits for the summed estimates may be tighter than they would be without the assumption.

The methodology was similar to that used for abundance measures in section 5.7.2 above. For each species  $i$ , all the pairs  $(k_{1m}, k_{2m})$  of neighbouring populations of species  $i$  were defined for  $m = 1, \dots, P_i$ , where  $P_i$  was the total number of pairs of neighbouring populations of species  $i$ . The negative log-likelihood corresponding to (5.12) is

$$\ell_P = \sum_{i=1}^I \sum_{m=1}^{P_i} \left\{ \log \sigma_i + \frac{1}{2} \left( \ln\_R0_{k_{1m}} - \ln\_R0_{k_{2m}} \right)^2 / \sigma_i^2 \right\}. \quad (5.24)$$

The estimate of the standard deviation  $\sigma_i$  similar to (5.14) is given by

$$\hat{\sigma}_i^2 = \sum_{m=1}^{P_i} \left( \ln\_R0_{k_{1m}} - \ln\_R0_{k_{2m}} \right)^2 / P_i, \quad (5.25)$$

and the final negative log-likelihood analogous to (5.15) is

$$\ell_P = \sum_{i=1}^I P_i \left( \log \tilde{\sigma}_i + \frac{1}{2} \hat{\sigma}_i^2 / \tilde{\sigma}_i^2 \right), \quad (5.26)$$

where, similarly to (5.16),  $\tilde{\sigma}_i$  is the estimate of  $\sigma_i$  taking account of a lower bound  $\sigma_{\min}$ :

$$\tilde{\sigma}_i = \max(\hat{\sigma}_i, \sigma_{\min}). \quad (5.27)$$

We used the value  $\sqrt{2}/10$  for  $\sigma_{\min}$ , which was roughly equivalent to a lower bound of 0.1 on the standard deviations of the individual  $\ln\_R0_k$  parameters that comprised each pair. There was no need to replace  $P_i$  by  $P_i - 1$  because there were no means that needed to be estimated.

We allowed the Gulf Subregion to be a neighbour of the FarNorth Subregion even though these two were separated by Cape York. Otherwise there would have been no connection between the abundance of sharks in the Gulf and the abundance on the east coast. For the two Rockhampton Subregions we set RockOff to be the neighbour of Stanage and FraserIn, and considered RockEst to be a ‘‘spur’’ neighbouring only RockOff: the oceanic Subregions were made neighbours but the estuarine Subregion’s only neighbour was its adjacent oceanic Subregion. These assumptions affected the assessment results only to the point that consistent results would have been impossible to obtain without them.

Importantly, the pairs used consisted only of species–Subregion combinations that had high enough abundances to be included in the model. Not all species were abundant in every Subregion and those that were not abundant were excluded.

This likelihood term was the only place in the analysis where the habitat measures from section 5.5 affected the model results. The  $\ln\_R0$  parameters were scaled to be logs of densities per kilometre of coastline and it was the densities, not the absolute population sizes, that were encouraged by the penalty term (5.26) not to vary much between Subregions.

## 5.8 Calculation of maximum sustainable yield

### 5.8.1 Statement of the problem

The maximum sustainable yield (MSY) from a fished population is the maximum annual yield that can be taken from it indefinitely into the future under deterministic conditions with no random variation in, e.g., recruitment. Calculation of MSY involves writing a function to calculate the yield as a function of the instantaneous fishing mortality rate ( $F$ ) and optimising it over  $F$ . The yield calculation could be done by running the actual population model for many years until it reaches steady state, but that is time-consuming when many simulations are being analysed. The following technique can be used instead.

The calculation of MSY can be broken down into four steps.

1. Find the yield per recruit (YPR) as a function of  $F$ ; YPR does not take account of the lower recruitment relative to virgin, which results from lowering the parental stock by fishing.
2. Find the recruitment proportion, relative to virgin, that results from the lower parental stock. Again this is a function of  $F$ . Multiply this by YPR to arrive at the yield per virgin recruit (YPVR).
3. Optimise YPVR over  $F$ .
4. Multiply the optimised YPVR by the virgin number of recruits (the population size parameter) to find MSY.

Steps 1, 3 and 4 are straightforward when the natural mortality rates, weight-at-age, vulnerability parameters and population-size parameters are known. Step 2 is more difficult and needs to take account of the feedback of decreased parental stock into decreased recruitment, which then (when the recruits grow up) further reduces the parental stock.

For the model described in this chapter, the only model-parameter values needed are those for the vulnerability parameters and the population size parameters. All other relevant parameters are fixed from the demographic analysis in chapter 2.

### 5.8.2 Calculation of yield per recruit

We assumed age-dependent natural mortality with instantaneous rate  $M_a$  at age  $a$ , sex-and-age-dependent vulnerability  $V_{g a}$ , mid-year weight-at-age  $W_{g a}$  and a sex ratio of 1:1 female to male recruits. For an animal of sex  $g$  and age  $a$  that is alive at the beginning of a year, the probability that it will survive to the end of the current year is

$$S_{g a}^{\text{current}} = \exp(-M_a)(1 - V_{g a} U)$$

where  $U = 1 - \exp(-F)$  is the harvest rate corresponding to the prescribed instantaneous fishing mortality rate  $F$ . The probability that a newly-born animal will survive until the end of the year in which it is aged  $a$  is

$$S_{g a} = \prod_{j=0}^a S_{g j}^{\text{current}}.$$

The yield is assumed to be taken in a fishing pulse in the middle of the year, i.e. after half the natural mortality has been applied. The yield per recruit is

$$\text{YPR} = \frac{1}{2} U \times \sum_{g=1}^2 \left\{ \sum_{a=0}^{a_{\max}-1} S_{g a-1} W_{g a} \exp(-\frac{1}{2} M_a) V_{g a} + S_{g a_{\max}-1} W_{g a_{\max}} \exp(-\frac{1}{2} M_{a_{\max}}) V_{g a_{\max}} / (1 - S_{g a_{\max}}^{\text{current}}) \right\}, \quad (5.28)$$

where the initial factor of  $\frac{1}{2}$  is the proportion of recruits of each sex  $g$ , and the term involving  $a_{\max}$  covers the ‘‘plus group’’ which contains all animals aged  $a_{\max}$  or more.

The parental stock size is calculated at the beginning of the year. The parental stock size per recruit, considering female animals only, is equal to

$$B/R = \frac{1}{2} \left\{ \sum_{a=0}^{a_{\max}-1} S_{1 a-1} f_a + S_{1 a_{\max}-1} f_{a_{\max}} / (1 - S_{1 a_{\max}}^{\text{current}}) \right\},$$

where  $f_a$  is the fecundity of females at age  $a$ , which is approximated by the proportion mature (Table 7, page 23) multiplied by the start-of-year weight of a female of age  $a$ . The symbol  $B$  denotes parental stock size (as opposed to the vulnerable biomass which was denoted  $B_{s,t}$  above, with subscripts for Subregion and year), and  $R$  denotes number of recruits (both sexes combined).

### 5.8.3 Calculation of recruitment ratio

The calculations above provide the ratio  $B/R$  for a population fished at the rate  $F$ , and the ratio  $B_0/R_0$  for the virgin population when  $F = 0$ . We now need to calculate the ratio  $R/R_0$ .

Define the variable  $\lambda$  by

$$B/R = \lambda B_0/R_0$$

where  $1/r_{\text{lim}} \leq \lambda < 1$ . If  $\lambda < 1/r_{\text{lim}}$  the corresponding value of  $F$  should be disallowed in the optimisation, e.g., by setting the yield to zero or some negative number. In the stock-recruitment relationship (2.3) from chapter 2, the population is not allowed to go beyond the point at which the limiting recruitment compensation ratio  $r_{\text{lim}}$  takes effect, because the corresponding value of  $F$  would produce a population collapse.

The Beverton-Holt equation (2.2) can now be written as

$$R/R_0 = \frac{r\lambda R/R_0}{1 + (r-1)\lambda R/R_0},$$

which can be solved for  $R/R_0$  as a function of  $\lambda$ :

$$R/R_0 = \frac{\lambda r - 1}{\lambda(r-1)}.$$

Then the parental stock size ratio is given by

$$B/B_0 = \lambda R/R_0 = \frac{\lambda r - 1}{r - 1}$$

and the yield is

$$Y = (R/R_0) \text{YPR} = \frac{\lambda r - 1}{\lambda(r-1)} \text{YPR},$$

where YPR is given by (5.28).

The yield is then maximised over different values of  $F$  to produce the maximum sustainable yield (MSY) and the level of fishing that gives rise to MSY (denoted  $F_{\text{MSY}}$ ).

#### 5.8.4 Maximum sustainable yield for multiple species

All the calculations in sections 5.8.2 and 5.8.3 were performed separately for each species. They usually produced different values of  $F_{\text{MSY}}$  for species that could occur in the same Subregion.

We did not believe that it was feasible to fish species in the same Subregion at different levels of  $F_{\text{MSY}}$ . Therefore we employed a precautionary principle. For each Subregion, we set  $F_{\text{MSY}}$  to the lowest value for any species present in the model for that Subregion. Any higher level of fishing would have overfished one or more species. As a consequence our estimate of  $F_{\text{MSY}}$  for a particular Subregion was less than the true value for most of the species in that Subregion. We believed this method of MSY estimation to be preferable to allowing overfishing of any species.

#### 5.8.5 Software

The MSY calculations were programmed in the software *R* (R Core Team 2015), using parameter estimates produced by the model written in ADMB (Fournier *et al.* 2011). The optimisation was performed using the *R* routine “optimize” which implements derivative-free one-dimensional optimisation within a given interval. The interval was chosen as  $0 < F < 3 \text{ yr}^{-1}$ .

The above methodology was applicable to both the maximum-likelihood point and the Markov chain Monte Carlo (MCMC) simulations. It was needed only for the retained (“thinned”) MCMC simulations, not the intermediate ones. We retained only every 50th simulation. Hence the execution time for calculation of MSY from the MCMC results was much shorter than for the MCMC itself.

## 6. Results from the population dynamic model

### 6.1 Overview

The model provided a large range of possible population sizes, and there were no practical upper limits to the population sizes. This was a consequence of the standardised catch-rate time series (chapter 4), which had either no trend or an increasing trend in the majority of Subregions. There were no other data from which the population sizes could be gauged. The fits to the catch-rate time series were very poor, and fitted catch rates were close to constant (see section 6.4.3 below).

Therefore we concentrate on MCMC simulations rather than the overall maximum likelihood estimates, and discuss the parameter values from various lower percentiles of total maximum sustainable yield (total-MSY), summed over all species and Subregions.

As an example of the variation, the maximum likelihood estimate of total-MSY was very large at 58,830t, and this was the starting point for MCMC as conducted by the software ADMB (Fournier *et al.* 2011). The estimate with the second-highest likelihood from the 10,000 retained MCMC simulations, however, was much less at 8835 t. This second value was still much higher than any historical harvest size.

Excluding the first 500 saved points, which could be viewed as influenced by the maximum likelihood point, the highest 100 likelihood values of the remaining 9500 points had a range of total-MSY from 3483 t to 941,000t. These points had negative log-likelihood (NLL) values between  $-719.4$  and  $-709.7$ ; *cf.* the maximum-likelihood NLL value of  $-755.9$ . Lower NLL values are better from the model's perspective, and imply that the corresponding parameter values are more compatible with the input data. The actual values of NLL are not important, only the difference between one NLL value and another, which measures how likely one simulation is relative to another.

In contrast to the lack of any practical upper limit to the total-MSY, a lower limit for total-MSY was well defined. The primary reason for this is that all simulated values of MSY had to be consistent with the catch history (chapter 3, Figure 14) and the fact that there had been no widespread fall in standardised catch rates (chapter 4, Figure 17). The catch history (Figure 14) shows that a total harvest of around 1500 t or more was sustained from 2000 to 2008, and the harvest only fell when new management measures (total allowable commercial catch and the "S" licence symbol) were introduced to the fishery.

The historical catch sizes and catch rates indicate that fisheries targeting sharks in Queensland could sustain state-wide harvests of about 1500t indefinitely in the absence of the management changes. The only possible concerns are in the Whitsunday and Stanage Subregions (Figure 17, pages 59–60), where the catch rates decreased between the years 2000 and 2012. Some of the confidence limits on those catch rates are wide. The Stanage Subregion makes only a small contribution to the total harvest, but the Whitsunday Subregion makes a larger contribution (Figure 14). We are unable to explain why the catch-rate time series in the Stanage Subregion and, to a lesser extent, the neighbouring Whitsunday Subregion were so different to the other Subregions.

Of the lowest 1% of simulated total-MSY values, the one with the lowest NLL was 1445 t (NLL =  $-704.2$ ). Restrictions to the lowest 0.5%, 0.2% and 0.1% give respective total-MSYs of 1273 t (NLL =  $-703.3$ ), 1165 t (NLL =  $-693.9$ ) and 1075 t (NLL =  $-693.4$ ). The lowest of all the 10,000 retained simulated values of total-MSY was 722 t (NLL =  $-685.1$ ). All of these values are above the reported Queensland state-wide commercial shark catch of 459 t for the 2013 calendar year.

Vulnerability parameters were estimated more accurately than the population sizes. Length frequencies from the observer data were informative for these parameters. Dome-shaped vulnerability functions for the larger whalers limit the sizes at which these species are

vulnerable to fishing, but hammerheads remain vulnerable over most of their size ranges (see section 6.3).

The limiting species for  $F_{MSY}$  (see section 5.8.4 above) was the great hammerhead in Subregions where it was present. That is to say, under the MSY scenario all species were fished at the great-hammerhead level of  $F_{MSY}$ . This was the species most at risk of overfishing, mainly due to its long life-span, low natural mortality rate and vulnerability to the gillnet fishery throughout most of its size range.

Where great hammerhead was not present (see Table 21) the next limiting species was scalloped hammerhead. It was the species second most at risk of over-fishing, for the same reasons as great hammerhead. Where neither of these large hammerhead species was present, the limiting species was either milk shark (Rockhampton Estuarine Subregion) or sharpnose shark (Moreton Subregion). The probably reason for these species being at greater risk than others is that they are vulnerable to gillnet fishing for their whole lives, whereas larger sharks are vulnerable for only a short part of their lives.

The species that was fished at the lowest proportion of its species-specific MSY was the common blacktip shark (*Carcharhinus limbatus*). This species appears to be at the least risk of over-fishing.

## 6.2 Maximum sustainable yield and biomass

We focus on the lower end of the estimates of maximum sustainable yield (MSY), because the upper-end estimates are extremely large and are considered to be unrealistic. The lowest 25% of total-MSY estimates (summed over all Subregions and species) are plotted as a histogram in Figure 19. The right-hand tail of this histogram, i.e., the 75% of values that are not plotted in Figure 19, is extremely long and extends out to MSY values totalling hundreds of thousands of tonnes. Such values, though they are not at odds with model's input data (harvest sizes and catch rates), are not realistic.

The left-hand side of Figure 19 shows a sharp drop-off from many total-MSY values around 2000t to only a few less than 1000t. This happens because MSY estimates have to be compatible with the fishery's history of harvest sizes and standardised catch rates. As discussed above, the history of harvest size provides evidence for a long-term sustainable state-wide harvest of 1500t or more and catch rates have trended upwards in most regions.

In order to help visualise where the MSY values sit within the broader model estimates, the lowest 50% of total-MSY estimates are plotted against the corresponding negative log-likelihood (NLL) values in Figure 20. This plot shows that the model prefers total-MSY estimates around 5000 t or more, as these have the lowest NLL values.

Within the MSY range of 5000t or more, there is hardly any difference between the low NLL values: hence there is no strong evidence that total-MSY must be greater than 5000t. The first ten retained MCMC simulations (i.e., the first 500 of the complete set of MCMC simulations) were excluded from Figure 20 because the early NLL values were strongly influenced by the maximum likelihood point which the software ADMB uses as the MCMC starting point.

Two representative parameter vectors were selected for further study. These correspond to the points labelled 1 and 2 respectively in Figure 20. Point 1 was selected as a "substitute maximum-likelihood" estimate because the overall maximum-likelihood estimate was very large (58,830t) and may have been unrealistic due to deficiencies in the input data. It was selected because

- it had a low NLL value, i.e., the model quantified it as quite likely, and
- all of the points in Figure 20 with smaller total-MSY values (i.e., points to the left of Point 1) had substantially higher NLL values, making them much less likely than Point 1.

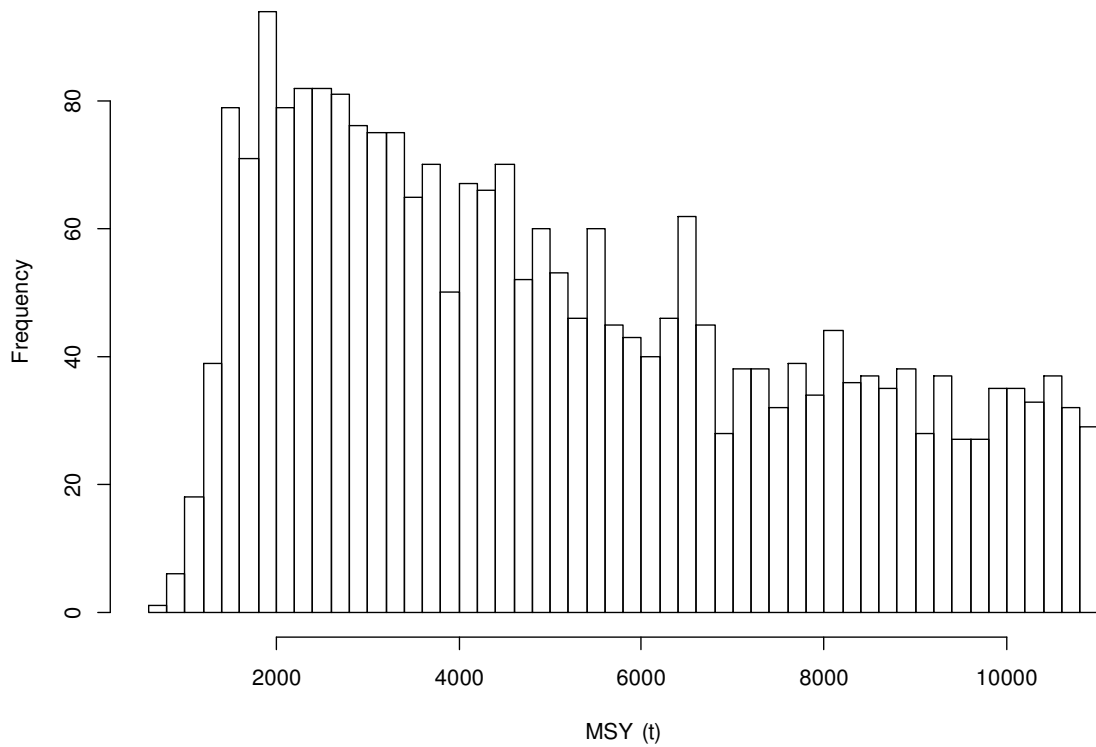


Figure 19: Histogram of the lowest 25% of total-MSY estimates from the model's MCMC simulations.

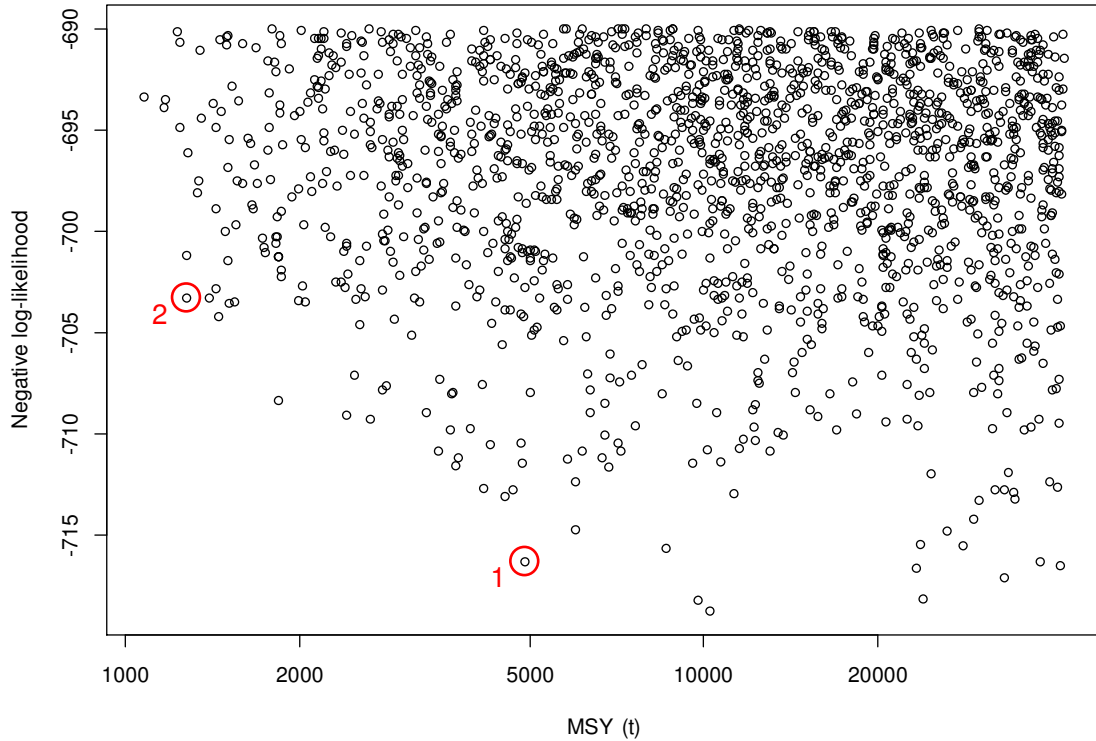


Figure 20: Scatter plot of the lowest 50% of total-MSY estimates from the model's MCMC simulations, against their negative log-likelihood (NLL) values. Only NLL values less than  $-690$  are shown. The plot shows that the model prefers total-MSY estimates around 5000 t or more, as these give rise to the lowest NLL values. Representative points labelled 1 and 2 were used as respectively a substitute maximum-likelihood point and a minimum-MSY point.

By “substitute maximum-likelihood” we intend to convey the meaning of a point that is not a great deal less likely than the maximum-likelihood point but whose total-MSY value is closer to historical harvest sizes.

Point 2 we describe as a “minimum-MSY” estimate. This point was chosen because

- its total-MSY was at the low end of simulated values (i.e., it is close to the left-hand side of Figure 20) and
- all points with lower MSY values had substantially greater (less likely) NLL values, making them much less likely than Point 2.

One alternative to these studying these parameter values would be to compute the maximum likelihood estimates with total-MSY restricted to 5000 t or less and with total-MSY restricted to 1300 t or less. Given the huge range of uncertainty in the model results, we did not consider it necessary to do this, but it could be undertaken in future.

The studies of the two representative parameter vectors discuss only MSY and biomass estimates, not vulnerability functions, although the vulnerability functions were required to calculate MSY and biomass. Vulnerability functions were estimated relatively precisely by the model and we have studied them using all 10,000 retained simulations (see section 6.3).

### 6.2.1 Representative Parameter Vector 1: Substitute maximum-likelihood estimate

Point 1 on Figure 20 has a total-MSY of 4903 t and a negative log-likelihood of  $-716.3$ , comparable to the lowest NLL values of the lower 50% of total-MSY simulations. Hence it can be inferred that the model has no strong preference for total-MSY values greater than 5000 t, and Point 1 can be regarded as at the low end of highly likely values.

MSY estimates and some other important population parameters from the parameter vector corresponding to Point 1 are listed in Table 25. A condensed summary of MSY by species and Management Region is presented in Table 26. In addition to MSY, Table 25 also lists the vulnerable and parental biomasses as proportions of virgin that would correspond to MSY fishing, together with the fishing level  $F_{\text{MSY}}$  for MSY fishing of each Subregion, and finally the value that  $F_{\text{MSY}}$  would have if it were possible to target individual species without catching others. As remarked above, the value of  $F_{\text{MSY}}$  for a Subregion is that for great hammerhead when that species is present in the Subregion, other the value for scalloped hammerhead, milk shark or sharpnose shark.

Because of the discrepancy in the proportions of sharpnose sharks recorded between the Fishery Observer Program and the JCU–FRDC tagging experiment on the east coast (see section 1.4.4), the split of MSY and biomass levels into species for small sharks may be in error. Therefore it may be wise to group the small sharks together, especially sharpnose and milk shark, and accept that it is impossible to estimate species-specific MSY levels for them.

