Shark futures: Sustainable management of the NSW whaler shark fishery

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June, 2020

FRDC Project No **2010/062**

ISBN 978-1-76058-394-1 (print)

ISBN 978-1-76058-395-8 (online)

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FRDC Project Number 2010/062

2020

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Peddemors, V., Macbeth, W., Collins, D., Goulstone, A., Ives, M., Ovenden, J., Butcher, P. (2020) Shark futures: Sustainable management of the NSW whaler shark fishery. Port Stephens, NSW, June 2020. 190 pp. ISBN 978-1-76058-395-8 (online)

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In submitting this report, the researcher has agreed to FRDC publishing this material in its edited form.

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Acknowledgments

First and foremost, the Principal Investigator would like to thank Paul Butcher, the project executant, for his passion and enthusiasm and Will Macbeth for his knowledge on the NSW Ocean Trap & Line Fishery and managing the observer program for the shark component of this fishery, plus his considerable contribution to this Final Report. It has been a privilege to work with Jenny Ovenden and Dean Blower and contribute to the development of a new genetic pathway for population estimates, based on genetic effective population size and implemented here as NeOGen software.

Jenny Ovenden and the project team thank the University of Queensland for access to facilities and resources following withdrawal of same by the Queensland Government. In particular, we thank Cynthia Riginos and Mike Bennett and members of their research groups in the School of Biological Sciences and the School of Biomedical Sciences for their collaborative support for the completion of this work. In this report, text relating to Objective 1 was written as a 'plain language' summary of work performed for this project by Dean Blower (in collaboration with members of the project team), which formed the basis for Dean's PhD thesis at the University of Queensland. Full scientific details of Dean Blower's work can be found in publications that are first-authored by him and in his PhD thesis (see bibliography).

Many thanks to those fishery managers whom we had the pleasure to work with throughout the project, including (but not limited to) David Makin, Fiona McKinnon, and Veronica Silberschneider who also kindly provided valuable comments on an earlier draft of our report.

We wish to acknowledge the scientists who have contributed their expertise to various components of the project (C. Baduel, A. Bowling, M. Broadhurst, S. Cooke, L. Christidis, L. Gutowsky, L. Hearn, Y. Li, J. Mandelman, J. Mueller, A. Reichelt-Brushett), the technical team that processed the samples used in this project (C. Barnes, P. Geraghty, J. Marshall, S. McGrath, S. Provost), the post-graduate students who collaborated in this research (D. Blower, J. Gilbert, N. Pleizier) and M. O'Leary and C. Brooks who provided administrative support to the project. Carolyn Stewartson from FRDC provided much appreciated ongoing encouragement and support for this project.

We are indebted to various mathematical modellers, including B. Cullis (University of Wollongong) who led the modelling work for Objective 2, K. Lee (Sydney Institute of Marine Science) for Objective 6, and R. Millar for Objective 3.

All of the commercial shark fishers who cooperated with this study are thanked for their patience, hospitality and assistance during sampling operations, particularly the fishers associated with the fishing vessels 'Menrae' and 'Joanne Glenn'.

Abbreviations

AFMA	Australian Fisheries Management Authority
ARGOS	Advanced Research and Global observation Satellites
CFL	Centred fork length
CLOP	Commercial Line-fishing Observer Program
CMR	Capture-mark-recapture
C-Ne	Contemporary effective population size
CPUE	Catch per unit effort
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSOP	Commercial Shark-fishing Observer Program
DEWHA	Department of the Environment, Water, Heritage and the Arts
EIS	Environmental Impact Statement
FL	Fork length
FMS	Fishery Management Strategy
FW	Fin weight
FSANZ	Food Standards Australia New Zealand
H-Ne	Historical effective population size
IMOS ATF	Integrated marine observing System Animal Tracking Facility
IPM Ne	Independent Pcrit mean Ne: An independent calculation of Ne at many small increments of Pcrit and averaged to give an Ne estimate (harmonic mean) that balances accuracy with power
IUCN	International Union for Conservation of Nature
LW	Landed weight
N	Total population size
Nc	Number of reproductively capable adults
Ne	Effective population size (i.e. the number of individuals effectively participating in producing the next generation)
Ne-dem	Effective population size estimate based on demographic information
Ne-gene	Effective population size estimated from genetic data (in the absence of demographic data)
NPOA	National Plan of Action