The species-specific  $F_{\text{MSY}}$ -values in Table 25 are high ( $> 0.6 \text{ yr}^{-1}$ ) for the common blacktip shark (*C. limbatus*), hardnose shark and spinner shark. This is mainly because many mature animals of these species are not vulnerable to fishing. Vulnerability functions will be discussed in section 6.3 below. The results for the hardnose shark will have to be re-examined in future, because many hardnose sharks recorded by the observers had lengths well above the assumed average maximum length  $L_{\infty}$  to which this species grows from Table 6. The main consequence of this problem for the current assessment is that the model has estimated that adult hardnose sharks were only partially vulnerable to fishing and so it may have overestimated the resilience of this species to fishing.

MSY fishing of the Subregion produces very high levels of vulnerable biomass and parental biomass for many species which have species-specific  $F_{\text{MSY}}$  values much greater than the region-specific ones (see the last four columns of Table 25).

Table 26 lists MSY estimates by species and Management Region. The state-wide estimates for the top three species (the two blacktip species and the bull shark) are each around 1000 t.



Values for the spot-tail shark and spinner shark are each around 400t. Estimates for the sharpnose shark and the two hammerhead species are around 250t. Other species have lower estimates. By Management Region, the estimates over all species are 1111t in the Gulf Management Region, 2121 t in the Northern Management Region and 1670 t in the Southern Management Region.

Tables 27 and 28 list biomass estimates. Table 27 lists, for each Population, the estimated virgin vulnerable biomass, current (mid-2013) vulnerable biomass as a proportion of virgin, virgin parental biomass and current parental biomass as a proportion of virgin. Parental biomass was defined on female sharks only, as is common fisheries stock assessment (Goodyear and Christensen 1984). Table 28 summarises the virgin vulnerable biomass by species and Management Region.

Table 25: Estimated MSY values for Representative Parameter Vector 1 (substitute maximum-likelihood estimate). The table shows the estimate of MSY in tonnes for each Population in the model, the vulnerable biomass as a proportion of virgin under MSY fishing, the parental biomass as a proportion of virgin under MSY fishing, the value of instantaneous fishing mortality rate  $F$  that produces MSY for the Subregion (measured in  $\text{yr}^{-1}$ ), and the value of  $F$  that would produce MSY for the species if targeting of particular shark species were possible ( $\text{yr}^{-1}$ ). The limiting species for  $F_{\text{MSY}}$  in each Subregion is listed in boldface.

Population	MSY	$B_{\text{vul}}/\text{virgin}$	$B_{\text{parent}}/\text{virgin}$	$F_{\text{MSY}}^{\text{reg}}$	$F_{\text{MSY}}^{\text{sp}}$
Gulf Milk	34.7	0.670	0.616	0.058	0.113
Gulf CreekWhaler	9.1	0.627	0.550	0.058	0.110
Gulf SpotTail	121.5	0.655	0.589	0.058	0.125
Gulf Tilstoni	512.5	0.773	0.691	0.058	0.150
Gulf Bull	258.8	0.781	0.710	0.058	0.160
Gulf Winghead	26.0	0.794	0.691	0.058	0.155
Gulf Scalloped	69.0	0.625	0.485	0.058	0.082
<b>Gulf Great</b>	<b>79.8</b>	<b>0.447</b>	<b>0.385</b>	<b>0.058</b>	<b>0.058</b>
FarNorth Milk	39.4	0.670	0.616	0.058	0.113
FarNorth CreekWhaler	15.7	0.627	0.550	0.058	0.110
FarNorth Hardnose	20.0	0.840	0.864	0.058	0.935
FarNorth SpotTail	107.0	0.655	0.589	0.058	0.125
FarNorth Tilstoni	355.7	0.773	0.691	0.058	0.150
FarNorth Scalloped	65.2	0.625	0.485	0.058	0.082
<b>FarNorth Great</b>	<b>80.2</b>	<b>0.447</b>	<b>0.385</b>	<b>0.058</b>	<b>0.058</b>
Lucinda Sharpnose	7.6	0.843	0.828	0.058	0.379
Lucinda Milk	17.5	0.670	0.616	0.058	0.113
Lucinda CreekWhaler	13.8	0.627	0.550	0.058	0.110
Lucinda Hardnose	10.0	0.840	0.864	0.058	0.935
Lucinda SpotTail	65.3	0.655	0.589	0.058	0.125
Lucinda Tilstoni	209.4	0.773	0.691	0.058	0.150
Lucinda Spinner	20.2	0.954	0.909	0.058	0.630
Lucinda Bull	111.7	0.781	0.710	0.058	0.160
Lucinda Scalloped	33.7	0.625	0.485	0.058	0.082
<b>Lucinda Great</b>	<b>35.7</b>	<b>0.447</b>	<b>0.385</b>	<b>0.058</b>	<b>0.058</b>
Whitsunday Milk	18.6	0.670	0.616	0.058	0.113
Whitsunday Hardnose	13.7	0.840	0.864	0.058	0.935
Whitsunday SpotTail	56.1	0.655	0.589	0.058	0.125
Whitsunday Tilstoni	105.4	0.773	0.691	0.058	0.150
Whitsunday Bull	101.3	0.781	0.710	0.058	0.160
Whitsunday Scalloped	31.7	0.625	0.485	0.058	0.082
<b>Whitsunday Great</b>	<b>30.6</b>	<b>0.447</b>	<b>0.385</b>	<b>0.058</b>	<b>0.058</b>

<b>Population</b>	<b>MSY</b>	$B_{\text{vul}}/\text{virgin}$	$B_{\text{parent}}/\text{virgin}$	$F_{\text{MSY}}^{\text{reg}}$	$F_{\text{MSY}}^{\text{sp}}$
Stanage Milk	12.9	0.670	0.616	0.058	0.113
Stanage SpotTail	36.9	0.655	0.589	0.058	0.125
Stanage Bull	90.9	0.781	0.710	0.058	0.160
Stanage Scalloped	23.4	0.625	0.485	0.058	0.082
<b>Stanage Great</b>	<b>18.5</b>	<b>0.447</b>	<b>0.385</b>	<b>0.058</b>	<b>0.058</b>
<b>RockEst Milk</b>	<b>7.5</b>	<b>0.438</b>	<b>0.371</b>	<b>0.113</b>	<b>0.113</b>
RockEst Limbatus	76.5	0.944	0.876	0.113	1.081
RockEst Bull	80.0	0.602	0.500	0.113	0.160
RockOff Sharpnose	8.1	0.843	0.828	0.058	0.379
RockOff Milk	5.6	0.670	0.616	0.058	0.113
RockOff Hardnose	18.3	0.840	0.864	0.058	0.935
RockOff SpotTail	15.5	0.655	0.589	0.058	0.125
RockOff Limbatus	41.0	0.971	0.934	0.058	1.081
RockOff Spinner	47.8	0.954	0.909	0.058	0.630
RockOff Bull	54.3	0.781	0.710	0.058	0.160
RockOff Scalloped	9.0	0.625	0.485	0.058	0.082
<b>RockOff Great</b>	<b>9.6</b>	<b>0.447</b>	<b>0.385</b>	<b>0.058</b>	<b>0.058</b>
FraserIn Milk	20.0	0.562	0.499	0.082	0.113
FraserIn SpotTail	47.2	0.553	0.475	0.082	0.125
FraserIn Limbatus	156.2	0.959	0.909	0.082	1.081
FraserIn Spinner	248.6	0.936	0.874	0.082	0.630
FraserIn Bull	191.6	0.701	0.613	0.082	0.160
<b>FraserIn Scalloped</b>	<b>37.9</b>	<b>0.485</b>	<b>0.337</b>	<b>0.082</b>	<b>0.082</b>
SunshineOff Sharpnose	31.8	0.788	0.769	0.082	0.379
SunshineOff Limbatus	42.7	0.959	0.909	0.082	1.081
SunshineOff Spinner	80.9	0.936	0.874	0.082	0.630
<b>SunshineOff Scalloped</b>	<b>7.9</b>	<b>0.485</b>	<b>0.337</b>	<b>0.082</b>	<b>0.082</b>
<b>Moreton Sharpnose</b>	<b>214.8</b>	<b>0.386</b>	<b>0.352</b>	<b>0.379</b>	<b>0.379</b>
Moreton Limbatus	590.7	0.826	0.649	0.379	1.081

Table 25, continued from previous page.

Table 26: MSY estimates by species and Management Region for Representative Parameter Vector 1 (substitute maximum-likelihood estimate).

<b>Species</b>	<b>Gulf</b>	<b>Northern</b>	<b>Southern</b>	<b>Total</b>
Sharpnose	–	15.7	246.6	262.3
Milk	34.7	101.5	20.0	156.2
CreekWhaler	9.1	29.6	–	38.6
Hardnose	–	62.0	–	62.0
SpotTail	121.5	280.7	47.2	449.5
Tilstoni	512.5	670.4	–	1183.0
Limbatus	–	117.5	789.6	907.1
Spinner	–	68.0	329.5	397.5
Bull	258.8	438.2	191.6	888.7
Winghead	26.0	–	–	26.0
Scalloped	69.0	163.0	45.8	277.8
Great	79.8	174.6	–	254.4
<b>Total</b>	<b>1111.4</b>	<b>2121.4</b>	<b>1670.3</b>	<b>4903.0</b>

Table 27: Estimated virgin biomass and current biomass as a proportion of virgin, in each Population in the model, for Representative Parameter Vector 1 (substitute maximum-likelihood estimate). The table lists both vulnerable biomass and parental biomass, measured in tonnes.

<b>Population</b>	Virgin $B_{vul}$	Cur. $B_{vul}/virgin$	Virgin $B_{parent}$	Cur. $B_{parent}/virgin$
Gulf Milk	925	0.913	394	0.901
Gulf CreekWhaler	258	0.897	130	0.875
Gulf SpotTail	3311	0.905	1615	0.887
Gulf Tilstoni	11832	0.950	17428	0.926
Gulf Bull	5915	0.964	11502	0.952
Gulf Winghead	584	0.957	863	0.930
Gulf Scalloped	1971	0.935	2506	0.910
Gulf Great	3184	0.919	5432	0.905
FarNorth Milk	1051	0.938	448	0.932
FarNorth CreekWhaler	448	0.926	225	0.913
FarNorth Hardnose	425	0.969	485	0.977
FarNorth SpotTail	2916	0.932	1422	0.922
FarNorth Tilstoni	8212	0.966	12096	0.947
FarNorth Scalloped	1861	0.957	2365	0.942
FarNorth Great	3201	0.948	5461	0.939
Lucinda Sharpnose	161	0.971	112	0.973
Lucinda Milk	465	0.930	198	0.924
Lucinda CreekWhaler	394	0.915	198	0.901
Lucinda Hardnose	214	0.965	244	0.974
Lucinda SpotTail	1780	0.923	868	0.912
Lucinda Tilstoni	4833	0.958	7118	0.937
Lucinda Spinner	378	0.992	1597	0.982
Lucinda Bull	2554	0.969	4966	0.958
Lucinda Scalloped	963	0.945	1224	0.918
Lucinda Great	1424	0.929	2430	0.916
Whitsunday Milk	496	0.886	211	0.874
Whitsunday Hardnose	292	0.944	333	0.958
Whitsunday SpotTail	1529	0.874	745	0.856
Whitsunday Tilstoni	2432	0.931	3582	0.893
Whitsunday Bull	2316	0.948	4504	0.928
Whitsunday Scalloped	906	0.910	1152	0.864
Whitsunday Great	1222	0.883	2084	0.862
Stanage Milk	344	0.959	146	0.956
Stanage SpotTail	1005	0.954	490	0.948
Stanage Bull	2078	0.983	4041	0.978
Stanage Scalloped	667	0.971	848	0.958
Stanage Great	738	0.963	1259	0.957
RockEst Milk	159	0.835	68	0.821
RockEst Limbatus	757	0.986	3396	0.971
RockEst Bull	1240	0.940	2411	0.925
RockOff Sharpnose	172	0.950	120	0.956
RockOff Milk	150	0.886	64	0.878
RockOff Hardnose	389	0.944	444	0.959
RockOff SpotTail	421	0.877	205	0.862
RockOff Limbatus	754	0.993	3386	0.976
RockOff Spinner	894	0.991	3779	0.978
RockOff Bull	1241	0.958	2412	0.947
RockOff Scalloped	258	0.922	328	0.900
RockOff Great	384	0.907	655	0.892

<b>Population</b>	Virgin $B_{vul}$	Cur. $B_{vul}/virgin$	Virgin $B_{parent}$	Cur. $B_{parent}/virgin$
FraserIn Milk	454	0.937	193	0.930
FraserIn SpotTail	1090	0.930	531	0.920
FraserIn Limbatus	2079	0.994	9329	0.986
FraserIn Spinner	3391	0.992	14329	0.984
FraserIn Bull	3490	0.972	6785	0.962
FraserIn Scalloped	995	0.950	1265	0.927
SunshineOff Sharpnose	515	0.974	358	0.974
SunshineOff Limbatus	568	0.994	2548	0.989
SunshineOff Spinner	1103	0.993	4663	0.989
SunshineOff Scalloped	208	0.961	264	0.952
Moreton Sharpnose	1762	0.967	1223	0.967
Moreton Limbatus	2267	0.993	10173	0.983

Table 27, continued from previous page.

Table 28: Virgin vulnerable biomass estimates by species and Management Region for Representative Parameter Vector 1 (substitute maximum-likelihood estimate). Values are in tonnes.

<b>Species</b>	<b>Gulf</b>	<b>Northern</b>	<b>Southern</b>	<b>Total</b>
Sharpnose	–	333	2277	2610
Milk	925	2665	454	4045
CreekWhaler	258	842	–	1100
Hardnose	–	1319	–	1319
SpotTail	3311	7651	1090	12052
Tilstoni	11832	15477	–	27309
Limbatus	–	1511	4913	6424
Spinner	–	1272	4494	5766
Bull	5915	9429	3490	18834
Winghead	584	–	–	584
Scalloped	1971	4655	1203	7830
Great	3184	6969	–	10153
<b>Total</b>	<b>27981</b>	<b>52124</b>	<b>17920</b>	<b>98026</b>

In the Queensland shark fishery there can be big differences between vulnerable biomass (i.e., biomass of animals vulnerable to fishing) and parental biomass. Some species have “dome-shaped” vulnerability functions and are vulnerable only for a relatively short “window” in their life spans. If they survive fishing over this period they can belong to the parental biomass but no longer the vulnerable biomass. Hence the parental biomass can be much larger than the vulnerable biomass. This observation applies particularly to the larger whaler sharks, especially the common blacktip (*C. limbatus*), spinner shark and bull shark (see Table 27).

Table 28 shows a total virgin vulnerable biomass of sharks in Queensland of 98,000 t, comprising 28,000 t in the Gulf, 52,000 t in the Northern Management Region and 18,000 t in the Southern Management Region. The species with the greatest virgin vulnerable biomass is the Australian blacktip (*C. tilstoni*), followed by the bull shark, spot-tail shark and great hammerhead. The common blacktip (*C. limbatus*) has a much lower vulnerable biomass not because it isn't abundant but because it is only vulnerable to fishing for a relatively short period during its life span.

### 6.2.2 Representative Parameter Vector 2: Approximate minimum-MSY estimate

Point 2 on Figure 20 has a total-MSY of 1273 t and a negative log-likelihood of  $-703.3$ , 13 units higher than Point 1, meaning that it was much less likely than Point 1. It was, however, the most likely of the simulations with total-MSY less than 1300 t. This point was regarded as an approximate minimum-MSY estimate and was in the bottom 0.5% of simulated total-MSY values (see section 6.1 above).

MSY estimates from Representative Parameter Vector 2 are listed in Tables 29 and 30, in the same formats and Tables 25 and 26. The MSY values are much lower than those in Tables 25 and 26. The lower MSYs are mainly due to lower estimates of population sizes, about which the model was extremely uncertain, but lower values of  $F_{\text{MSY}}$  also contribute. Some of the species-specific  $F_{\text{MSY}}$ -values in Table 29 are still quite high but not as high as those in Table 25.

Table 29: Estimated MSY values for Representative Parameter Vector 2 (minimum-MSY estimate). The table shows the estimate of MSY in tonnes for each Population in the model, the vulnerable biomass as a proportion of virgin under MSY fishing, the parental biomass as a proportion of virgin under MSY fishing, the value of instantaneous fishing mortality rate  $F$  that produces MSY for the Subregion (measured in  $\text{yr}^{-1}$ ), and the value of  $F$  that would produce MSY for the species if targeting of particular shark species were possible ( $\text{yr}^{-1}$ ). The limiting species for  $F_{\text{MSY}}$  in each Subregion is listed in boldface.

Population	MSY	$B_{\text{vul}}/\text{virgin}$	$B_{\text{parent}}/\text{virgin}$	$F_{\text{MSY}}^{\text{reg}}$	$F_{\text{MSY}}^{\text{sp}}$
Gulf Milk	9.2	0.799	0.762	0.032	0.113
Gulf CreekWhaler	5.0	0.774	0.723	0.032	0.118
Gulf SpotTail	29.4	0.788	0.744	0.032	0.129
Gulf Tilstoni	95.0	0.864	0.808	0.032	0.143
Gulf Bull	17.2	0.874	0.828	0.032	0.161
Gulf Winghead	4.3	0.898	0.837	0.032	0.179
Gulf Scalloped	25.7	0.801	0.702	0.032	0.090
<b>Gulf Great</b>	<b>10.4</b>	<b>0.421</b>	<b>0.386</b>	<b>0.032</b>	<b>0.032</b>
FarNorth Milk	10.7	0.799	0.762	0.032	0.113
FarNorth CreekWhaler	6.0	0.774	0.723	0.032	0.118
FarNorth Hardnose	5.3	0.916	0.930	0.032	1.308
FarNorth SpotTail	27.7	0.788	0.744	0.032	0.129
FarNorth Tilstoni	58.0	0.864	0.808	0.032	0.143
FarNorth Scalloped	26.1	0.801	0.702	0.032	0.090
<b>FarNorth Great</b>	<b>12.5</b>	<b>0.421</b>	<b>0.386</b>	<b>0.032</b>	<b>0.032</b>
Lucinda Sharpnose	1.5	0.898	0.888	0.032	0.321
Lucinda Milk	4.9	0.799	0.762	0.032	0.113
Lucinda CreekWhaler	3.8	0.774	0.723	0.032	0.118
Lucinda Hardnose	2.3	0.916	0.930	0.032	1.308
Lucinda SpotTail	16.0	0.788	0.744	0.032	0.129
Lucinda Tilstoni	59.5	0.864	0.808	0.032	0.143
Lucinda Spinner	2.6	0.970	0.942	0.032	0.562
Lucinda Bull	16.5	0.874	0.828	0.032	0.161
Lucinda Scalloped	10.3	0.801	0.702	0.032	0.090
<b>Lucinda Great</b>	<b>7.0</b>	<b>0.421</b>	<b>0.386</b>	<b>0.032</b>	<b>0.032</b>
Whitsunday Milk	4.9	0.799	0.762	0.032	0.113
Whitsunday Hardnose	2.7	0.916	0.930	0.032	1.308
Whitsunday SpotTail	19.3	0.788	0.744	0.032	0.129
Whitsunday Tilstoni	26.0	0.864	0.808	0.032	0.143
Whitsunday Bull	29.1	0.874	0.828	0.032	0.161
Whitsunday Scalloped	8.9	0.801	0.702	0.032	0.090
<b>Whitsunday Great</b>	<b>5.6</b>	<b>0.421</b>	<b>0.386</b>	<b>0.032</b>	<b>0.032</b>

<b>Population</b>	<b>MSY</b>	$B_{\text{vul}}/\text{virgin}$	$B_{\text{parent}}/\text{virgin}$	$F_{\text{MSY}}^{\text{reg}}$	$F_{\text{MSY}}^{\text{sp}}$
Stanage Milk	3.1	0.799	0.762	0.032	0.113
Stanage SpotTail	11.9	0.788	0.744	0.032	0.129
Stanage Bull	17.2	0.874	0.828	0.032	0.161
Stanage Scalloped	4.9	0.801	0.702	0.032	0.090
<b>Stanage Great</b>	<b>3.7</b>	<b>0.421</b>	<b>0.386</b>	<b>0.032</b>	<b>0.032</b>
<b>RockEst Milk</b>	<b>3.2</b>	<b>0.438</b>	<b>0.371</b>	<b>0.113</b>	<b>0.113</b>
RockEst Limbatus	26.4	0.925	0.852	0.113	0.829
RockEst Bull	82.8	0.608	0.503	0.113	0.161
RockOff Sharpnose	1.7	0.898	0.888	0.032	0.321
RockOff Milk	1.6	0.799	0.762	0.032	0.113
RockOff Hardnose	3.8	0.916	0.930	0.032	1.308
RockOff SpotTail	5.2	0.788	0.744	0.032	0.129
RockOff Limbatus	7.5	0.978	0.955	0.032	0.829
RockOff Spinner	3.3	0.970	0.942	0.032	0.562
RockOff Bull	14.4	0.874	0.828	0.032	0.161
RockOff Scalloped	2.2	0.801	0.702	0.032	0.090
<b>RockOff Great</b>	<b>2.8</b>	<b>0.421</b>	<b>0.386</b>	<b>0.032</b>	<b>0.032</b>
FraserIn Milk	8.5	0.528	0.463	0.090	0.113
FraserIn SpotTail	28.4	0.529	0.451	0.090	0.129
FraserIn Limbatus	79.3	0.940	0.880	0.090	0.829
FraserIn Spinner	97.6	0.919	0.849	0.090	0.562
FraserIn Bull	117.7	0.680	0.585	0.090	0.161
<b>FraserIn Scalloped</b>	<b>10.9</b>	<b>0.488</b>	<b>0.337</b>	<b>0.090</b>	<b>0.090</b>
SunshineOff Sharpnose	1.9	0.752	0.728	0.090	0.321
SunshineOff Limbatus	24.0	0.940	0.880	0.090	0.829
SunshineOff Spinner	18.3	0.919	0.849	0.090	0.562
<b>SunshineOff Scalloped</b>	<b>2.8</b>	<b>0.488</b>	<b>0.337</b>	<b>0.090</b>	<b>0.090</b>
<b>Moreton Sharpnose</b>	<b>13.9</b>	<b>0.396</b>	<b>0.357</b>	<b>0.321</b>	<b>0.321</b>
Moreton Limbatus	110.0	0.802	0.638	0.321	0.829

Table 29, continued from previous page.

Table 30: MSY estimates by species and Management Region for Representative Parameter Vector 2 (minimum-MSY estimate).

<b>Species</b>	<b>Gulf</b>	<b>Northern</b>	<b>Southern</b>	<b>Total</b>
Sharpnose	–	3.3	15.8	19.1
Milk	9.2	28.4	8.5	46.1
CreekWhaler	5.0	9.7	–	14.8
Hardnose	–	14.1	–	14.1
SpotTail	29.4	80.2	28.4	138.0
Tilstoni	95.0	143.6	–	238.5
Limbatus	–	34.0	213.3	247.3
Spinner	–	5.9	116.0	121.9
Bull	17.2	159.9	117.7	294.8
Winghead	4.3	–	–	4.3
Scalloped	25.7	52.4	13.7	91.8
Great	10.4	31.6	–	42.0
<b>Total</b>	<b>196.2</b>	<b>563.1</b>	<b>513.4</b>	<b>1272.8</b>

Again, as for Representative Parameter Vector 1, because of the discrepancy in the proportions of sharpnose sharks recorded between the Fishery Observer Program and the JCU–FRDC tagging experiment (see section 1.4.4), it is not wise to rely on species-specific results for MSY and biomasses for small sharks.

MSY fishing of each Subregion again produces very high levels of vulnerable biomass and parental biomass for the species that are not the limiting species for  $F_{MSY}$  in their Subregions (see columns “ $B_{vul}/virgin$ ” and “ $B_{parent}/virgin$ ” in Table 29).

In Table 30 the state-wide estimates of MSY for the bull shark and the two blacktip species are around 240–300 t, and those for the spot-tail shark and spinner shark are around 120–140 t. The state-wide estimate for the sharpnose shark is using representative parameter vector 2 was 19 t, less than that for the milk shark (46 t), due to the uncertainty of estimation of population-size parameters in the model. These species were the other way around for representative parameter vector 1 (Table 26).

The MSY estimate for the scalloped hammerhead in Table 30 (92 t) using representative parameter vector 2 is about double that of the great hammerhead (42 t), whereas they were about equal for representative parameter vector 1 (Table 26). This happened because great hammerhead was the limiting species for  $F_{MSY}$  in the majority of Subregions: deliberately selecting a low estimate of total-MSY for Representative Parameter Vector 2 has also chosen a low level of MSY fishing for great hammerhead, which in turn has lowered the level of fishing applied to all other species in the Subregion.

By Management Region, the estimates over all species using representative parameter vector 2 were 196 t in the Gulf, 563 t in the Northern Management Region and 513 t in the Southern Management Region. When compared to current catch levels, these highly conservative MSY estimates are still well above the reported shark catches on the east coast for the 2013 calendar year, which were 157 t for the Northern Management Region and 80 t for the Southern. The estimate for the Gulf Management Region is slightly greater than the reported catch of 221 t. As noted though, MSY values produced using representative parameter vector 2 represent the lowest 0.5% of simulated estimates. As such, they are considered to be highly conservative estimates.

Tables 31 and 32 list biomass estimates, similarly to Tables 27 and 28. Again, as found above for Representative Parameter Vector 1, the parental biomass is a good deal larger than the vulnerable biomass for the common blacktip (*C. limbatus*), spinner shark and bull shark (Table 31). Large individuals of these species contribute to reproduction but are generally not vulnerable to the Queensland fishery. Also as found above, the parental biomass of small whalers is generally smaller than the vulnerable biomass, as these species are vulnerable to fishing throughout their adult lives.

Some of the estimates of current population state of great hammerhead for Representative Parameter Vector 2 are close to MSY levels. Estimates for all other species are all above 0.55. Apart from the smaller whalers (spot-tail shark and smaller) and large hammerheads, both of which species groups are vulnerable to fishing as adults, the other species have current vulnerable biomass ratios and current parental biomass ratios greater than 0.7.

The total virgin vulnerable biomass of sharks in Queensland is shown as 33,800 t in Table 32, about a third of the value from Table 28 (the substitute maximum-likelihood estimate). This biomass is split as 7,700 t in the Gulf, 19,500 t in the Northern Management Region and 6,600 t in the Southern Management Region. The species with the greatest virgin vulnerable biomasses are the same as in Table 28, i.e., the Australian blacktip (*C. tilstoni*), followed by the bull shark and spot-tail shark. Then come the two large hammerhead species. Again the common blacktip (*C. limbatus*), although abundant, is low in vulnerable biomass because for most of its life it is not vulnerable to fishing.

Table 31: Estimated virgin biomass and current biomass as a proportion of virgin, in each Population in the model, for Representative Parameter Vector 2 (approximate minimum-MSY estimate). The table lists both vulnerable biomass and parental biomass, measured in tonnes.

Population	Virgin $B_{vul}$	Cur. $B_{vul}/virgin$	Virgin $B_{parent}$	Cur. $B_{parent}/virgin$
Gulf Milk	360	0.656	153	0.613
Gulf CreekWhaler	204	0.632	107	0.569
Gulf SpotTail	1168	0.649	583	0.595
Gulf Tilstoni	3436	0.794	4899	0.703
Gulf Bull	615	0.861	1202	0.816
Gulf Winghead	150	0.853	262	0.762
Gulf Scalloped	1004	0.769	1426	0.703
Gulf Great	769	0.476	573	0.436
FarNorth Milk	420	0.805	179	0.787
FarNorth CreekWhaler	241	0.783	127	0.750
FarNorth Hardnose	182	0.918	246	0.939
FarNorth SpotTail	1099	0.794	548	0.768
FarNorth Tilstoni	2100	0.892	2995	0.831
FarNorth Scalloped	1018	0.880	1446	0.841
FarNorth Great	930	0.696	693	0.671
Lucinda Sharpnose	53	0.911	33	0.917
Lucinda Milk	192	0.803	81	0.786
Lucinda CreekWhaler	153	0.777	80	0.745
Lucinda Hardnose	80	0.917	108	0.939
Lucinda SpotTail	636	0.791	317	0.766
Lucinda Tilstoni	2154	0.881	3071	0.817
Lucinda Spinner	85	0.977	316	0.946
Lucinda Bull	590	0.914	1153	0.883
Lucinda Scalloped	400	0.861	568	0.800
Lucinda Great	518	0.640	385	0.614
Whitsunday Milk	193	0.697	82	0.670
Whitsunday Hardnose	91	0.874	123	0.905
Whitsunday SpotTail	765	0.687	381	0.648
Whitsunday Tilstoni	941	0.815	1342	0.718
Whitsunday Bull	1041	0.868	2034	0.817
Whitsunday Scalloped	347	0.791	492	0.700
Whitsunday Great	417	0.489	311	0.456
Stanage Milk	122	0.881	52	0.872
Stanage SpotTail	474	0.872	236	0.856
Stanage Bull	614	0.955	1200	0.938
Stanage Scalloped	192	0.926	273	0.893
Stanage Great	276	0.795	206	0.778
RockEst Milk	67	0.781	29	0.763
RockEst Limbatus	267	0.976	933	0.954
RockEst Bull	1272	0.921	2486	0.901
RockOff Sharpnose	61	0.835	38	0.851
RockOff Milk	61	0.662	26	0.639
RockOff Hardnose	129	0.857	175	0.896
RockOff SpotTail	208	0.656	103	0.621
RockOff Limbatus	241	0.974	844	0.916
RockOff Spinner	107	0.972	397	0.930
RockOff Bull	514	0.878	1005	0.844
RockOff Scalloped	86	0.792	122	0.748
RockOff Great	207	0.523	154	0.491



<b>Population</b>	Virgin $B_{\text{vul}}$	Cur. $B_{\text{vul}}/\text{virgin}$	Virgin $B_{\text{parent}}$	Cur. $B_{\text{parent}}/\text{virgin}$
FraserIn Milk	187	0.866	80	0.852
FraserIn SpotTail	626	0.856	312	0.836
FraserIn Limbatus	982	0.986	3437	0.965
FraserIn Spinner	1237	0.983	4602	0.964
FraserIn Bull	2016	0.941	3940	0.921
FraserIn Scalloped	260	0.904	369	0.862
SunshineOff Sharpnose	29	0.900	18	0.900
SunshineOff Limbatus	297	0.979	1039	0.955
SunshineOff Spinner	232	0.977	863	0.959
SunshineOff Scalloped	67	0.874	95	0.848
Moreton Sharpnose	128	0.788	80	0.786
Moreton Limbatus	499	0.953	1746	0.876

Table 31, continued from previous page.

Table 32: Virgin vulnerable biomass estimates by species and Management Region for Representative Parameter Vector 2 (minimum-MSY estimate). Values are in tonnes.

<b>Species</b>	<b>Gulf</b>	<b>Northern</b>	<b>Southern</b>	<b>Total</b>
Sharpnose	0	114	157	271
Milk	360	1054	187	1602
CreekWhaler	204	394	0	597
Hardnose	0	483	0	483
SpotTail	1168	3181	626	4975
Tilstoni	3436	5196	0	8632
Limbatus	0	508	1778	2286
Spinner	0	192	1469	1661
Bull	615	4032	2016	6663
Winghead	150	0	0	150
Scalloped	1004	2044	327	3375
Great	769	2348	0	3117
<b>Total</b>	<b>7706</b>	<b>19544</b>	<b>6561</b>	<b>33812</b>

### 6.3 Vulnerability estimates

The estimated length-dependent vulnerability functions to gillnet fishing are plotted for each species in Figure 21. The plots show the estimate from the substitute maximum likelihood point (section 6.2.1) as a solid line, and pointwise 95% confidence limits from all 10,000 retained MCMC simulations as dotted lines. For comparison, the plots also have vertical dashed lines at the values of  $L_0$  (average birth length) and  $L_\infty$  (average length to which old sharks grow) for female sharks from Table 6.

For the smaller whalers (up to spot-tail shark) the curves are logistic, starting at zero for very small sharks and finishing at 1 for very large sharks. The milk shark is an exception, for which it was impossible to fit a logistic curve as this species appeared to be vulnerable for its whole life. The vulnerability curve for the milk shark is a straight line equal to 1 at all lengths.

The logistic curves are well defined for most of the smaller whalers. A problem occurs with hardnose sharks which are estimated as being only 70% vulnerable at female  $L_\infty$ . A vulnerability curve is meant to be defined so that animals at some realistic size are 100% vulnerable. A level of only 70% is roughly equivalent to postulating a sub-population that never becomes vulnerable to fishing and hence that nobody ever sees, which makes the

population model infer a spurious resilience to fishing. The problem appears to stem from the model's input data, whereby a sizable number of hardnose sharks were recorded in the Fishery Observer Program at lengths much longer than  $L_{\infty}$ : the largest length recorded was about 140 cm, whereas  $L_{\infty}$  is only 87.9 cm (Smart *et al.* 2013). It appears that either the growth curve from Smart *et al.* (2013) needs to be revised to have a higher value of  $L_{\infty}$ , or the observers misidentified some sharks recorded as hardnose. The sample size of hardnose sharks analysed by Smart *et al.* (2013) was only 37, so it is possible that larger sharks of this species may be present in the fishery but didn't happen to be observed in that study. The number recorded by the observers was 597 (Table 3, section 1.2).

The fact that adult small whalers are usually fully vulnerable to fishing, because they don't grow large enough to avoid being caught by gillnetting, means that fishing directly reduces the parental biomass. Hence the ratio of parental biomass to vulnerable biomass for these species is relatively low (Tables 27 and 31).

The larger species have peaks in their vulnerability functions (dome-shaped vulnerability), and so much of the parental biomass is protected from the direct effects of fishing. These peaks occur at quite small lengths for the common blacktip, spinner shark and bull shark: indeed the peaks for common blacktip and spinner shark hit the lower bound of birth length  $L_0$  imposed on them in the model setup. The peak vulnerability for bull shark also hit its lower bound in some simulations. Therefore these three species have high ratios of parental biomass to vulnerable biomass in Tables 27 and 31. Once animals of these species have grown through the fairly narrow length-window in which they are vulnerable to fishing, the likelihood of their experiencing substantial fishing related mortalities declines.

The bull shark has nonzero asymptotic vulnerability at large lengths (between about 2% and 20%) in Figure 21, probably because it remains inshore in its adult life, whereas the common blacktip and spinner sharks may tend move offshore as they grow. The Australian blacktip, although generally smaller than the common blacktip, is vulnerable at larger sizes than the common blacktip, and also has a nonzero asymptote. The ratio of parental biomass to vulnerable biomass is much lower for the Australian blacktip than for the common blacktip (Tables 27 and 31).

The three hammerhead species are all vulnerable to gillnet fishing at quite large lengths because they can be caught by their heads. Hence fishing of these species can have a big effect on parental stock. This is especially the case for the great hammerhead, for which the peak in vulnerability occurs at a length of about two metres (Figure 21) and very large animals can be caught by gillnets.

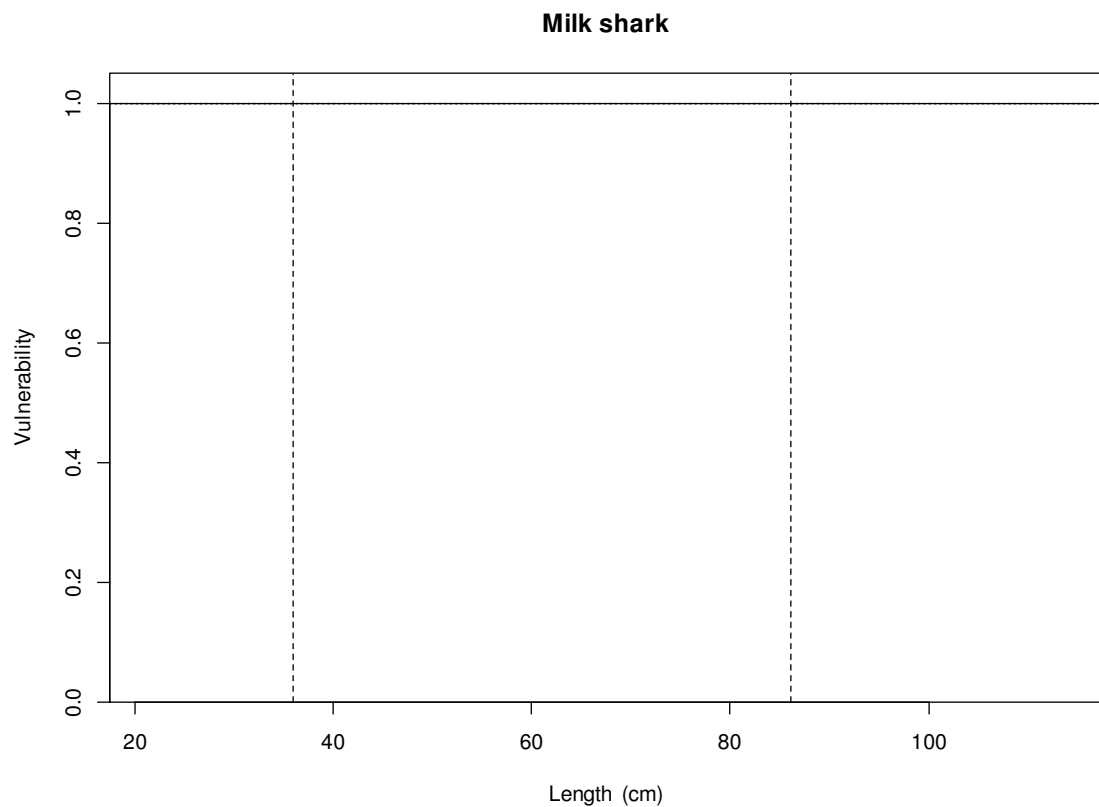
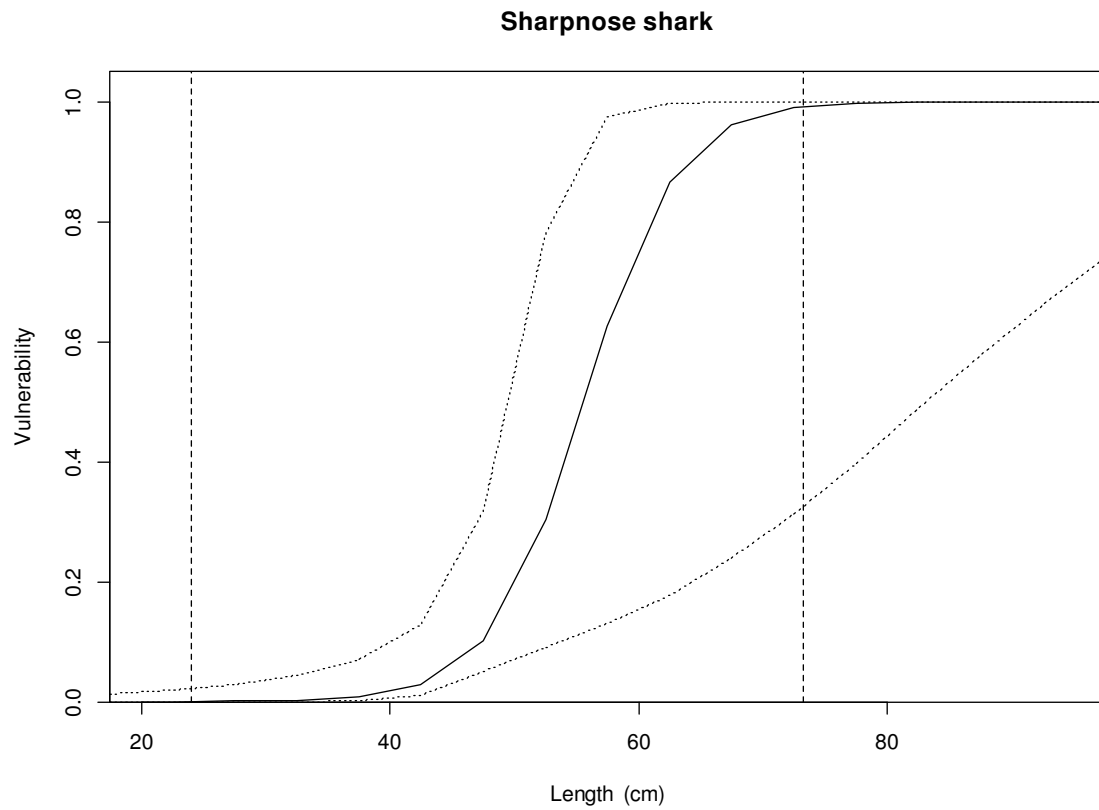
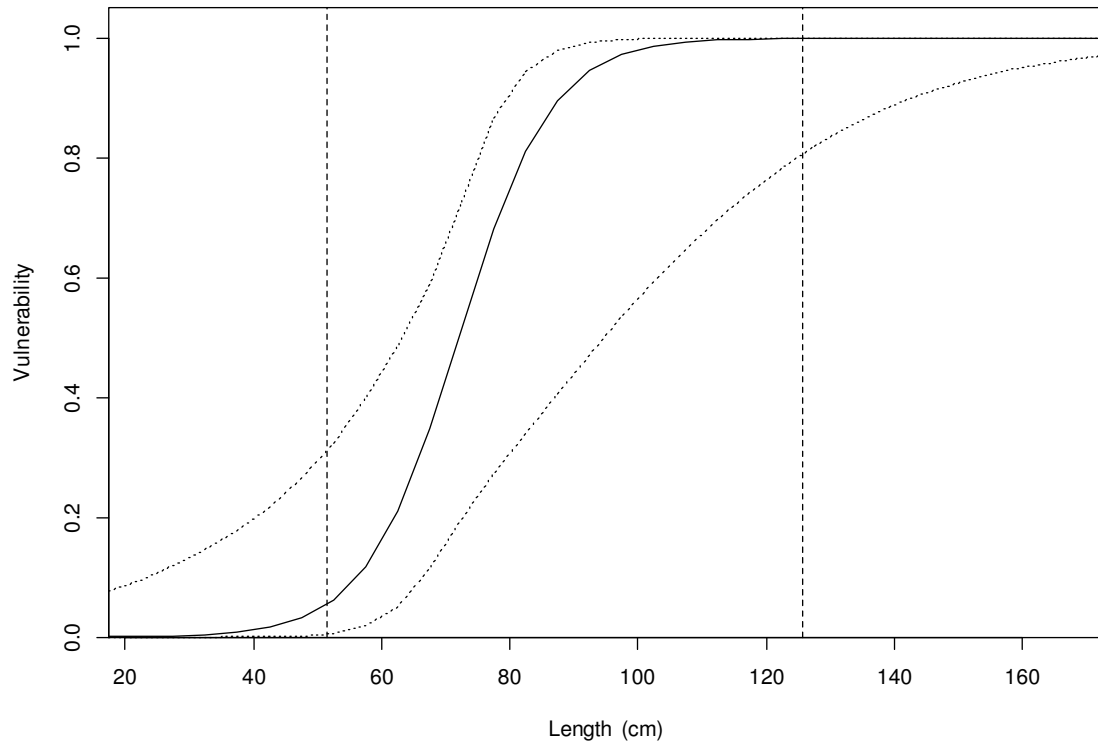


Figure 21: Vulnerability to gillnetting for each species of shark in the model. The solid curve is the substitute maximum-likelihood estimate from section 6.2.1, and the dotted curves are pointwise 95% confidence limits from all 10,000 simulations retained from Markov chain Monte Carlo. The vertical dashed lines are at  $L_0$  (birth length) and female  $L_\infty$  (average maximum length attained by old sharks) from Table 6. (Continued on next five pages)

### Creek whaler



### Hardnose shark

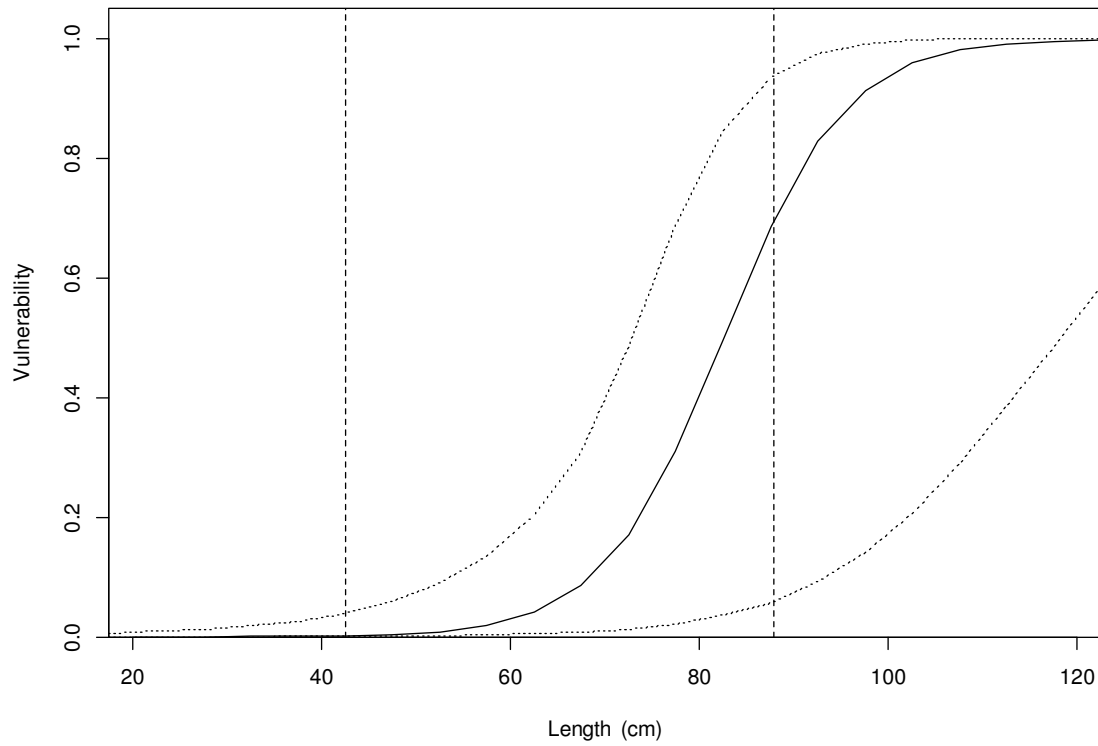
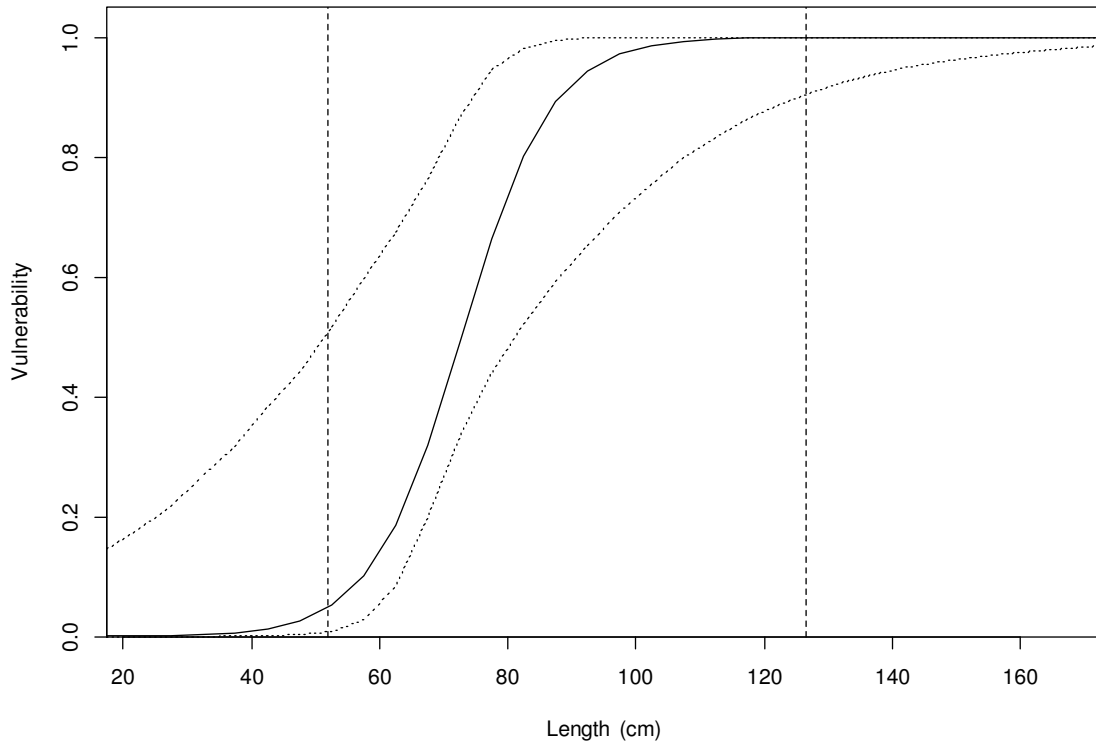
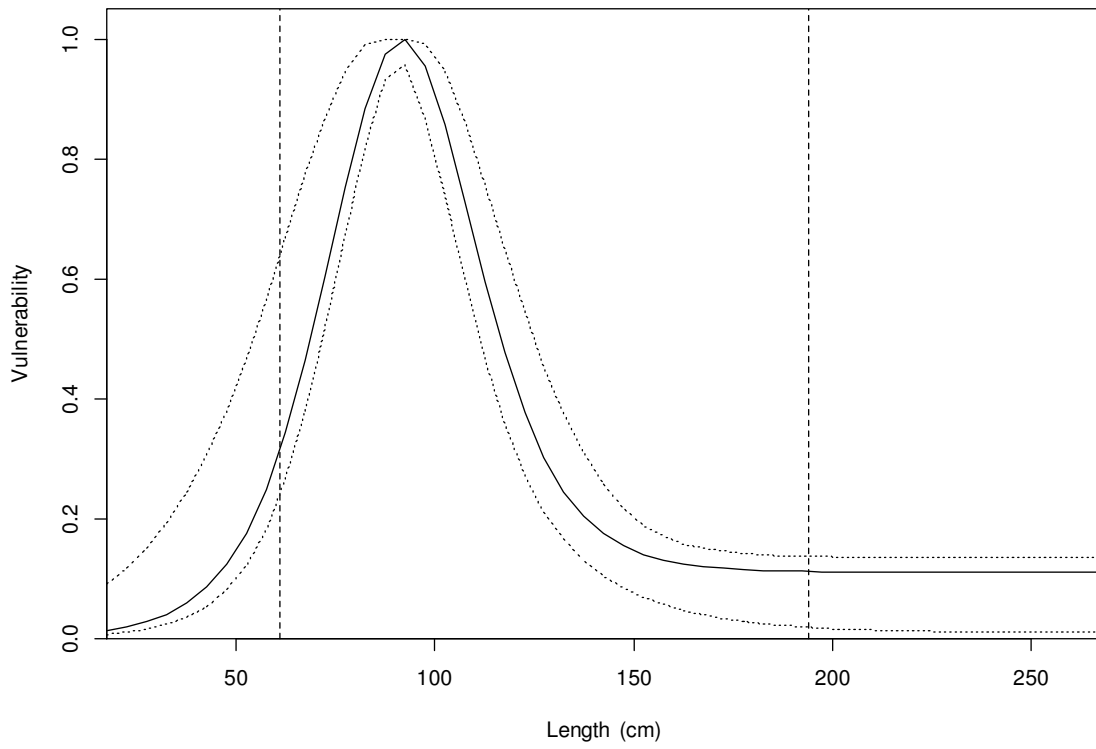


Figure 21, continued from previous page and on next four pages.