NRCMA	Northern Rivers Catchment Management Authority
NSW DPI	New South Wales Department of Primary Industries
OTLF	Ocean Trap & Line Fishery
OTLMAC	Ocean Trap & Line Management Advisory Committee
Pcrit	Genes with a critical probability of occurrence (usually low frequency genetic variants that are excluded from Ne estimation
PSAT	Pop-up satellite archival tag
PTMI	Provisional tolerable monthly dietary intake
PTWI	Provisional tolerable weekly dietary intake
SSM Ne-gene	Scaled simulated-matched Ne: the Ne-gene generated by the SharkSim simulation model developed during this research program.
TAC	Total allowable catch
TACC	Total allowable combined catch
TEP	Threatened, endangered and protected (species)
TL	Total length
TW	Trimmed weight
WW	Whole weight

Executive Summary

Concept

New South Wales Department of Primary Industries (NSW DPI) presents new information exploring the shark catch of the NSW Ocean Trap & Line Fishery and developing methods to ensure an accurately reported, sustainable and profitable fishery for large sharks is maintained.

A combination of novel genetic techniques, extensive field work, and numerical modelling was undertaken during this FRDC Shark Futures project.

This allowed development of an innovative way to bring together genetic and demographic data for estimating population size and modelling sustainable catch levels for target species. Identification of shark species has historically been problematic with many species lumped into similar groups in historical catch logbooks. The new NSW catch logbooks differentiate between shark species caught in commercial fisheries and a corresponding shark identification guide provided to fishers. We assess the effectiveness of this guidebook in providing accurate catch reporting and determine the minimum data required to be collected to enable fisheries managers and compliance officers to effectively regulate a large shark fishery. As management options have often included a trip limit of total allowable catch, we investigated the fate of sharks caught on demersal longlines and model factors affecting their post-release survivorship. This is particularly pertinent for non-selective fishing gear such as demersal longlines which hook species of conservation value and other bycatch as part of their normal fishing operations. Finally, we also assess the levels of metals and metalloids in shark product sold from this fishery to determine whether there could be any negative health implications for human consumers. Excessive levels of mercury and arsenic were detected and suggestions subsequently made on how to ensure product from NSW large shark fisheries are kept within the standards of Food Standards Australia New Zealand.

Background

Little was previously known about the catch composition of shark fisheries off the east coast of Australia. Off NSW, species of whaler shark historically represented at least 60% by weight of shark catches in the Ocean Trap & Line Fishery (OTLF). The historical annual shark catch within this fishery averaged around 173.2 (± 9.8) tonnes, but from 2005/06 this tonnage dramatically increased to a peak of 457.2 tonnes in 2006/07, representing a 200% increase over two years (Macbeth *et al.*, 2009). Although as many as 31 fishers landed whaler shark, 87%of the 2006 total catch comprised landings of only ten fishers, most of whom fished in northern NSW waters. Many of these fishers were 'new' to shark fishing, having targeted sharks primarily since the 2005/06 season. The OTLMAC raised concern that these fishers would jeopardise the business interests of the historical shark fishers considering the total catch limit of 90 tonnes of whaler shark for NSW proposed at that time. This research was initiated to investigate this 'new' shark fishery, determine the species composition of catch, assess accuracy of reporting by fishers and develop potential important indicators for data-poor shark fisheries that would assist in developing a sustainable fishery with reduced bycatch of non-target and TEP species.