**Spot-tail shark**

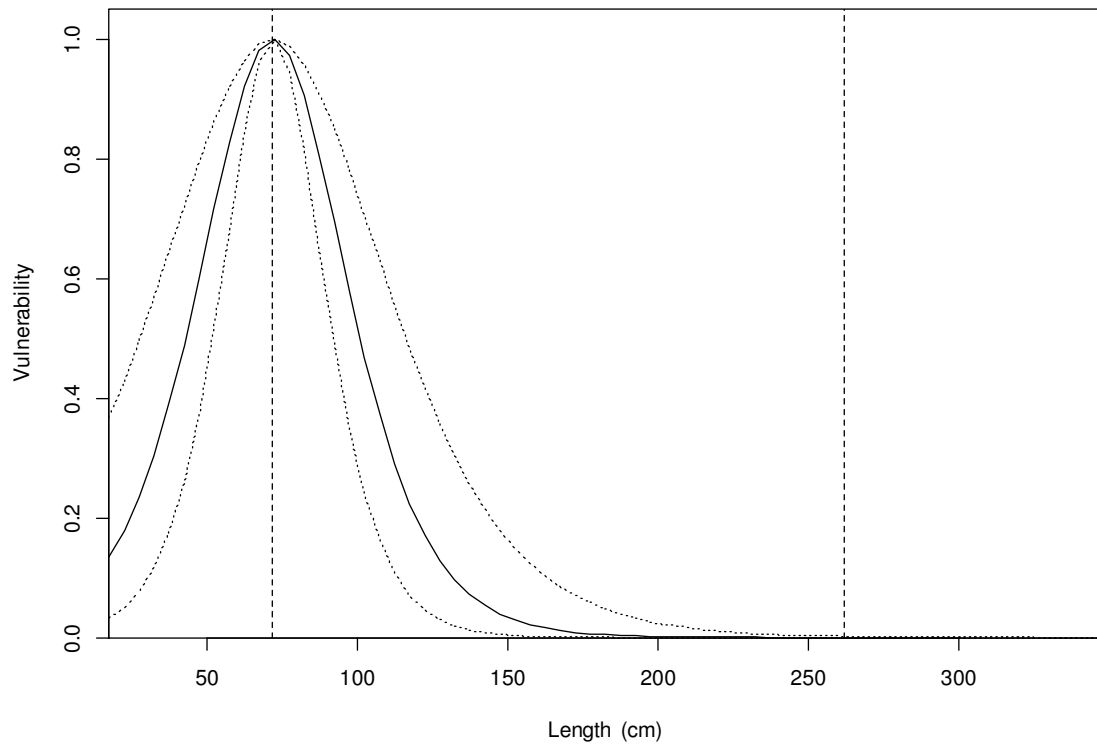


**Australian blacktip**



*Figure 21, continued from previous two pages and on next three pages.*

### Common blacktip



### Spinner shark

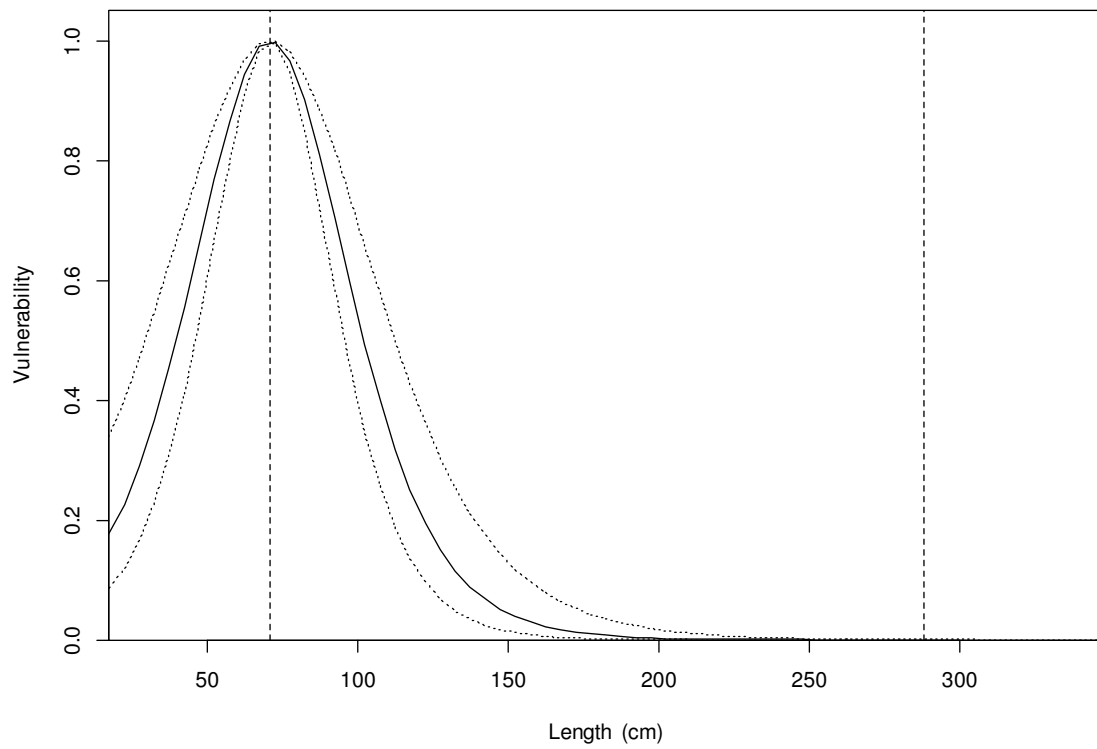
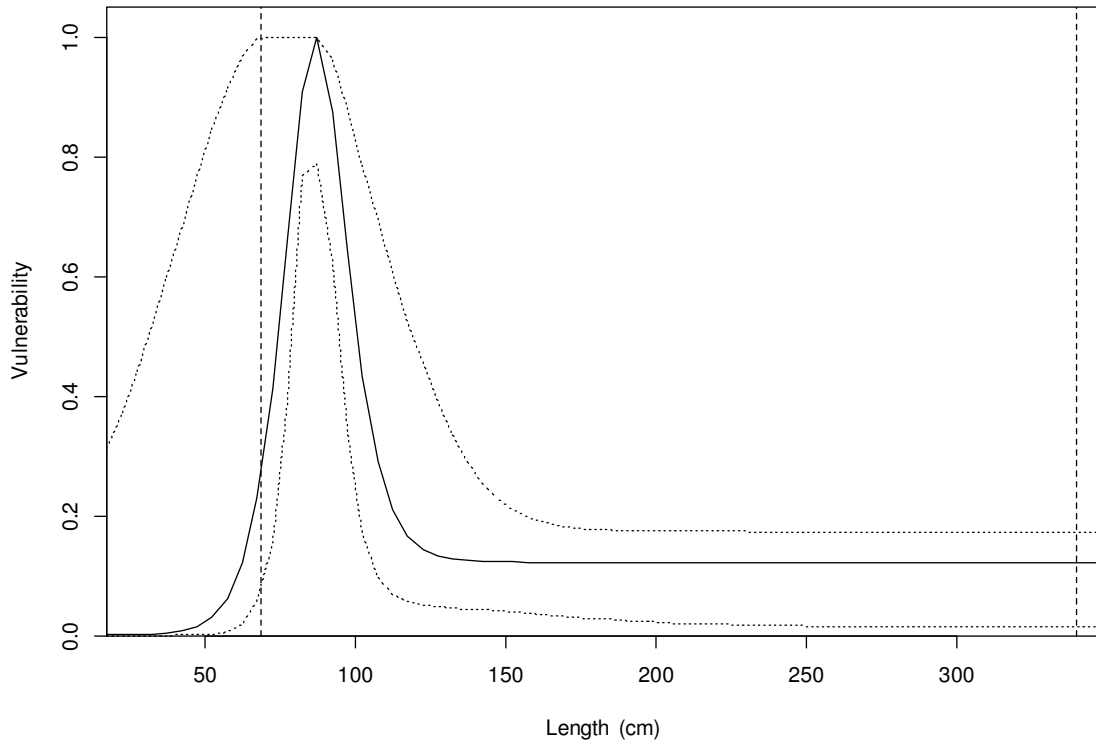


Figure 21, continued from previous three pages and on next two pages.

### Bull shark



### Winghead shark

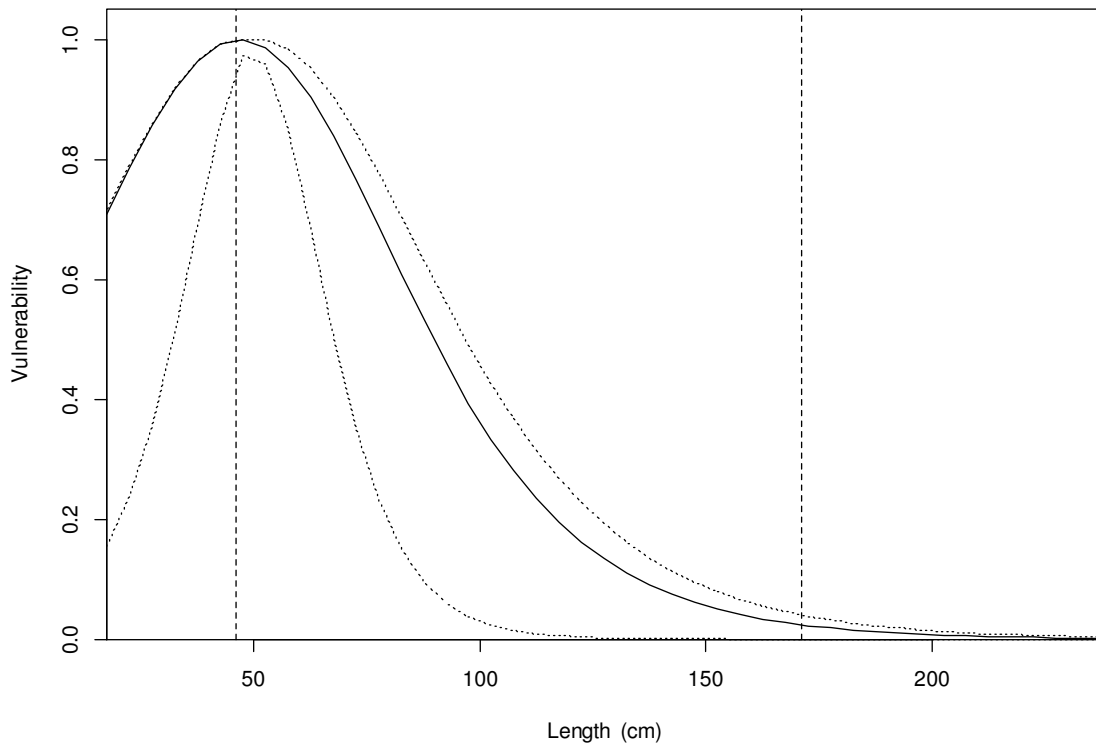
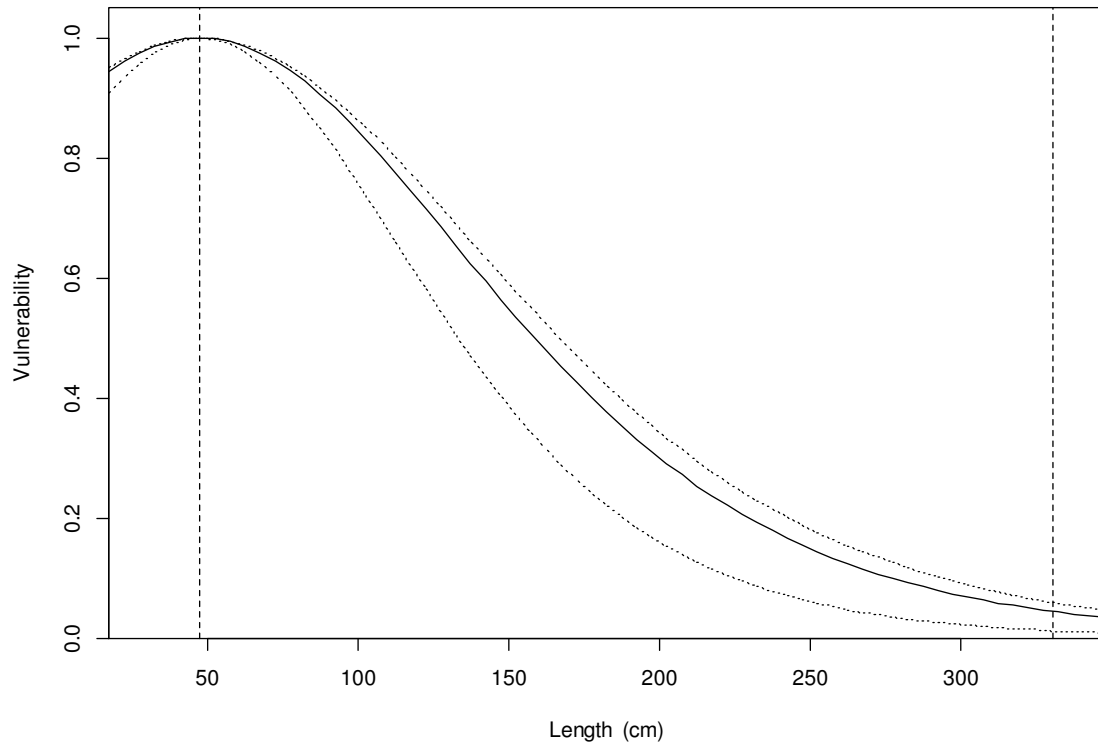


Figure 21, continued from previous four pages and on next page.

### Scalloped hammerhead



### Great hammerhead

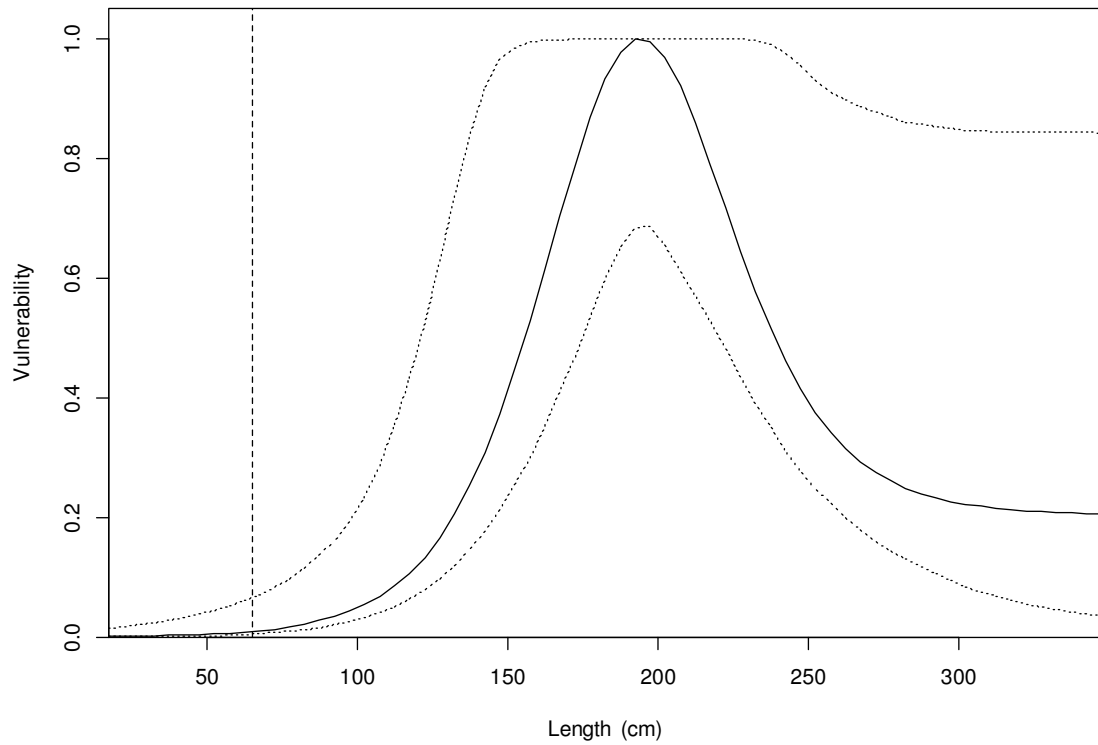


Figure 21, continued from previous five pages. The  $L_{\infty}$  value for the great hammerhead is 403 cm (Table 6) which is beyond the right-hand end of the graph.



## 6.4 Diagnostics

### 6.4.1 Serial plots of MCMC simulations

The Markov chain Monte Carlo (MCMC) performed by the ADMB software performed creditably in sampling the parameter space. Serial plots of the 10,000 retained values of total MSY and negative log-likelihood (NLL) are shown in Figures 22 and 23 respectively. They show no obvious trends and make frequent fluctuations into both high values and low values. In Figure 22 the total MSY descends below 2000 t on more than 30 clear separate occasions. In Figure 23, the NLL descends below  $-710$  on 14 clearly distinct occasions and below  $-705$  on more than 30 clear separate occasions.

Figures 24 and 25 respectively show serial plots of the vulnerability parameters  $L_{50}$  and  $L_{diff}$  (see Table 23, p. 75) for hardnose sharks, which were remarked upon as causing problems in section 6.3 above. Figure 24 shows many oscillations between 70 and 120 cm; 120 cm was the upper bound fixed for this parameter in model setup. There are a few excursions below 60 cm.

Figure 25 shows many oscillations of  $L_{diff}$  between about 10 cm and 40 cm, with a few fluctuations above 60 cm. One excursion hits the upper bound of 80 cm. Large values of this parameter cause problems by flattening out the vulnerability function in Figure 21, contributing to vulnerability levels well below 1 at the asymptotic length  $L_{\infty}$ . The MCMC methodology of ADMB still appears to have functioned as well as could be expected for this parameter.

### 6.4.2 Fits to species composition

Model fits to species composition data from the Fishery Observer Program are plotted in Figure 26. They show the data (bars), fits from the substitute maximum likelihood point from section 6.2.1 (solid lines) and 95% confidence limits (red dotted lines).

As remarked earlier in this report, the species composition data are only a snapshot collected over a short period of a few years (2006–2012). Therefore there is only a single species frequency to fit in each Subregion, not a time series.

The fits roughly follow the data but show a good deal of variation. The variation is caused by the constraint that the population size of a species has to be similar between neighbouring Subregions (section 5.7.5). In the absence of this constraint the model would fit the species composition data exactly, although the results would be highly inconsistent between regions.

It is important to note that these fits were made by number, as opposed to weight of a species. The difference between number and weight is greatest for the great hammerhead, of which relatively few were observed but they made a major contribution when measured by weight (Figure 11, page 34). Fitting by number correctly accounts for the uncertainty in the observed numbers, and assigns a high degree of error in the great hammerhead proportion irrespective of how much that species contributes by weight.

### 6.4.3 Fits to standardised catch rates

Model fits to the standardised catch rates from chapter 4 are plotted in Figure 27. They show the data (stars), fits from the substitute maximum likelihood point from section 6.2.1 (black solid line) and 95% confidence limits (red dotted lines).

The model found it impossible to accurately fit the changes in catch rates over time, as they were inconsistent between Subregions. Many of the Subregions showed upward trends in catch rates, which were impossible to fit. The fitted catch rates are therefore very close to constant. They have a slight downward slope for small simulated MSY values (see red dotted lines with a slight slope from top left to bottom right of each plot), but are almost horizontal for large simulated MSY values (the opposing red dotted lines).

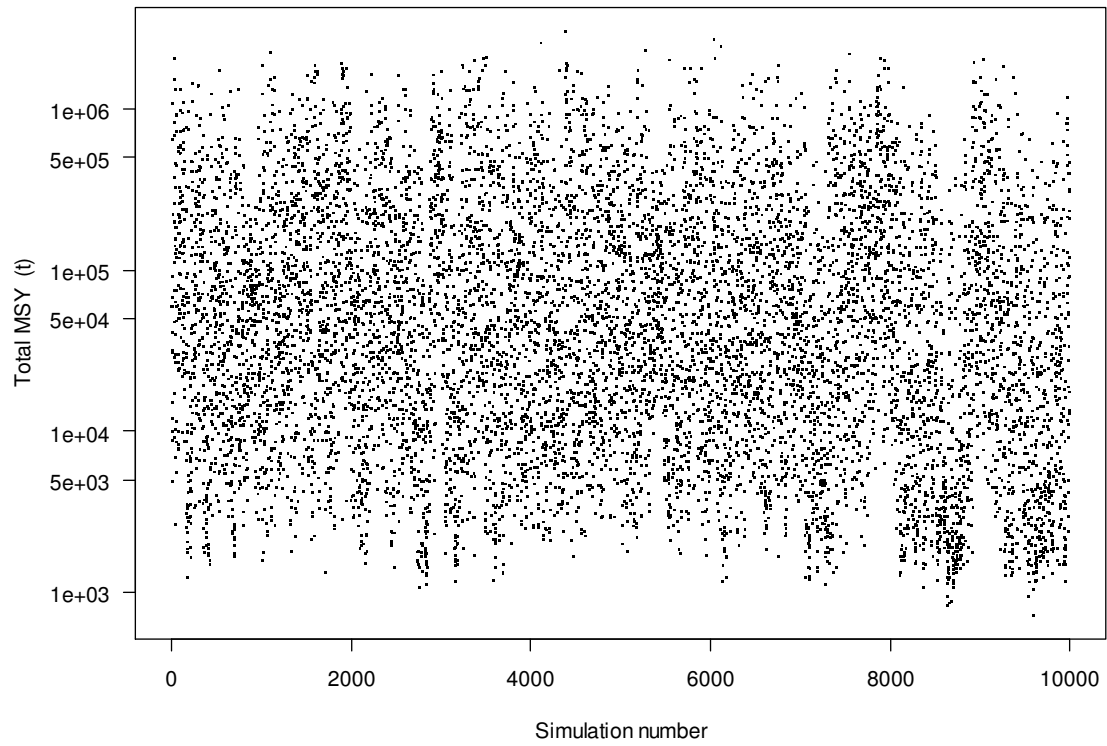


Figure 22: Serial plot of retained total-MSY values from the model's Markov chain Monte Carlo.

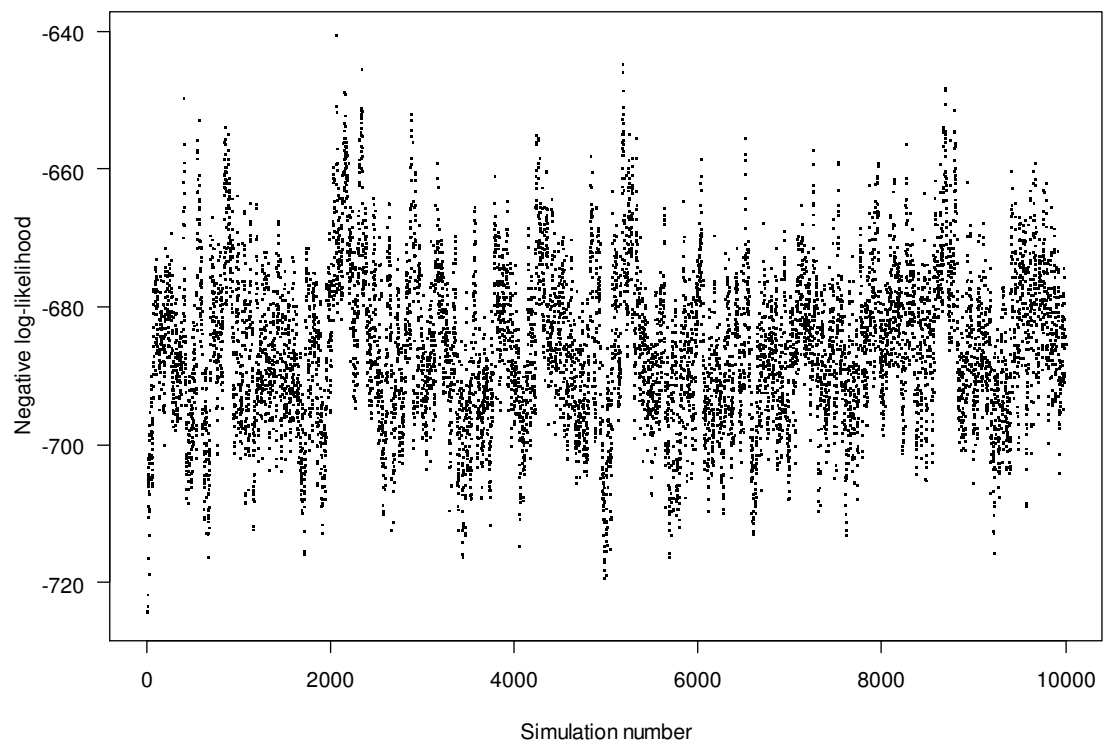


Figure 23: Serial plot of retained negative-log-likelihood values from the model's Markov chain Monte Carlo. The first few values (close to the maximum likelihood point,  $NLL = -755.9$ ) have been omitted so as not to compress the y-axis scale.

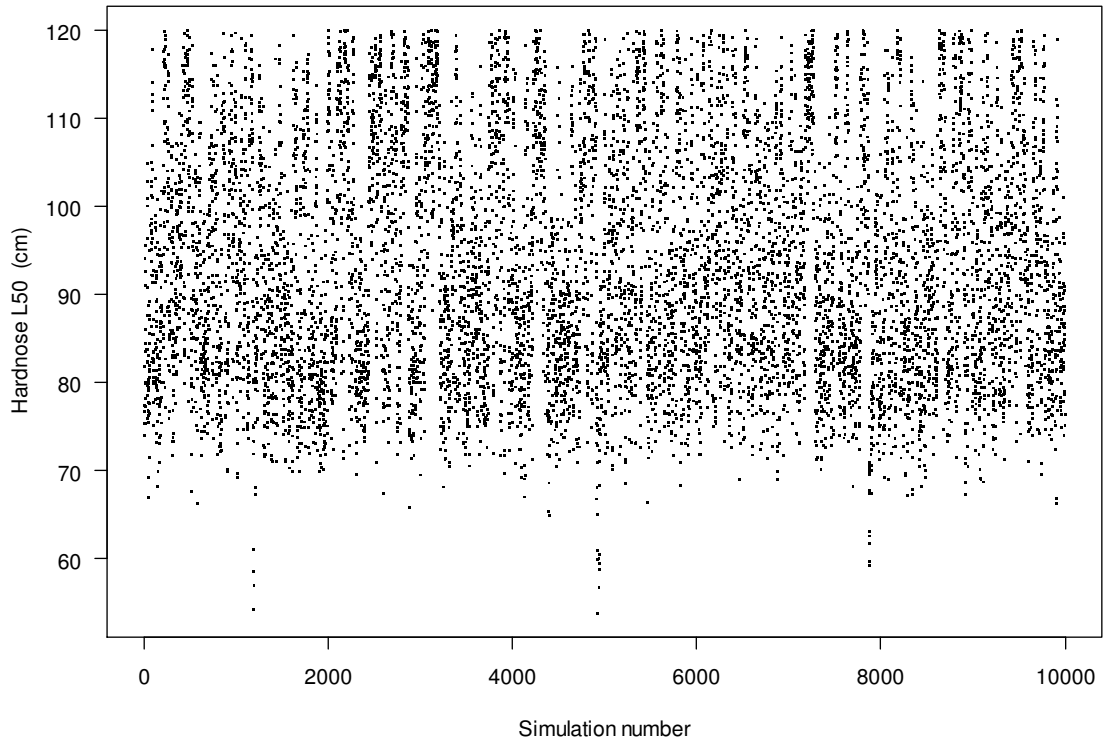


Figure 24: Serial plot of retained values of the L50 parameter for hardnose sharks from the model's Markov chain Monte Carlo.

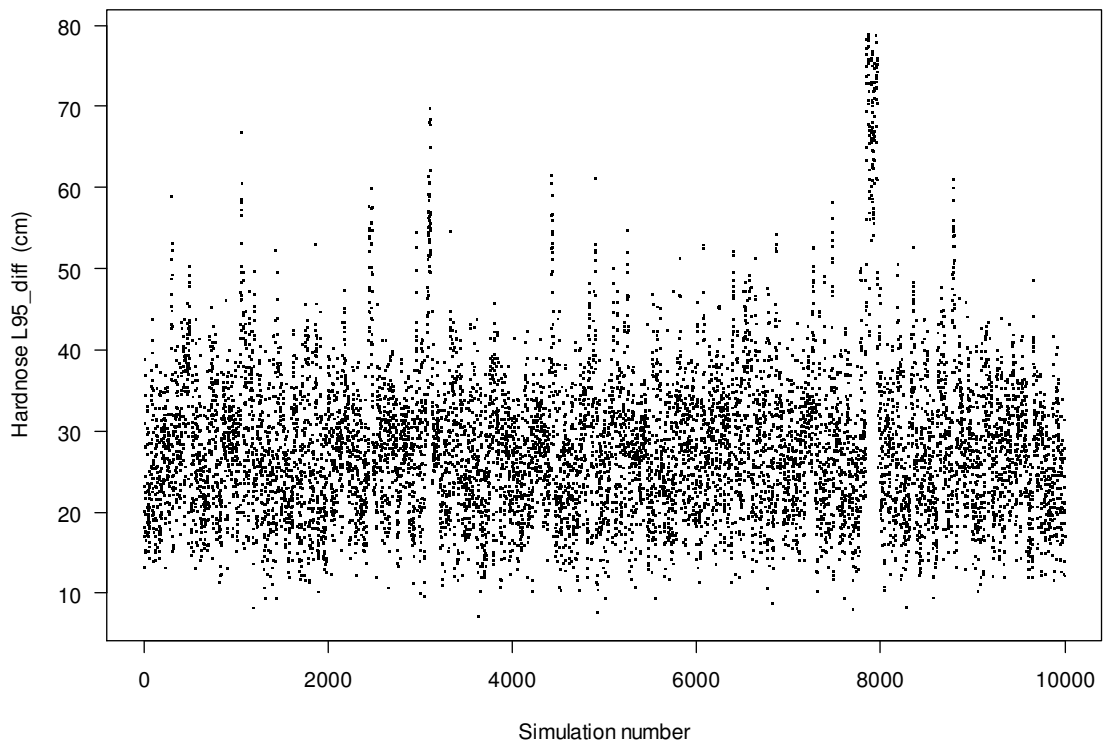


Figure 25: Serial plot of retained values of the L\_diff parameter for hardnose sharks from the model's Markov chain Monte Carlo.

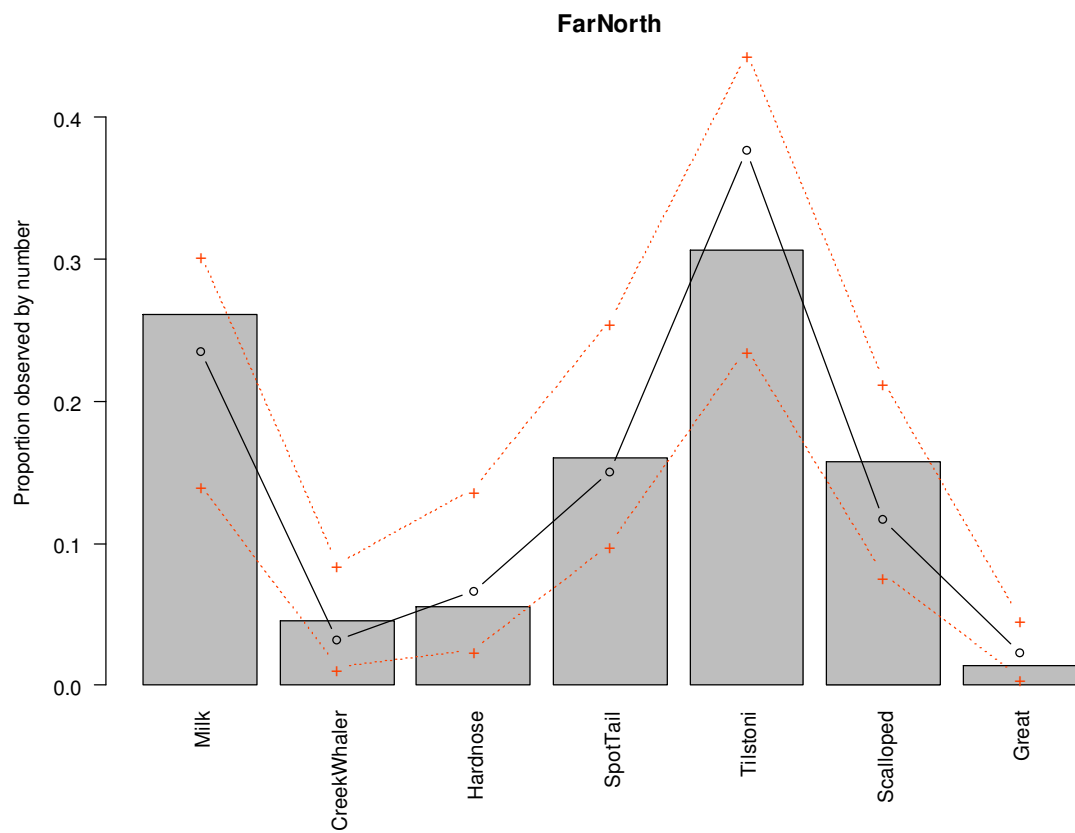
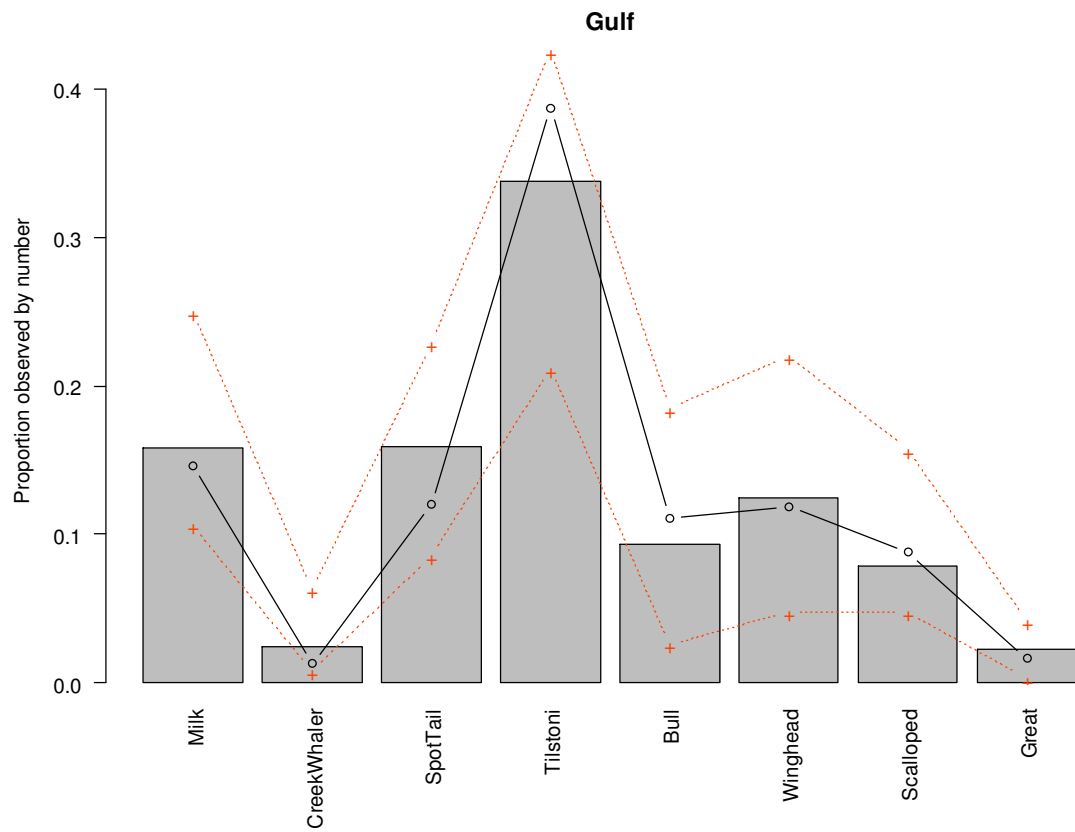


Figure 26: Fits to species composition data by number (as opposed to weight) from the Fishery Observer Program. The bars are the observed data. The solid line shows fits from the substitute maximum likelihood estimates (section 6.2.1), and the dotted lines are 95% confidence intervals from the 10,000 retained simulations. (Continued on next four pages)

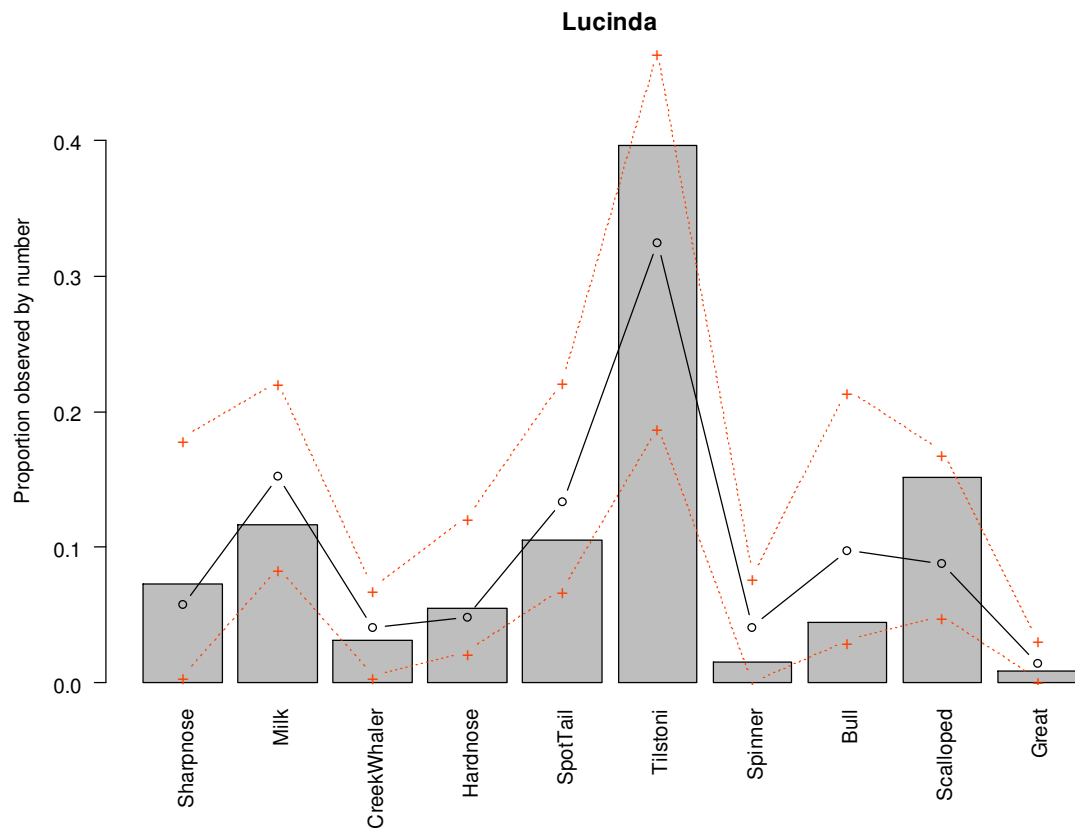


Figure 26, continued from previous page and on next three pages.

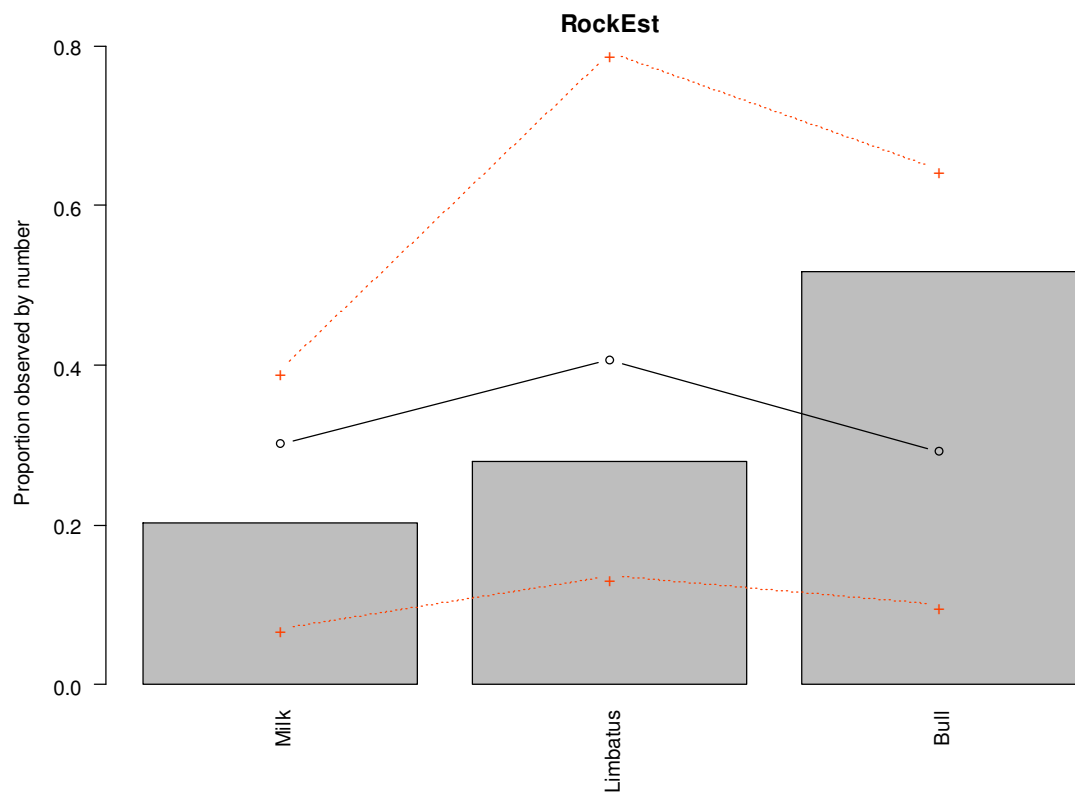
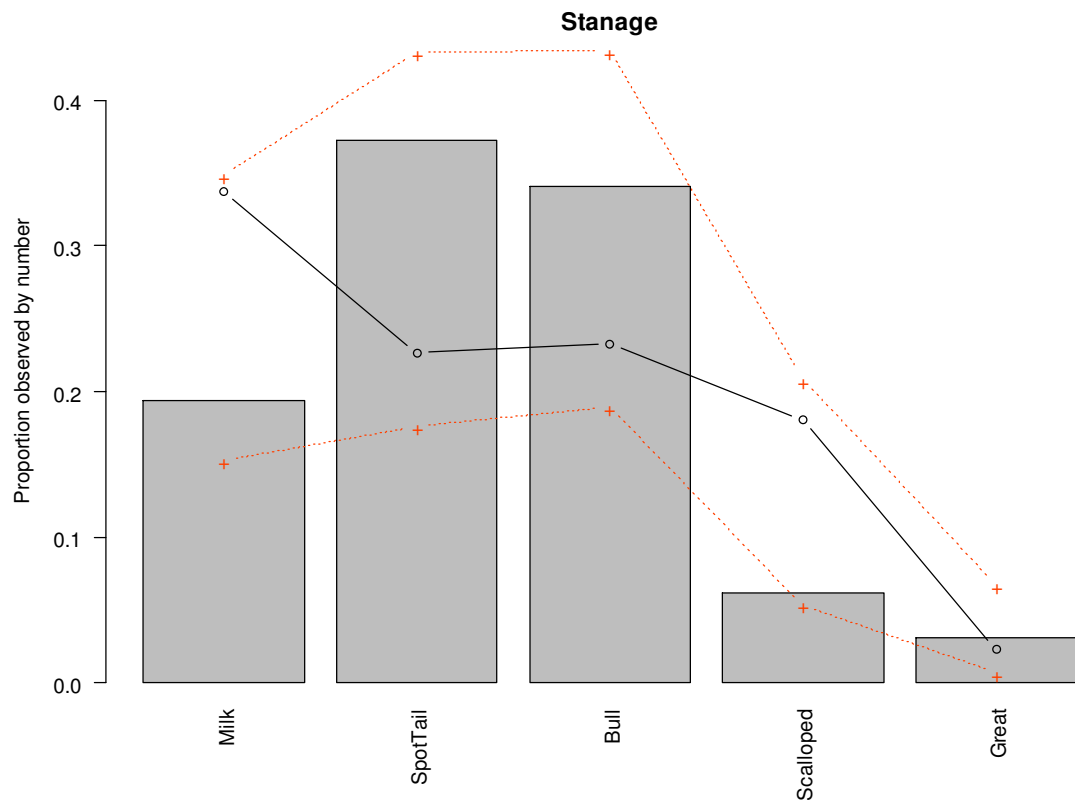


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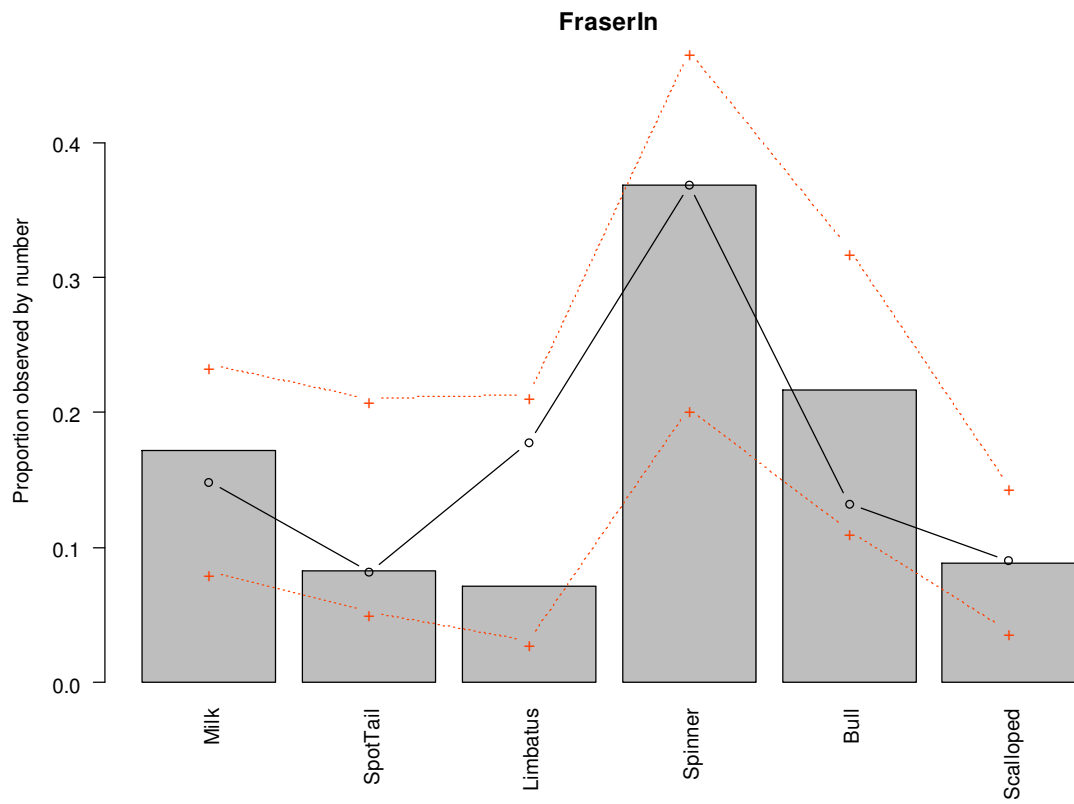
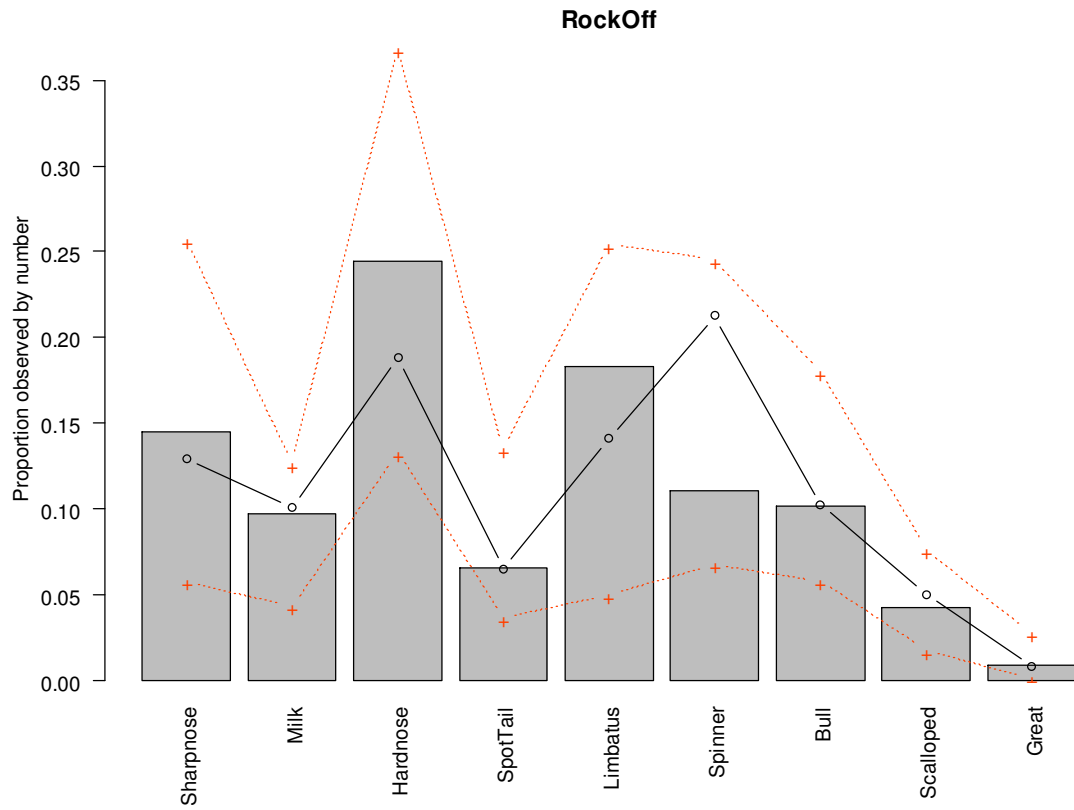


Figure 26, continued from previous three pages and on next page.