Objectives

Specifically, the objectives of this project were to:

1 Genetically resolve the effective population size of dusky and sandbar sharks targeted in the OTLF to explore new ways to model sustainable catch levels for these species;

2 Determine the short-term and distance movements of sandbar and dusky sharks to assist in the development of potential spatial management options like time-area (spatio-temporal) closures;

3 Develop a fishing technique that will decrease mortality of unwanted species, particularly threatened and protected species, to minimise environmental impact of the fishery;

4 Assess the effectiveness of the NSW DPI shark field ID-guide through ground-truthing on-board shark identification between fishers and observers, plus via genetic testing;

5 Educate the fishers targeting sharks about field identification of the shark species they are catching to ensure an accurate long-term database to monitor fishing of the shark populations in NSW;

6 Evaluate assessment methods and management indicators for the main shark species that may provide a model for future national and/or international data-poor shark fisheries;

7 Provide scientific data-based advice for management to ensure the future sustainability of shark populations.

Methodology

Each of the objectives used specific methods to address the topic being investigated. Many of these were specialised and are presented in detail in the relevant sections of this report and/or appendices. The genetic research obtained samples from animals caught in the commercial NSW Ocean Trap and Line Fishery and used them in developing a novel new population modelling approach. The new method infers population size for dusky and sandbar shark from empirical estimates of genetic effective population size using new modelling software developed during the project ("NeOGen"). Using a combination of chartered commercial shark fishers and demersal longlines set up with hook timers and in configurations to allow experimental manipulation, we simulated commercial fishing operations and assessed survivorship of catch, movements and post-release mortality rates of target sharks through use of telemetry and blood physiology. Biological samples and morphometrics were taken from all deceased animals and contributed to several studies, including determination of variation in fin to body weights, modelling minimum data that would be required for data-poor shark fisheries to assess catch, and assessing levels of pollutants in sharks caught in NSW and their potential implications for human consumption.

Key findings

The approaches employed allowed the compilation of a diverse and unique set of data that will provide fisheries managers with options on how to maintain a sustainable large shark fishery with reduced impact on non-target species, including threatened, endangered and protected (TEP) species.

We developed a new computer simulation software ("NeOGen") to interpret genetic effective population size in terms of a range of known demographic parameters to estimate population abundance. For dusky and sandbar sharks, the mathematical relationship between Ne and population size was determined and the ratio between Ne and the number of sexually mature adults (Ne / Nc) ≈ 0.6. On the eastern Australian coastline, the population of sandbar sharks was estimated to be larger (N ≈ 105,000) than the population of dusky sharks (N ≈ 35,000). Computer simulations aided by NeOGen showed that adult harvest exceeding the observed fishery harvest volumes in 2008 was found to be sustainable for both species, although juvenile harvest was predicted to be more sustainable than adult harvest. For both species, a decline of Ne was detected within a decade after harvest commencement, around the first age at maturity. Dusky sharks were found to be more vulnerable to exploitation than sandbar sharks; sustainable harvest volumes were smaller; Ne was lower and the decline in Ne was more pronounced.

Simulated fishing mortality caused a significant reduction in the estimated number of adults across 11 fishing scenarios tested and highlighted that dusky shark life-history characteristics make this species relatively more vulnerable to depletion. Our research indicated that the dusky shark in waters off eastern Australia may be considered a genetically open population, highlighting that fishing pressure throughout Australia should be taken into consideration when setting total catch limits for this species. The sandbar shark constitutes an 'eastern Australia population' and total catch limits could therefore be set for this species at a more regional level.

Telemetry data from released sandbar and dusky sharks highlight that although both species occupy similar water depths and water temperatures, there may be opportunity to establish increased targeting for one or the other species through depth-specific fishing. However, there was diel variation in use of the water column with sandbar sharks exhibiting a preference for deeper waters during daylight hours. Some sandbar sharks showed evidence of philopatry to the region of first capture which may present susceptibility to over-exploitation for this species. Although all tagged animals were chosen due to their apparent vigour, we still experienced relatively high levels of post-release mortality at 25% for sandbar and 12.5% for dusky sharks. This raises concern for potential high mortality rates of animals released (discarded) at sea as a regulatory requirement as it represents a source of unreported, or unconfirmed, fishing mortality that is difficult to include in modelling sustainable catch.