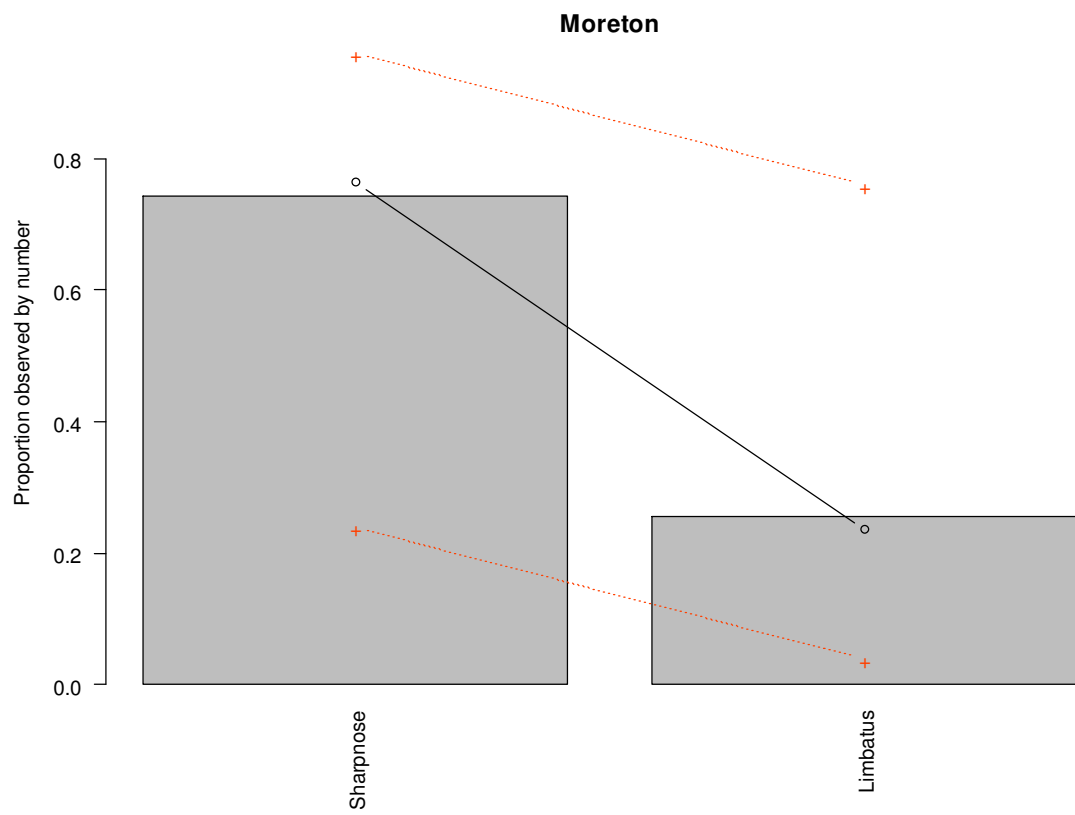
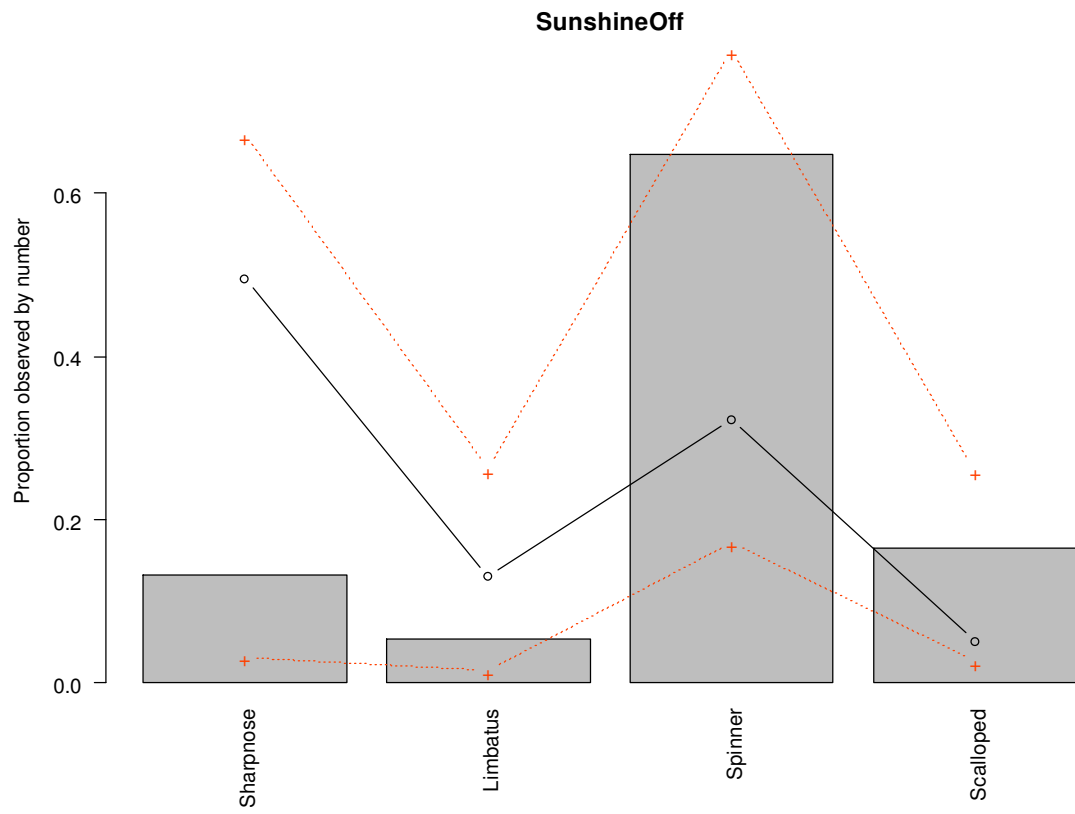


Figure 26, continued from previous four pages.



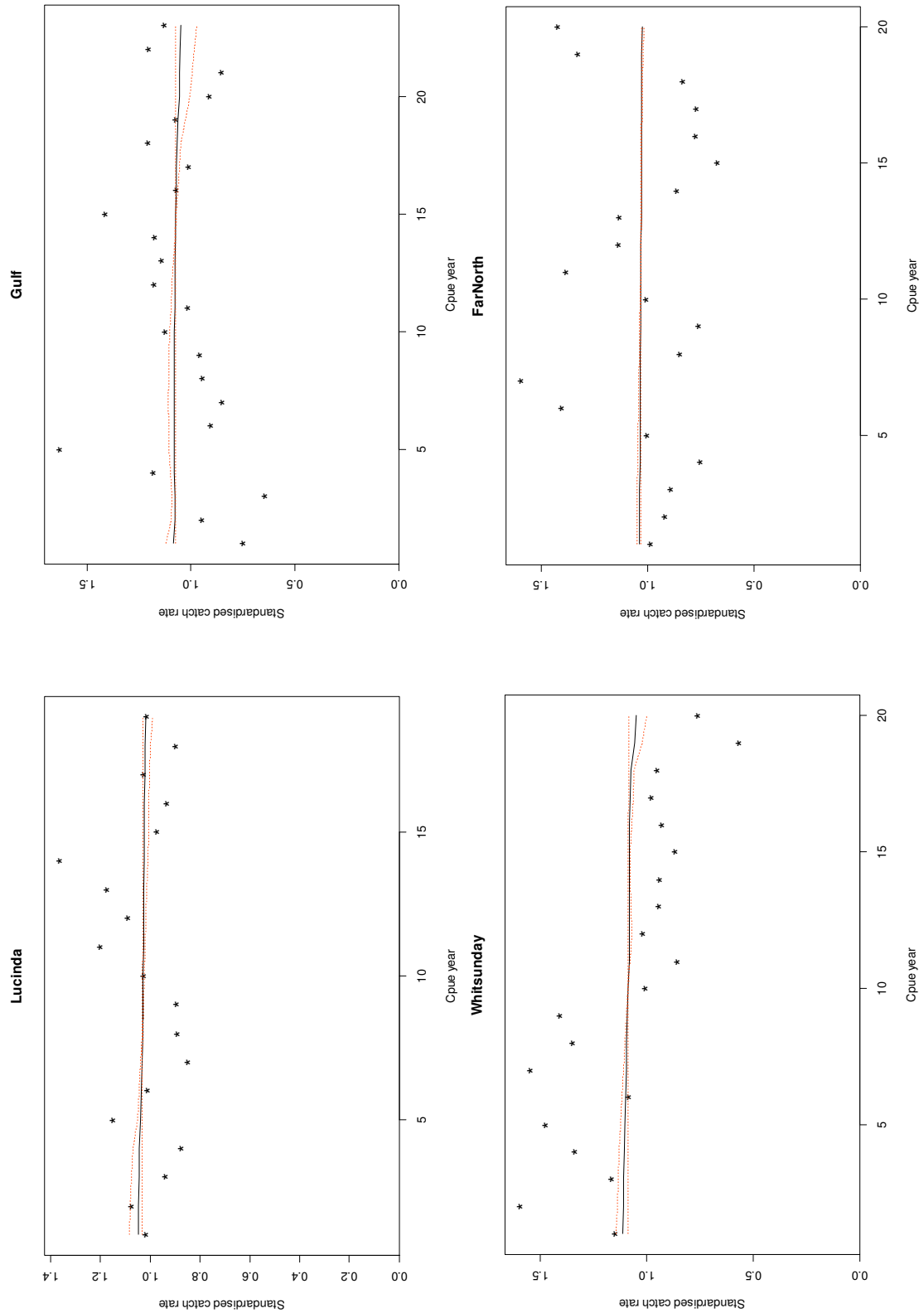


Figure 27: Model fits to standardised catch rates. The stars are the input data. The solid line is the substitute maximum likelihood fit from section 6.2.1, and the red dotted lines are 95% confidence limits from the 10,000 retained simulations. (Continued on next two pages)

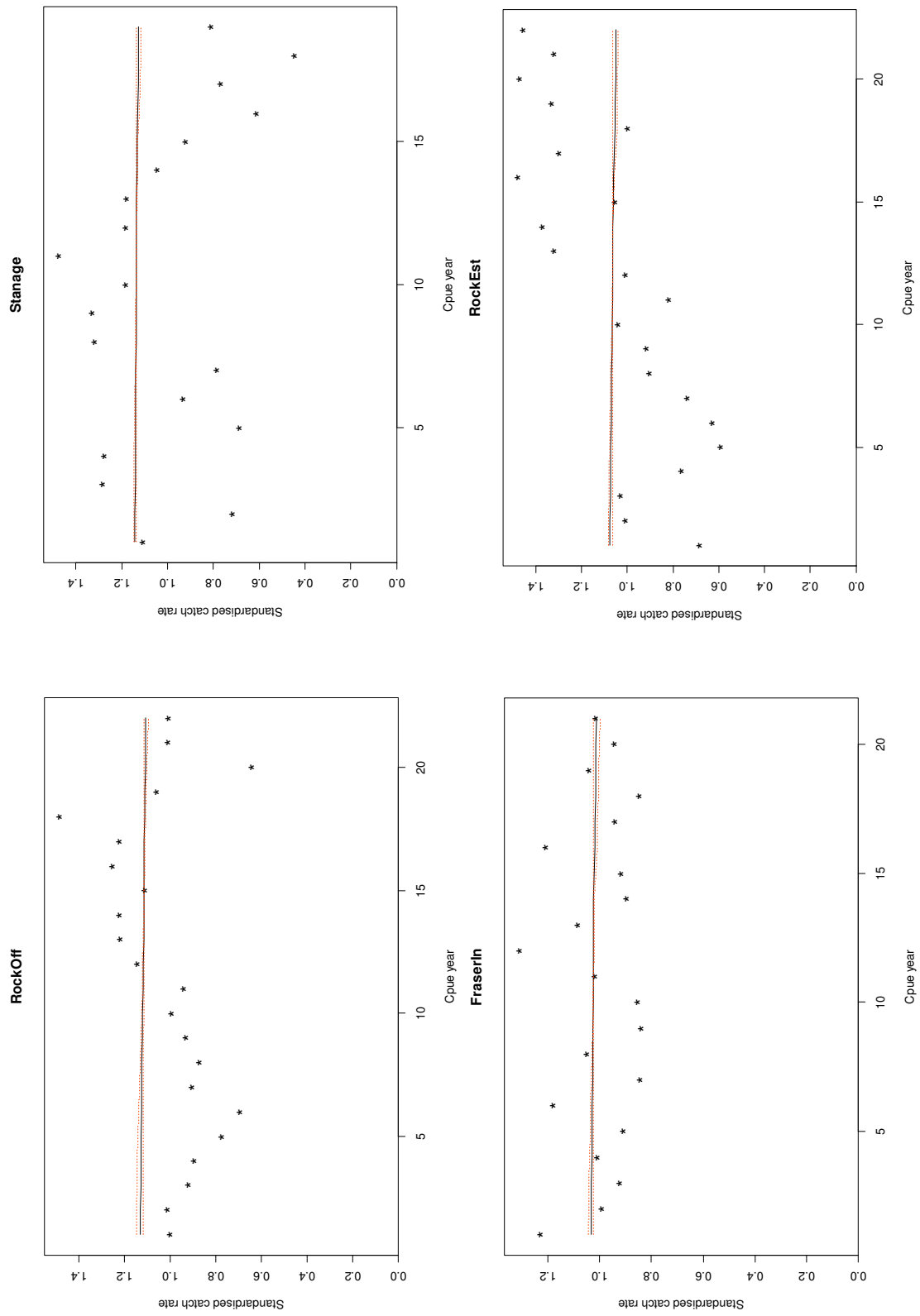


Figure 27, continued from previous page and on next page.

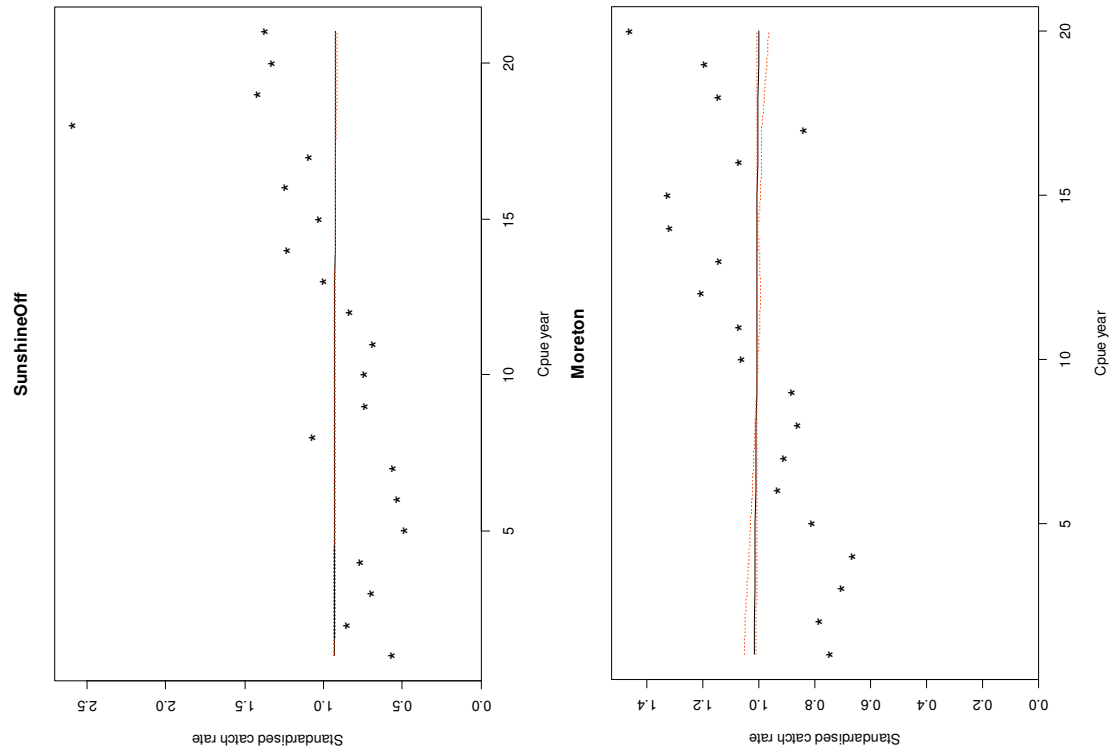


Figure 27, continued from previous two pages.

## 7. Discussion

### 7.1 Implications for fishery management

Model results indicate that the rate of fishing with the current total allowable commercial catch (TACC) of 600 t on the Queensland east coast is well below maximum sustainable yield (MSY), although the value of the latter is extremely uncertain and only lower limits for it are estimated with any precision. Current TACC and catch levels are considered sustainable. Maximum sustainable yield may well be greater than 4900 t for the whole of Queensland (the estimate discussed in section 6.2.1), and is almost certainly greater than 1273 t (the estimate discussed in section 6.2.2). For the east coast these figures equate to 3790 t and 1077 t respectively.

We note that the recent stock assessment of the Northern Territory shark fishery (Grubert *et al.* 2013) also estimated very high biomass ratios and concluded that there was almost no chance that that fishery was being overfished.

Any potential expansion of the Queensland shark fishery, however, should be considered with great care. Any shift in fishing technology or practices to fish for sharks in deeper water or further offshore, compared to how the gillnet fishery currently operates, would invalidate the assumptions of the assessment. The assessment has relied critically on data from the Fishery Observer Program and the assumption that this is typical of the fishery, including any fishers who were not willing to take observers onto their operations. The following major concerns relate to potential technological advance in the fishery:

- The larger whaler sharks (the common blacktip shark *Carcharhinus limbatus* and bigger) are currently fully vulnerable to fishing for only a fairly small part of their lives. Once they have grown through the period of vulnerability they become part of a largely unfished parental stock. This may no longer be the case if net fishing were to spread further offshore.
- Different species would be caught in deeper water; e.g., hound sharks (family Triakidae), carpet sharks (order Orectolobiformes), gulper sharks and dogfish (both in order Squaliformes). These species have not been assessed and may be more susceptible to overfishing than the species that have been assessed.
- Hammerhead sharks can withstand only a low level of fishing, partly because they are vulnerable to gillnet fishing over much of their lifespan, and they tend to migrate into deeper water as they mature. Advances in fishing technology may make them even more vulnerable to fishing than they currently are. Mature female scalloped hammerheads are currently not caught by the fishery. It would make a big difference to the population if they became vulnerable to fishing.

The way in which the shark fishery currently operates appears to function well for whaler sharks. The fishery targets only small individuals. The large, long-lived whaler sharks have some protection from fishing by being vulnerable only as juveniles, and these species can withstand quite high levels of fishing and still be fished at less than MSY (see last column of Table 25). Parental stocks of large whaler sharks are generally not vulnerable to net fishing in Queensland. This fishery strategy is the reverse of what is often stated as good fishery practice for bony fish, whereby individuals should be allowed to reproduce at least once before becoming vulnerable to retention by fishers. But for whaler sharks the current fishery appears to be protecting parental stocks of large whaler shark species from overfishing.

Small whaler sharks are vulnerable to fishing for most of their lives, and the assessment has shown that they actually may be more at risk of overfishing than the large whaler sharks. It should not be assumed that because they have shorter lifespans they are safe from overfishing.

Hammerhead sharks would be at risk of overfishing if the fishery were much larger, but they are not currently at risk. The above comments about large whaler sharks being largely safe from fishing do not apply to hammerheads, especially the great hammerhead.

It was possible to define regional catch rates of sharks only for all shark species combined, and these showed no consistent trends. Standardised catch rates in many of the Subregions in the model have trended upwards over the years of the commercial logbook system, especially in the southern Subregions. We are unable to explain these trends. They may be due at least partly to market forces, changes in targeting and better recording of harvests in logbooks.

Standardised catch rates in the Whitsunday and Stanage Subregions, which are adjacent and comprise the Bowen, Mackay and Stanage sampling regions for fishery monitoring, have shown downward trends. We are also unable to explain why these Subregions should trend downwards while neighbouring Subregions trend upwards.

The Whitsunday and Stanage Subregions should be monitored carefully over the next five to ten years to see whether shark catch rates continue to trend downwards there. This is especially important in view of the net-free zones that have been proposed for the Rockhampton Subregions (a 2015 Queensland election commitment). There is a risk that net-fishing effort may be displaced into the Whitsunday and Stanage Subregions.

## 7.2 Data limitations

The assessment has had to deal with some major data limitations that do not apply to many other fisheries:

- Species identification of sharks can be extremely difficult. This is especially true of whaler sharks and at juvenile stages of their life history.
- The Fishery Observer Program, while extremely valuable for species composition and length frequency data, ran for only a relatively short period (2006–2012 inclusive). Observer data back to the beginning of the commercial logbook system would have been very beneficial, but were not available. Also the assessment results would have been subject to slightly less random error if the observer coverage had more closely followed the spatial distribution of fishing effort (see Figures 9 and 10, page 33).
- Some sharks are caught and discarded by fishing operations that are not allowed to retain sharks. These catches are not recorded in logbooks. As a consequence, some species may experience additional fishing mortality that has not been taken into consideration in this assessment.

One data limitation which also occurs in other Queensland fisheries was the recording of fishing effort. Variables such as net depth and water depth were not recorded in logbooks. Also, formal gear or technology surveys, as conducted for the Queensland trawl fishery (see, e.g., O'Neill and Leigh 2007; Braccini *et al.* 2012a), have not been carried out on Queensland's net fisheries: therefore it is unclear to what extent the standardised catch rates derived in Chapter 4 may have been affected by technological improvements. Anecdotal evidence is that usage of deeper nets and power-assisted net reels has increased in recent years, but the extent and catch-rate impact of these changes are unknown (Dr Andrew Tobin, Project Team member, personal communication, 2015).

In the absence of greatly improved data collection programs, this fishery is likely to continue to suffer from lack of data, especially on species identification and discards. It should therefore be managed conservatively. Age distributions, which are very useful in the assessment of bony fish, are problematic for shark populations which may be segregated by age or sex, and because sharks commonly have dome-shaped vulnerability to capture whereby large individuals have much lower probability of capture than smaller individuals. Sharks can be accurately aged from rings in their vertebrae, but representative sampling of a wide range of age classes is not considered achievable for most shark species.

It is also important to note that it may not be suitable to fish shark populations at or near MSY limits due to the broader life-history constraints associated with shark species including reproductive constraints (see equation (2.3), p. 42, compared to equation (2.2) which applies to most bony fish). The margin between MSY-fishing and the population being unable to

reproduce itself is smaller for sharks than for most bony fish, and it is difficult for shark populations to recover if they are overfished.

### 7.3 Potential improvements to the assessment methodology

This section notes some points for consideration next time sharks are assessed in Queensland.

#### 7.3.1 *Potential improvements to the population dynamic model*

It was a major development to write the population model that could analyse all shark species simultaneously, cope with very limited data inputs (mainly catch rates that were not species-specific and which showed inconsistent trends), and could use the Fishery Observer Program data to best effect. There is, however, always room for improvement, and we suggest the following points to be considered when sharks are revisited:

- Relax the condition tying population densities together for shark populations of the same species in adjacent Subregions. The assessment imposed a minimum coefficient of variation (CV) of about 0.1 on the population densities, which allowed the model to choose its own CVs. Possibly, however, a setting of around 0.5 or even 1.0 would better fit the difference in catch-rate trends between the Subregions.
- Include recruitment deviations as model parameters in order to better fit catch rates. The model could fit positive recruitment deviations when catch rates are increasing and negative ones when they are decreasing. We deliberately excluded recruitment deviations from the model in order to reduce the total number of parameters, bearing in mind that the fishery was data poor. There may be merit in including them but the model would need one recruitment deviation per Subregion per year, which would add about 200 extra parameters to the model. Even then the recruitment deviations would not be species-specific: they would have to be viewed as, for example, an index of food supply for shark pups which would be common to all shark species.
- Consider reparameterising the logistic vulnerability function using parameters  $L_{05}$  and  $L_{95}$ , the lengths at 5% and 95% vulnerability to fishing. This would allow sensible bounds to be placed on the parameters, e.g.,  $L_{05} \geq L_0$  (the birth length) and  $L_{95} \leq L_\infty$  (the average length to which an old shark will grow). The current parameters are  $L_{50}$  and  $L_{95} - L_{50}$ , which are less amenable to these constraints. This reparameterisation would avoid the problem the assessment had with hardnose sharks, which were only 70% vulnerable at  $L_\infty$  (see section 6.3), although for this species the  $L_\infty$  value may need to be revised or the observer data may need to be corrected.
- Revise the use of the plus group, whereby sharks beyond the nominal maximum age don't die but stay in the same age class (albeit discounted for natural and fishing mortality). There is a strong case with sharks that the maximum age to which a species can live is likely to be quite a lot older than the oldest aged individual (section 2.2, Table 12, p. 43). The plus group as currently implemented, however, may go too far, especially for sharks with low natural mortality rates such as hammerheads: a plus group can result in a large bank of very old breeding animals that nobody has ever seen. A compromise involving some form of senescence (higher natural mortality rates for old sharks) may be in order.
- Include a time lag of one year between mating and recruitment in order to account for gestation. Natural mortality or fishing mortality of the mother could occur in this time, in which case the pups would not survive to recruitment.

#### 7.3.2 *Other potential improvements*

The following changes could be considered in order to improve the inputs to the population dynamic model:

- Consider including a fishing power term to stop the standardised catch rates from trending upwards. Then the catch rate time series that are currently showing no trend would become downward trending. There is, however, no strong evidence for a

significant change in fishing power in this fishery, so it may not be wise to include this term. There have been some advances in technology, e.g., increased usage of automatic reels to wind in nets.

- Revise the demographics for great hammerhead; currently  $M_{\text{juv}}/M_{\text{prod}}$  is only slightly less than 1 (Table 14, p. 45), which may be unrealistic. The comments above about the plus group in the population dynamic model are also relevant to the demographic analysis.
- Retrieve logbook data for all species caught in the gillnet fishery, not only sharks and grey mackerel. These data may help with analysis of catch rates and discard rates.
- Include recreational catch.
- Undertake a more thorough check of available tagging data and how the mortality rates from tagging experiments agree with those from demographic analysis.
- Consider an ecosystem model that may estimate the magnitude of trophic cascade effects of shark interactions with fisheries.

## **7.4 Potential improvements to input data for the assessment**

The points mentioned above focus on methodology and would offer minor improvement to future assessments, but by far the most desirable and valuable improvements would be in the quality of the input data. The following list describes some potential data sources that would be beneficial and that it might be possible to generate in future if resources are available:

- A survey of gear and technology in the inshore net fisheries, similar to those documented by O'Neill and Leigh (2007) and Braccini et al. (2012a) for the Queensland trawl fishery: such a survey would record changes in how fishing has been carried out since the 1970s. It would allow modelling of changes to fishing power over the years and hence would help to produce more accurate time series of catch rates.
- Some means of expert species identification of future commercial harvests: we do not believe it to be feasible to expect fishers to be able to identify the species of sharks (especially whalers) that they catch.
- Some means of recording the level and species composition of sharks that are caught by commercial fishers but then discarded.
- Accurate records of net length in commercial logbooks, to ensure that fishers record the length of net that they actually use, not the maximum length that they are allowed to use.
- Records of net depth and water depth in commercial logbooks for the inshore net fisheries.

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# Appendix 1 Shark Control Program data

## A1.1 Overview

The Shark Control Program (SCP) protecting popular east coast bathing beaches provided an additional potential data source for the assessment, but on the advice of the assessment's Project Team this was not used in the assessment. Data were available from the beginning of the SCP in 1962, twenty-six years before the commercial fishing logbook database began.

A major feature of these data was a long (roughly 15-year) initial period of depletion of local shark populations after shark control gear was introduced, before catch rates stabilised.

In common with the commercial fishery logbook data, the SCP data also suffered from lack of reliable species identification, as the shark control operators had similar difficulties to commercial fishers in identifying shark species. The only usable shark categories were very broad: whaler shark, tiger shark, hammerhead and white shark.

Other than the depletion effect, consistent trends that could be used as abundance indicators were not found in the SCP data. The Project Team for the assessment advised us not use the SCP data to generate inputs to the population model.

This chapter describes the SCP data and undertakes some exploratory analysis of it, but it was not used in the model. The analysis was carried out principally by Dr Peter Baxter of the Centre for Applications in Natural Resource Mathematics (CARM), University of Queensland.

Even if catch rates from the SCP data are not considered useful as abundance time series, future analysis could include some alternatives:

- The depletion effect could be useful for estimating the initial population density of sharks (per kilometre of beach) prior to the introduction of the gear. In historical instances when gear has been introduced to a beach, catch rates were initially high and then fell, even if there was pre-existing gear on another beach some kilometres away. An analysis of how close the pre-existing gear had to be to inhibit the depletion effect of new gear could provide an estimate of the effective beach length over which the new gear applies. Then the number of sharks caught during the depletion period could provide an estimator of the initial population density of sharks per kilometre of beach.
- After the end of the depletion period, the ongoing catch rate from the SCP could be assumed to be sustainable indefinitely, and hence could provide a measure of the reproductive productivity of the local shark population.
- Historical trends in the ratio of the catch rate of whaler sharks to the catch rate of tiger sharks could help to gauge the effect of fishing on whaler sharks. Tiger sharks are subject to only a very low level of fishing, whereas whaler sharks have much higher vulnerability to fishing. A separate analysis should be done for each gear type, as whaler and tiger sharks will have different vulnerability levels to the gear types.

Time constraints did not permit us to pursue these avenues, but they may be beneficial to a future stock assessment when sharks are revisited.

A more detailed description of some aspects of the SCP has been provided in section 1.5, page 37.

## A1.2 Catches and catch rates in the Shark Control Program

Figure 28 plots the annual catches (numbers of all taxa combined) by gear type, and clearly shows the gradual switchover of preferred gear type from nets to drum lines with the aim of reducing bycatch. This switchover is one of many confounding factors that affect catch-rate

time series from the SCP data. The “Other” gear type in Figure 28 merely denotes unrecorded gear type, and is still either net or drum line in each instance.

The spatial coverage of the SCP data is shown in Figure 29. There is a wide range of latitude, from Cairns in the north to the Gold Coast in the south. The Gulf of Carpentaria and the east coast north of Cairns are not covered. SCP gear tends to be installed near human population centres.

Catch rates from the SCP data for all taxa are plotted in Figure 30. They generally decrease over time in most of the regions, due mainly to a combination of local depletion effects at bathing beaches and numerous gear adjustments to reduce bycatch.

The breakdown of the catch by taxon is shown in Figure 31. This figure shows the major shark categories of unidentified whaler, tiger shark and unidentified hammerhead. The categories for miscellaneous whaler (which comprises various reported whaler species), miscellaneous blacktip whaler and individual whaler species are not reliable and should be aggregated with the unidentified whaler category for analysis (W. D. Sumpton, personal communication, 2014). As discussed many times through this report, whaler species are very difficult to identify and a shark with black tips to its fins is not necessarily a blacktip shark. Tiger sharks are caught mainly on drum lines, while hammerheads are caught mainly in nets. Whalers are caught by both gear types.

The major bycatch taxa from Figure 31 are benthic rays, turtles, pelagic rays, sawfish (a type of ray), dolphins and dugongs. Many adjustments have been made over the years to minimise these catches while still allowing the gear to catch dangerous sharks.

The seasonality of shark catches in SCP gear is illustrated in Figure 32. Sharks are more active and hence more likely to be caught when the water is warm in summer. Also many sharks move inshore to give birth in the spring. Together these factors result in higher catch rates during spring and summer.

Catches and catch rates of sharks are plotted in Figure 33. These are raw, unstandardised catch rates. The catch rates fall over the years in most regions, as was the case for all taxa combined. Again this is mainly due to a combination of local depletion and gear adjustments intended to reduce bycatch. These two effects would have to be accounted for before the data could be used to provide catch rates that are genuine indicators of abundance over wide regions.

Figure 34 compares annual catches of tiger and whaler sharks by gear type. It confirms the effect seen in Figure 31 that tiger sharks are caught mainly by drum lines and whaler sharks by both drum lines and nets.

Depletion of local populations of animals caught in SCP nets is shown in Figure 35. The number of animals caught begins at a high level, even though the effort is low. From a start in the early 1960s, the catch falls until the late 1980s, and has remained roughly steady since then, albeit with large fluctuations. It should be noted that the drop in the final year in Figures 34 and 35 is mainly due to incomplete data for those years.

Figures 36–39 show catch sizes and catch rates of whaler sharks, tiger sharks, hammerhead sharks and benthic (bottom-dwelling) species by region. The most notable effect is the depletion effect over a period of 15–20 years after gear is first introduced to a region. This would have to be dealt with before any analysis could be conducted of catch rates as indicators of abundance.

Figure 39 was intended as a guide to when nets changed from being bottom-set (anchored to the sea bottom) to being top-set (suspended from floats that were anchored to stop them moving). It is possible that they show some such effect in the late 1970s, but it is not very clear. Larger numbers of benthic species than expected were caught by drum lines in regions from Cairns to Bundaberg, especially the Townsville region. Checks of the data for the

Townsville region concluded that this was apparently a real effect caused by the drum-line hooks lying on the sea bottom at low tide.

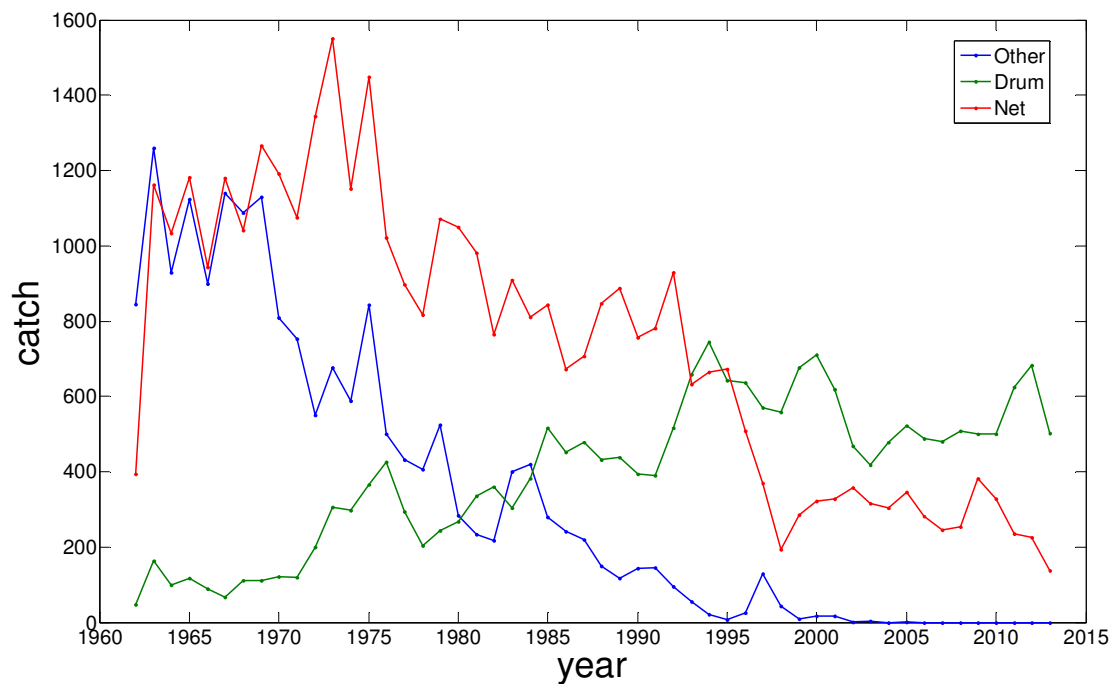


Figure 28: Shark Control Program catches of all taxa by gear type, showing the rise in use of drum lines and fall in use of nets over the years. These are the only two gear types: the “Other” gear type merely signifies that the gear type was not recorded. Catch is measured in number of animals caught per year.

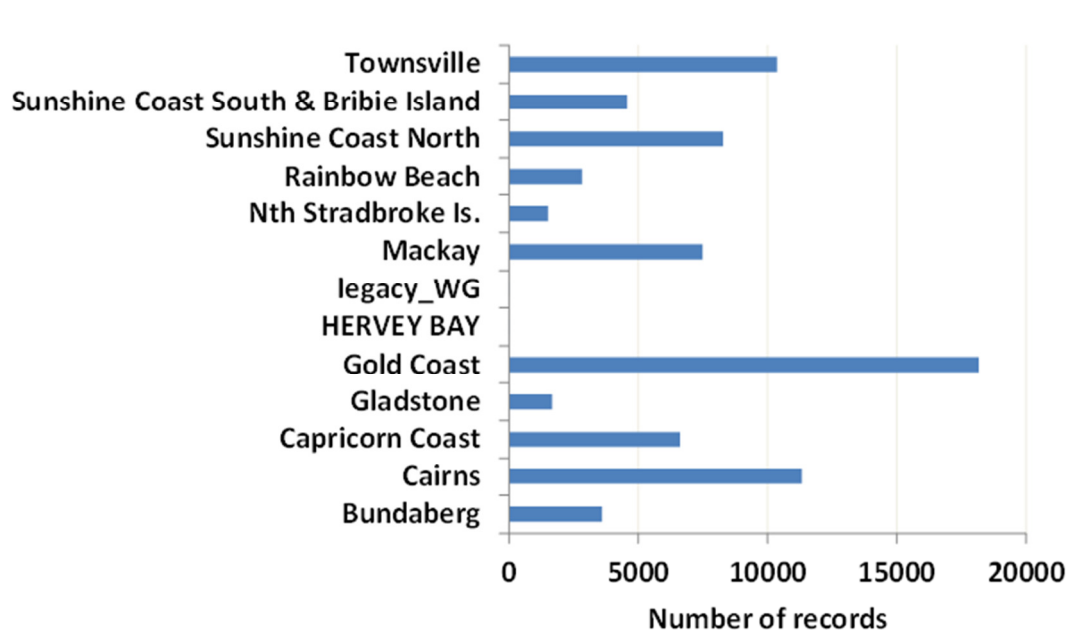


Figure 29: Spatial coverage of the SCP, showing that it concentrates on beaches close to human population centres on the east coast of Queensland, but has a good spread from north to south.



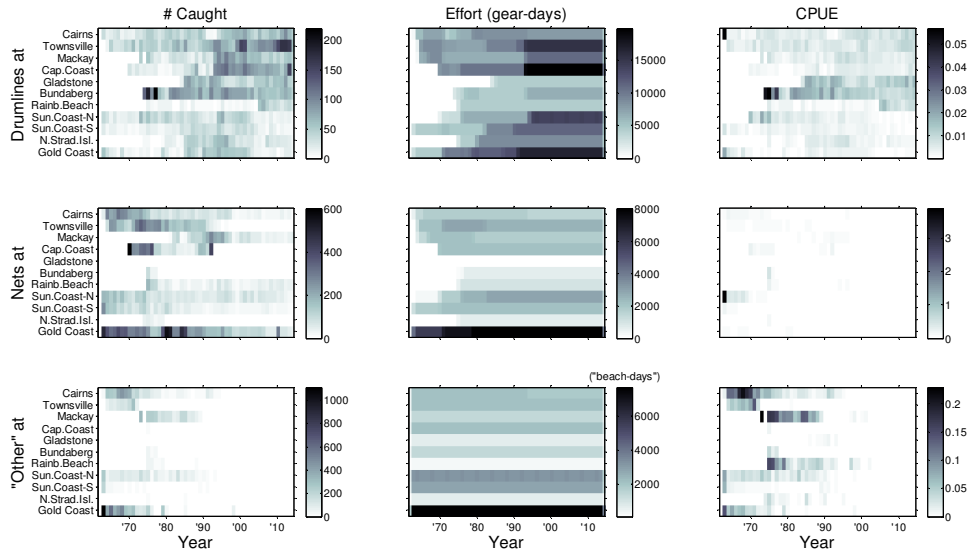


Figure 30: Catch, effort and catch per unit effort (CPUE) by gear type and region for all taxa caught by the SCP.

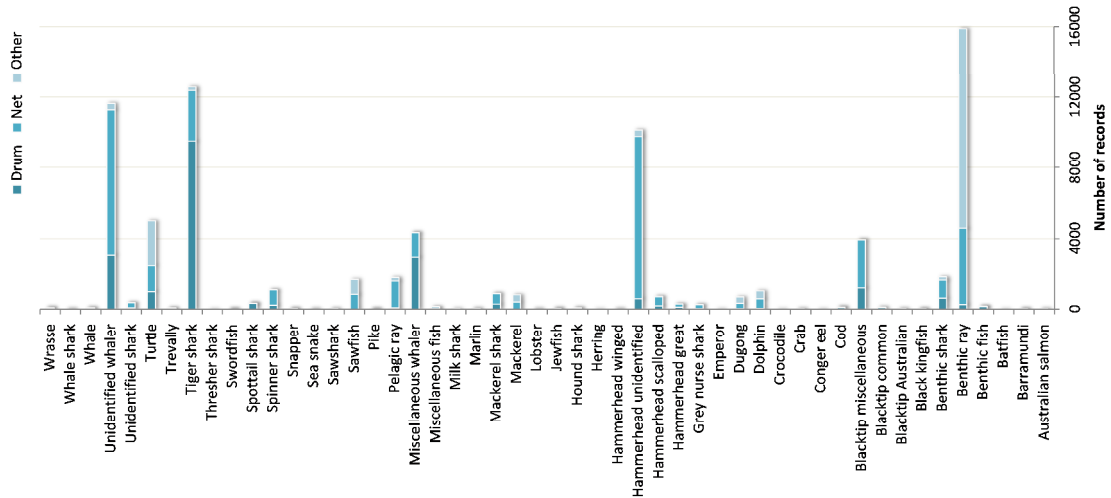


Figure 31: Breakdown of the SCP catch by taxon.

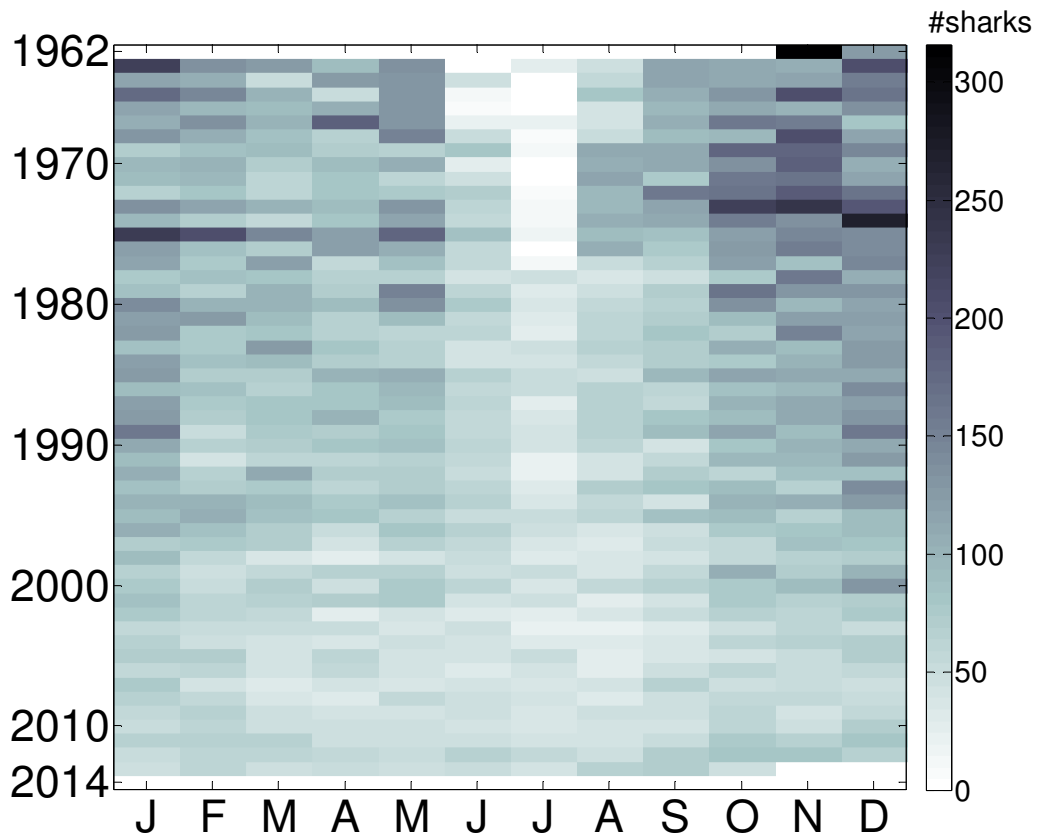


Figure 32: Seasonality of SCP catches of sharks, showing the annual peak in summer and trough in winter. Sharks are more active in the warmer months.