Our investigations into establishing fishing practices that would reduce unwanted catch highlight that soak times of less than 5 hours are preferred, however, this may be difficult for logistical reasons on commercial demersal longline fishing vessels. Additionally, our temporal analyses of hooking suggests that restricting both setting and retrieval of gear to nocturnal activities may substantially reduce bycatch. In addition, the fuller the moon was (irrespective of cloud cover), the quicker baits were taken after setting the gear.

Accurate reporting of catch is a prerequisite of effective monitoring and setting of catch quotas to allow sustainable fishing. NSW fishers are expected to report shark catch to species level but, even though an ID guide was prepared to assist fishers, some discrepancies between observer and fisher catch records existed. Analyses of these indicate that fishers still mistake species with similar characteristics (e.g. black fin tips/hammer-shaped heads) highlighting that continued monitoring is required to ensure fishers accurately report their catch. Our data suggest that real-time reporting of catch using electronic logbooks or via a smart device could substantially reduce such reporting error. Alternatively, we suggest that all retained sharks should be returned to port with heads attached and be available for random inspections by fisheries compliance officers prior to trimming.

As observer and compliance programs are expensive to maintain, we investigated which features would be required to be recorded, at minimum, for enabling assessment of catch composition in data-poor shark fisheries. We conclude that, in addition to reporting the total number of individuals and total trimmed (dressed) weight, fishers should report a length measurement and sex for each shark caught. Our analysis of catch weight variables highlights the importance of establishing a standard for how fishers are allowed to trim the carcass to enable accurate landed tonnage to be calculated and to enable species identification by compliance officers.

Examination of fin weight to body weight ratios indicate that smaller sharks have a higher percentage fin weight, however smaller fins are not as valuable as large fins. Our assessment of pollutants in shark product highlights that harvesting smaller (<1.5m) whaler sharks would ensure levels of mercury and arsenic in flesh and fins sold for human consumption are within recommended levels suggested by Food Standards Australia New Zealand. Additionally, from an ethical perspective, smaller sharks yield less ratio of trim (waste) to product.

Implications for relevant stakeholders

The key findings provide fisheries managers with options on maintaining a fishery targeting large whaler sharks. Historically, a small community of fishers represented the major portion of fishers landing large whaler sharks. The development of a large shark fishery based on a user-pays (for on-board observers and additional management reporting requirements) system all but stopped this fishery in NSW as the fishers deemed it economically unviable after experiencing a concurrent drop in fin-price.

Our project indicates that a large shark fishery, particularly for sandbar sharks, is feasible given the population estimates determined using our NeOGen model. However, certain minimum data need to be recorded in fisher logbooks and with some changes to legislative requirements e.g. heads kept on all shark carcasses landed. Fishers will need to determine whether this is cost-effective for them, including the proposal for the fishery to only operate nocturnally and with lines set for a shorter time to enable higher survivorship of captured unwanted species. The proposal to limit landed carcasses to 1.5m total length for human health reasons, reduced waste of off-cuts following carcass dressing for sale, plus likely higher sustainability of the fishery, may lead to fishers deciding that shark fishing is economically unviable if they are unable to access larger sharks with more valuable fins.

Recommendations

Development of electronic logbooks needs to include fields for length and sex for individual sharks caught.

Considering the importance of landing sharks of less than 1.5m total length, experiments should be conducted to establish size-selective fishing measures.

Determining the post-release survivorship for other shark species caught on demersal long-lines requires further research to ensure all fishery-related mortalities are incorporated in population modelling to ensure sustainable shark fisheries.

This study suggested some philopatry for sandbar sharks. Almost all shark species that have been tracked through various forms of telemetry have exhibited philopatry in some form. As this behavioural trait may impact susceptibility to localised fishing pressure, more effort should be initiated into telemetry of commercially valuable shark species to determine movements, habitat use and philopatry. Researchers should be encouraged to participate in the Australian tagging database administered by the IMOS Animal Tracking Facility if their project is funded through the FRDC.