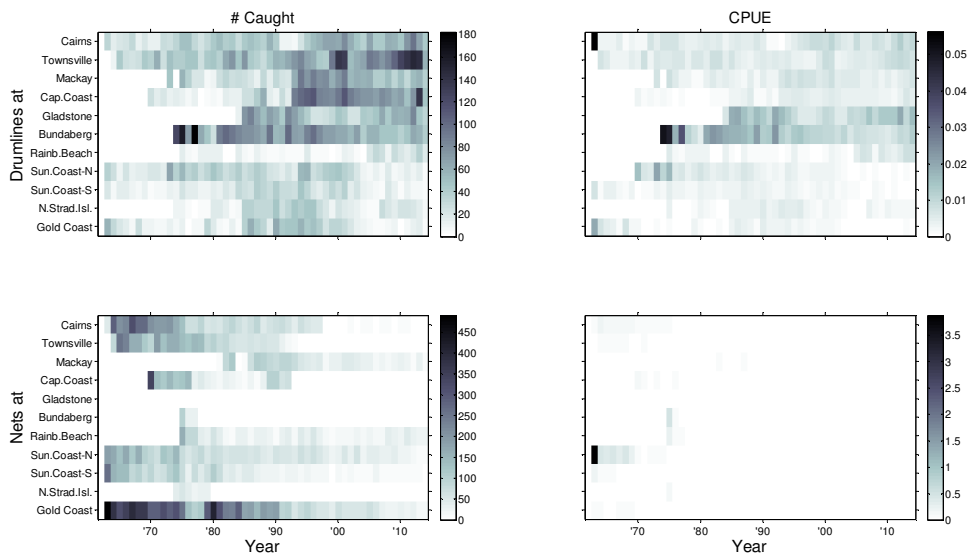


Figure 33: Catch and CPUE of sharks by the SCP, by year and region.

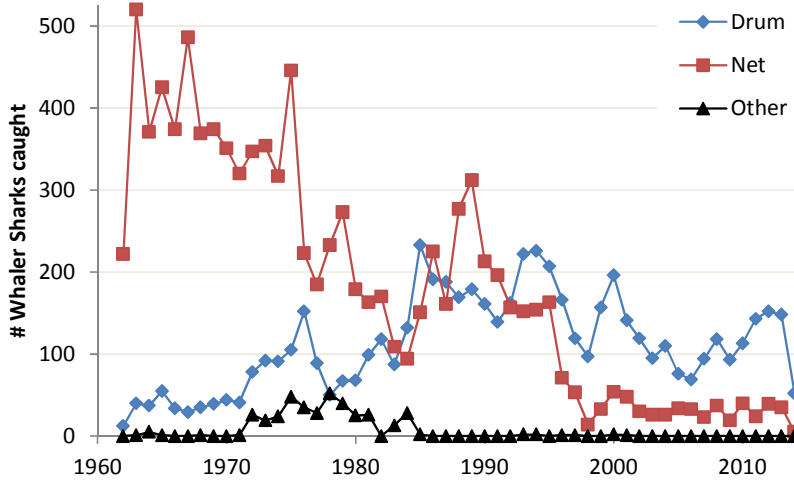
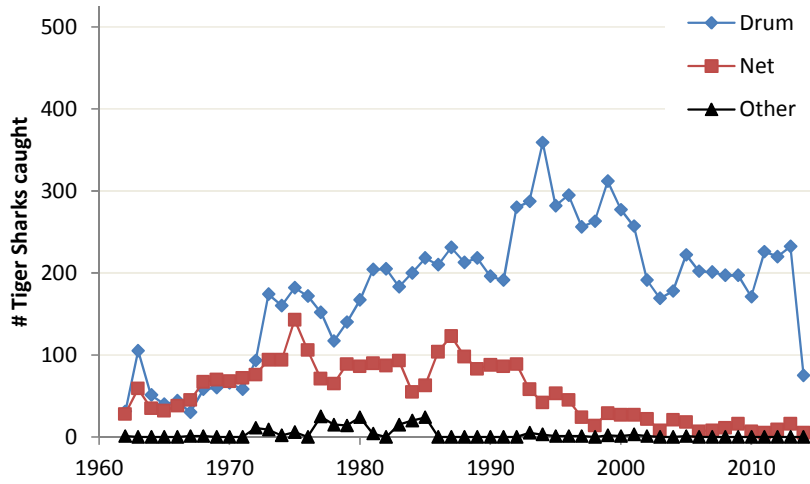


Figure 34: Comparison of SCP catches of tiger sharks and whaler sharks, showing that at least some whaler species are more vulnerable to nets than tiger sharks are.

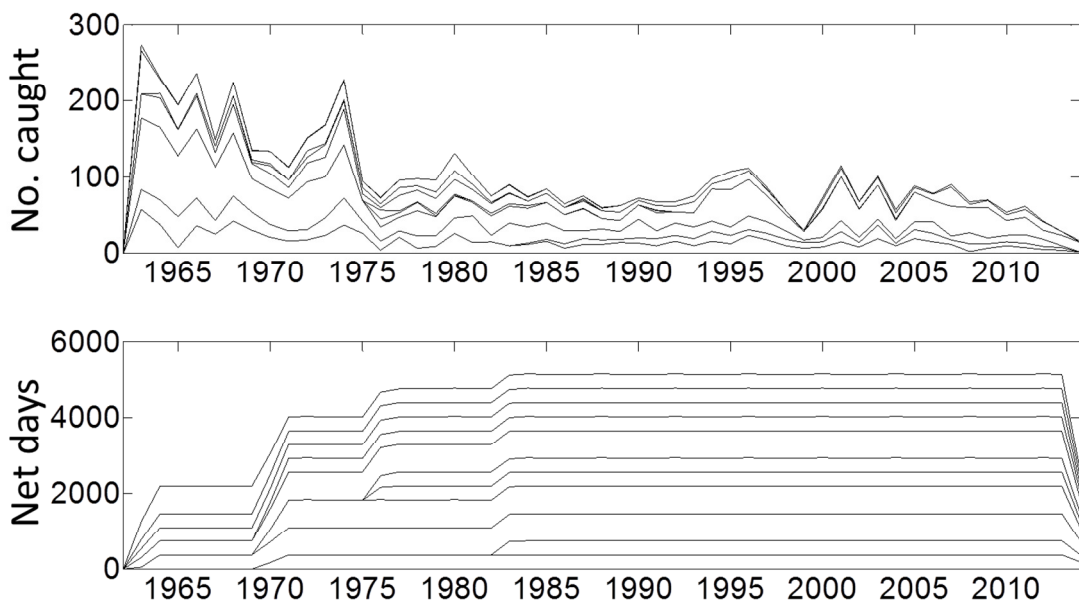


Figure 35: SCP net catches and effort from the Sunshine Coast North region, all taxa combined, showing depletion since the beginning of the SCP.

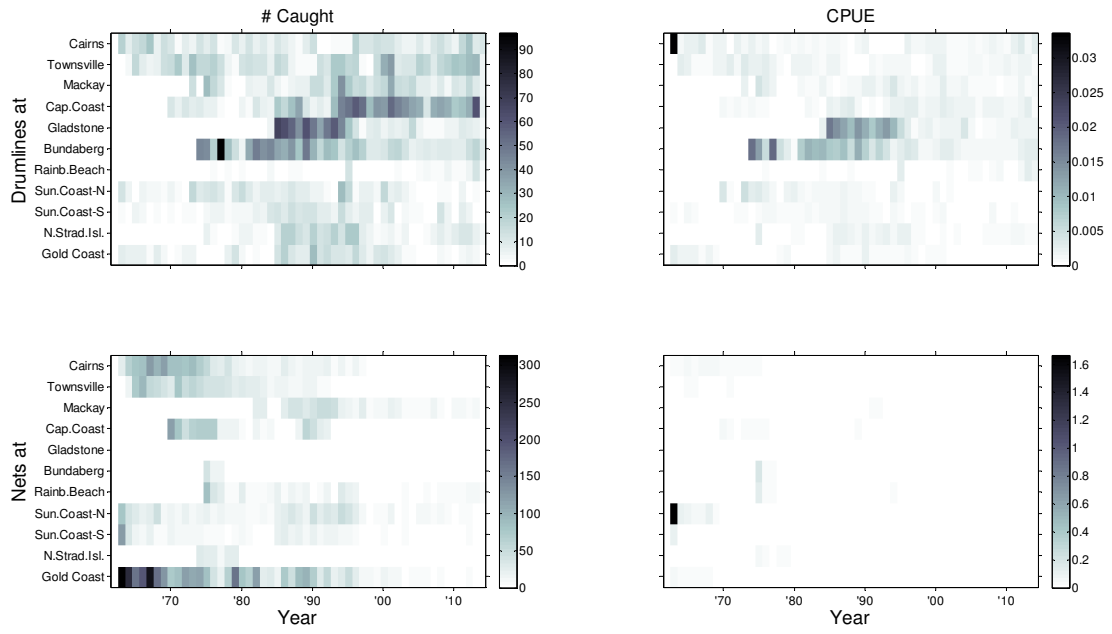


Figure 36: Catch and CPUE of whaler sharks in the SCP.

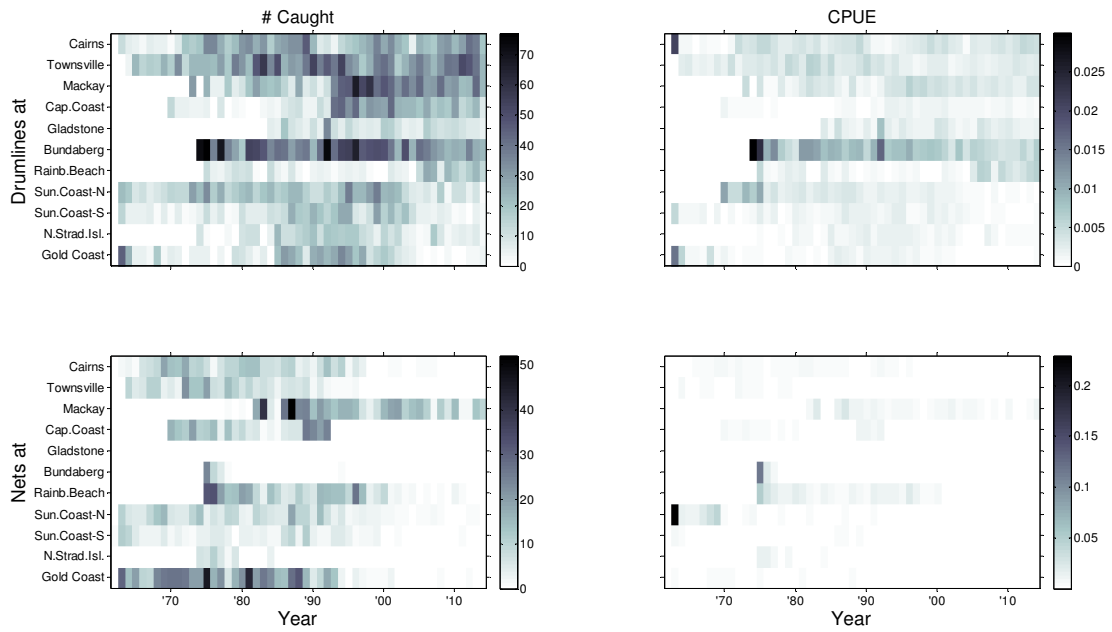


Figure 37: Catch and CPUE of tiger sharks in the SCP.

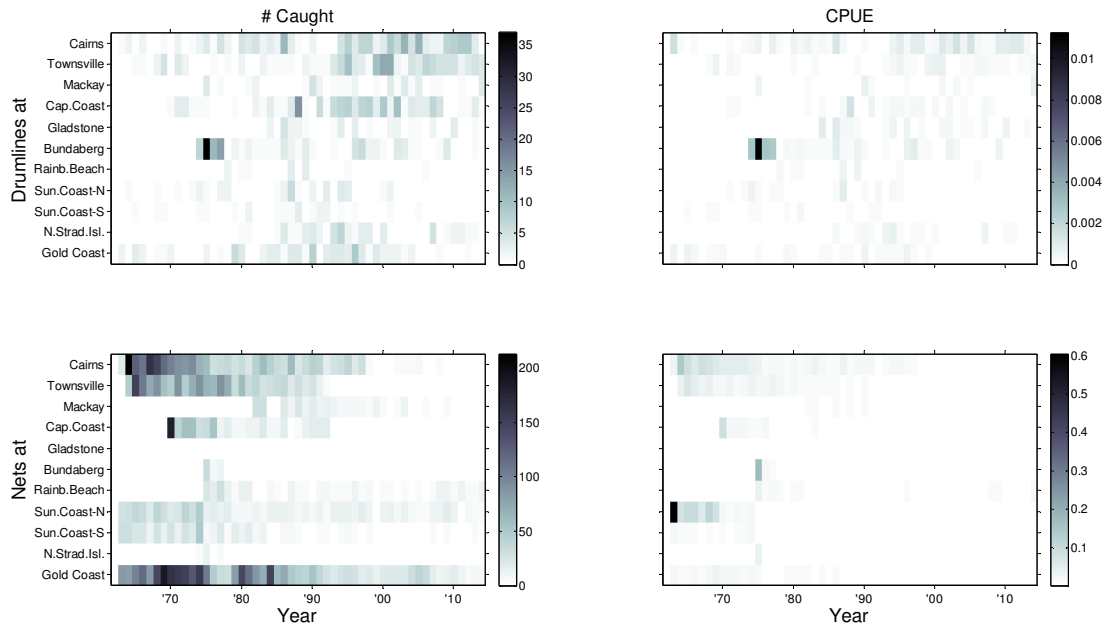


Figure 38: Catch and CPUE of hammerhead sharks in the SCP.

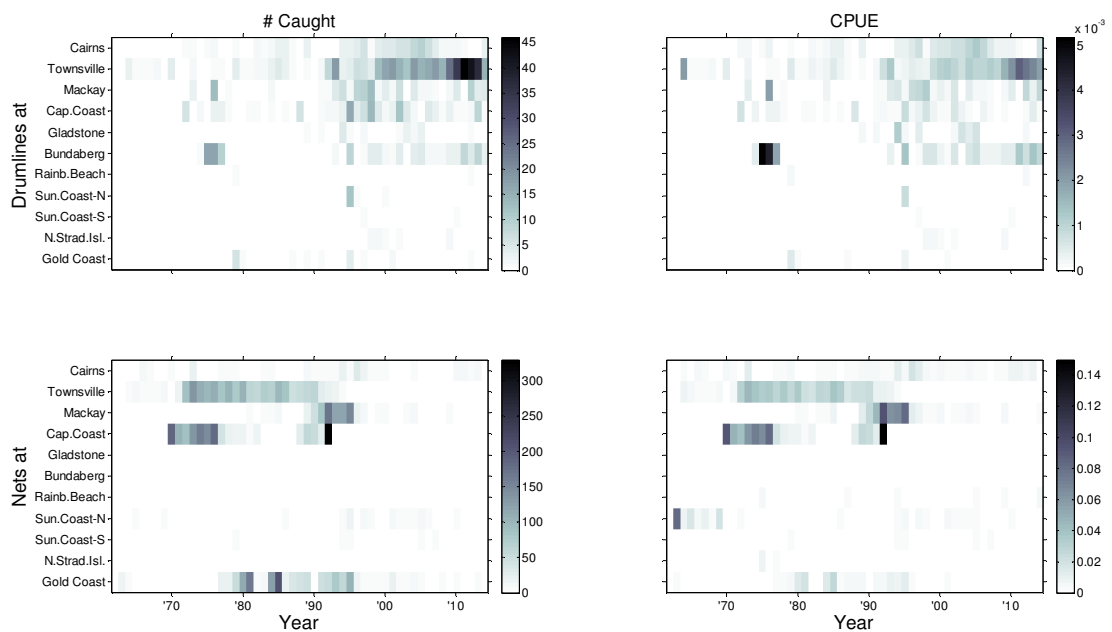


Figure 39: Catch and CPUE of benthic (bottom-dwelling) species in the SCP, intended as an indicator to change of practices in setting the gear.

## Appendix 2: R code for demographic analysis

```
#####  
# Demographic analysis of sharks  
# George Leigh, December 2014  
  
# Note that for many species both fishing mortality and natural  
# mortality differ between sexes, but this is not taken account of  
# in this model. Females often go inshore to give birth (safer area  
# for pups to inhabit), but they also may lose their appetites, so F  
# may be either higher or lower for females. Mature female  
# scalloped hammerheads go well offshore at other times, and are  
# almost never caught. Usually female sharks live longer than  
# males, so M would be greater for males.  
  
##### Setup  
  
Mlow = 0.001 # Lower limit of interval in which to search for M  
Mhigh = 3 # Upper limit of interval in which to search for M  
  
SexRatDef = 1 # Default sex ratio of pups born  
SurvMaxAgeDef = 0.005 # Default for target proportion of females that  
# survive to observed maximum age (currently not used)  
MratJuvDef = 2 # Default ratio of juvenile to adult M in virgin population  
FratDef = 1 # Default ratio of F to M at which the maximum  
# productivity kicks in when fishing only adults  
MratJuvMinDef = 1 # Default minimum value of ratio of juvenile M to  
# adult M at maximum productivity (currently not used)  
PopRatDef = 0.4 # Default ratio of fished spawning biomass to virgin  
# spawning biomass at which maximum productivity kicks in  
  
##### Define the function that will  
# do the work.  
  
Demog = function(a50, a95, MaxAge, PupFreq, LitterSize, MratJuv =  
  MratJuvDef, Frat = FratDef, PopRat = PopRatDef, lPlus = FALSE,  
  SexRat = SexRatDef) {  
  # Parameters:  
  # - a50 = age at 50% maturity of females  
  # - a95 = age at 95% maturity of females  
  # - MaxAge = observed maximum age (lifespan is greater than this)  
  # - PupFreq = pupping frequency  
  # - LitterSize = mean litter size  
  # - lPlus = flag: TRUE = include a plus group; FALSE = take the  
  # lifespan to be MaxAge  
  # - SexRat = sex ratio of new-born pups (female to male)  
  # - SurvMaxAge = proportion of pups that eventually survive to  
  # maximum observed age (as distinct from maximum possible age)  
  # - MratJuv = juvenile M when no fishing, as a multiple of adult M  
  # - Frat = fishing mortality rate on adults at which maximum  
  # productivity kicks in, as a multiple of adult M  
  # - PopRat = ratio of fished spawning biomass to virgin spawning  
  # biomass at which maximum productivity kicks in  
  Ages = 0:MaxAge  
  nAges = length(Ages)  
  # Calculate proportion of females mature at each age  
  if (a95 > a50) {  
    Mat = 1 / (1 + exp(-log(19) * (Ages - a50) / (a95 - a50)))  
  } else {  
    Mat = as.numeric(Ages >= a50)  
  }  
  Mat[Ages == 0] = 0 # No maturity in first year, overrides a50 and a95  
  # logistic curve  
  a5 = max(a50 - (a95 - a50), 1) # Age at 5% maturity  
  PupsProd = Mat * PupFreq * LitterSize # Pups produced by age, before  
  # applying mortality
```

```

Pups = function(Z1, Z2){ # Total number of female pups produced in a
#   female shark's lifetime; Z1 = juvenile total mortality; Z2 =
#   adult total mortality.
# Assume pup is born at the end of the year, due to lengthy
# gestation. Therefore apply the full year's mortality.
Z = rep(Z1, nAges)
Z[Ages >= a5] = Z2
Zcum = cumsum(Z) # Cumulative mortality since birth
Scum = exp(-Zcum) # Survival rate since birth
ScumMid = exp(-(Zcum - 0.5 * Z)) # Mid-year survival
# Include the plus group, if required.
if (lPlus) {
  Scum[nAges] = Scum[nAges] / (1 - exp(-Z[nAges]))
  ScumMid[nAges] = ScumMid[nAges] / (1 - exp(-Z[nAges]))
}
PupsLive = Scum * PupsProd # Live pups as a function of age
# Return total female pups produced, and probability of surviving
# beyond the highest age observed.
c(sum(PupsLive) * SexRat / (1 + SexRat), ScumMid[nAges] / sum(ScumMid)) #
# Total female pups, and proportion for the final age class
}

f0 = function(M) # Function for virgin state; M = adult M here. We
# want the total number of female pups produced per female shark
# born to equal 1.
Pups(MratJuv * M, M)[1] - 1
M0 = uniroot(f0, c(Mlow, Mhigh))$root # Virgin value of adult M

# Now apply fishing with F equal to some multiple of M, for adults
# only. Assume that juvenile M falls in compensation, as in Smith
# et al. 1998. Again we want the total number of female pups
# produced per female shark born to equal 1.
f1 = function(M) # Now M = juvenile M.
Pups(M, (1 + Frat) * M0)[1] - 1
M1 = uniroot(f1, c(Mlow, Mhigh))$root # Fished value of juvenile M
if (M1 < M0) cat("Problem\n")

# Now take away the fishing and find the maximum number of female
# pups that can be produced per female shark born.
rlim = Pups(M1, M0)[1]
# Finally find the recruitment compensation ratio, but for sharks
# this will be limited by rlim. At population size ratio PopRat,
# We have the equation  $r * \text{PopRat} / (1 + (r - 1) * \text{PopRat}) = \text{rlim} * \text{PopRat}$ ,
# and need to solve that to find r. The solution is given
# by the following assignment.
r = (1 - PopRat) * rlim / (1 - PopRat * rlim)
if (rlim > 1 / PopRat) cat("Problem\n")

c(M1, M0, rlim, r, Pups(M1, (1 + Frat) * M0)[2])
}

##### Test case (Tilstoni) to check
# it before we automate it
DemogEx = Demog(5.65, 6.65, 16, 1, 3, MratJuv = 2.0, Frat = 1.0,
  PopRat = 0.4, lPlus = FALSE)
Demog(5.65, 6.65, 16, 1, 3, MratJuv = 2.5, Frat = 1.0, PopRat = 0.4,
  lPlus = FALSE)
Demog(5.65, 6.65, 16, 1, 3, MratJuv = 3.5, Frat = 1.0, PopRat = 0.4,
  TRUE) # Can't get sensible results with a plus group.
Demog(5.65, 6.65, 25, 1, 3, MratJuv = 2.5, Frat = 1.0, PopRat = 0.4,
  lPlus = FALSE) # Results seem most sensible when we use max age = max
# observed age.

##### Automate with data from
# spreadsheets.
Growth = read.csv("GrowthCopied.csv", header = TRUE)
Repro = read.csv("ReproductionRounded.csv", header = TRUE)
CommonNames = Growth$Common.name[Growth$Common.name != "Pigeye shark"]

```

```

DemogMat = array(0, dim = c(length(CommonNames), length(DemogEx) + 1))
dimnames(DemogMat) = list(CommonNames, c("", "M1", "M0", "rlim", "r", "Surv"))
lHH = CommonNames %in% c("Winghead shark", "Scalloped hammerhead",
  "Great hammerhead") # Hammerheads need higher juvenile mortality.

for (i in CommonNames) {
  lG = Growth$Common.name == i
  lR = Repro$Common.name == i
  MratJuvCur = 3.5
  if (lHH[match(i, CommonNames)]) MratJuvCur = 6.0
  if (i == "Aust. sharpnose shark") MratJuvCur = 3.57
  if (i == "Hardnose shark") MratJuvCur = 3.75
  if (i == "Spot-tail shark") MratJuvCur = 3.95
  DemogMat[i,] = c(MratJuvCur, Demog(Repro$a50..yr.[lR], Repro$a95..yr.[lR],
    Growth$amax..yr.[lG], Repro$Interval..yr.[lR],
    Repro$Litter.size[lR], MratJuv = MratJuvCur, Frat = 1.0, PopRat = 0.2,
    lPlus = FALSE))
}
DemogMat[, "M1"] = DemogMat[, "M1"] / DemogMat[, "M0"]
DemogMatNoPlus = DemogMat

for (i in CommonNames) {
  lG = Growth$Common.name == i
  lR = Repro$Common.name == i
  MratJuvCur = 3.5
  if (i == "Aust. sharpnose shark") MratJuvCur = 3.78
  if (i == "Milk shark") MratJuvCur = 3.10
  if (i == "Creek whaler") MratJuvCur = 3.35
  if (i == "Hardnose shark") MratJuvCur = 4.01
  if (i == "Spot-tail shark") MratJuvCur = 4.19
  if (i == "Aust. blacktip shark") MratJuvCur = 2.74
  if (i == "Common blacktip shark") MratJuvCur = 2.84
  if (i == "Spinner shark") MratJuvCur = 4.77
  if (i == "Bull shark") MratJuvCur = 6.03
  if (i == "Winghead shark") MratJuvCur = 4.31
  if (i == "Scalloped hammerhead") MratJuvCur = 6.86
  if (i == "Great hammerhead") MratJuvCur = 17.92
  DemogMat[i,] = c(MratJuvCur, Demog(Repro$a50..yr.[lR], Repro$a95..yr.[lR],
    Growth$amax..yr.[lG], Repro$Interval..yr.[lR],
    Repro$Litter.size[lR], MratJuv = MratJuvCur, Frat = 1.0, PopRat = 0.2,
    lPlus = TRUE))
}
DemogMat[, "M1"] = DemogMat[, "M1"] / DemogMat[, "M0"]
DemogMatPlus = DemogMat

round(DemogMatNoPlus, 6)
round(DemogMatPlus, 6)

write.csv(DemogMatPlus, file = "Demographics.csv")

```