Fishery models incorporating animal movement need to be developed.

Keywords

Shark fishery, sandbar shark, dusky whaler, effective population size, telemetry, survivorship, demersal longline, logbook, blood biochemistry, bioaccumulation.

Introduction

Background

Little was previously known about the catch composition of shark fisheries off the east coast of Australia. Off NSW, species of whaler shark historically represented at least 60% by weight of shark catches in the Ocean Trap & Line Fishery (OTLF). The historical annual shark catch within this fishery averaged around 173.2 (± 9.8) tonnes (average first point of sale value = AUS$1.2 million), but from the 2005/06 fishing season (inclusive) this tonnage dramatically increased to a peak of 457.2 tonnes (average first point of sale value = AUS$3.2 million), representing a 200% increase over two years (Macbeth *et al.*, 2009). Although as many as 31 fishers landed whaler shark, 87% of the 2006 total catch comprised landings of only ten fishers, most of whom fished in northern NSW waters. Many of these fishers were 'new' to shark fishing, having targeted sharks primarily since the 2005/06 season. The OTLMAC raised concern that these fishers would jeopardise the business interests of the historical shark fishers considering the total catch limit of 90 tonnes of whaler shark for NSW proposed at that time.

Following representation by industry and verified reports of increased fishing effort targeting large shark species, particularly on the mid-north and north coasts of NSW, NSW DPI investigated this fishery and confirmed that fishing effort was shifting away from other sectors of the OTLF, the Ocean Trawl Fishery or the Commonwealth's Eastern Tuna and Billfish Fishery and into the northern NSW shark fishery. This validated the concerns from some members of the NSW Seafood Industry Advisory Council (SIAC) that the viability of long-term historical shark fishers in NSW may be threatened by the rapid catch increase attributable to these 'new' entrants into the fishery, who claimed to be targeting a previously untargeted species, the sandbar shark *Carcharhinus plumbeus*.

The historical lack of knowledge of species caught within the NSW shark fishery led to an inability to effectively manage this increasingly important fishery and resulted in a precautionary approach being taken by NSW DPI fisheries managers. The shark component of the OTLF has been recognised as constituting high risk in the OTLF FMS (Table 6.2, NSW DPI 2006b). Improved research and data collection for the shark component of the OTLF was also highlighted as a key management response in the OTLF EIS (NSW DPI 2006a). A newly established NSW DPI specialist Shark Working Group, including active shark fishers, reporting to the NSW SIAC recommended that the more recent fishery targeting sandbar sharks be separately managed within the Ocean Trap and Line Fishery (OTLF) and be provided a separate catch quota from the historical shark quotas.

Unfortunately, shark species identification was problematic in the historical catch records. The increase in records of 'Sharks, unspecified' from an average of 35 tonnes (1997/98 – 2004/05) to 75 tonnes (2005/06 – 2006/07) highlights the management imperative to improve catch records, including species identification.

As a precautionary management response, NSW DPI implemented a total catch limit of 160 tonnes for the 2008/09 fiscal year, while committing itself to increasing the scientific knowledge base to allow managers to set more robust sustainable shark quotas within the OTLF. Subsequently, an annual TAC of 126.5 tonnes (with a 110 tonne cap on whaler shark species) was determined for the 2009/10 and 2010/11 fiscal years following concern about the uncertainty of the data underpinning sustainability of the fishery (Bruce, 2010). Under this revised TAC, the first point of sale value of $900,000 represented a three-fold decrease in the value of the fishery to local economies. Within the northern NSW region, this catch reduction may have had substantial regional socio-economic repercussions (Harrison, 2009). This illustrates the financial and likely social consequence of inadequate data on which to set catch limits that can otherwise potentially optimise ecological, economic and social outcomes for the fishery.

The NSW DPI scientific program for shark fisheries grew substantially between 2006 and 2009 to address sustainability concerns for this northern NSW fishery, and the OTLF more broadly.

The NSW Commercial Fishing Trust funded Commercial Line-fishing Observer Program (CLOP) that started in 2007 specifically included collection of detailed biological data and samples from shark catches as part of standard onboard protocols (Macbeth and Gray, 2015). Subsequently, the Commercial Shark-fishing Observer Program (CSOP) was initiated during the 2008/09 fiscal year with funding from NSW DPI and the Northern Rivers Catchment Management Authority (NRCMA) (Macbeth *et al.*, 2009).

During the first half of 2008, NSW DPI also formulated and implemented new commercial catch reporting systems (integrated 'field identification kits' and daily commercial catch and effort forms) and a logistical framework for data and sample collection, management and storage (including regionally located scientific observers and sample storage facilities). To determine the potential for more integrated whaler shark management between NSW and the Commonwealth (AFMA), Power and Peddemors (2010) reviewed catch data for each institution. This analysis indicated limited overlap in catch between Commonwealth and State shark fishers, highlighting the State-based responsibility to manage this fishery.

The substantial investment by NSW DPI (exceeding $450,000 by July 2010), NRCMA ($75,000) and AFMA ($20,000) provided strong baseline data on the spatial and temporal components of the fishery, shark species composition, biological samples of caught sharks, and an understanding of the fishing methods used by OTLF shark fishers. In response to the information provided by the CSOP, NSW DPI fisheries managers implemented tighter new management regimes in 2008/9 which, following consultation with DEHWA and the CSIRO, included further modification of the annual TAC in September 2010 to 126.5t. As highlighted above, these limits were set using the precautionary principle due to lack of data on stock size and structure, movements of target shark species and concerns regarding at-sea high-grading and discard of carcasses.

This study aims to complete the final pieces in the data jig-saw puzzle to enable on-going long-term sustainable shark fishing in NSW waters (Figure 1). It also has strong potential to develop practical and cost-effective stock assessment and management approaches that are highly relevant to data-poor fisheries around Australia, and internationally.

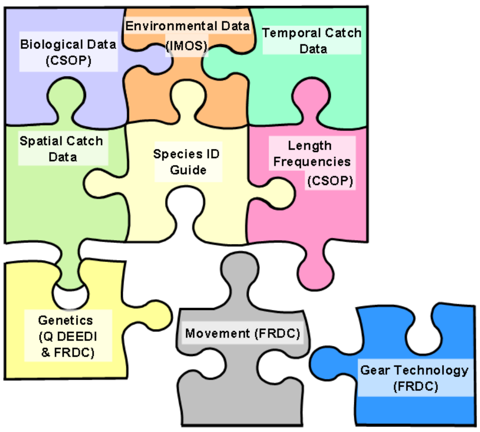


Figure 1 Stylised diagram of the data pieces required for the sound management of the NSW shark fishery. Already completed pieces include (1) biological data [CSOP]; (2) Environmental data [IMOS]; (3) spatial catch [log books]; (4) temporal catch [log books]; (5) species ID [guide]; (6) length frequencies [CSOP]; plus pieces still required: (7) genetic stock size & structure [Qld DEEDI]; (8) movements [FRDC] and (9) gear technology [FRDC]

Need

World-wide, shark fisheries are reputedly unsustainable. The NPOA Sharks and IUCN list over-fishing as a major threat to Australian shark populations. In NSW, the OTLF accounts for most large sharks caught. Both the FMS and EIS recognise this component as requiring urgent research due to the perceived high risk to targeted whaler shark species due to their known low fecundity and resultant susceptibility to over-fishing.

The OTLMAC and NSW SIAC reiterated concern following the rapid expansion of the large shark fishery during the mid-2000s. The impact of this expansion on the so-called ‘historical shark fishers’ was queried.

An independent review by CSIRO on behalf of DEWHA highlighted the lack of knowledge to effectively manage this fishery (Bruce, 2010). Subsequently, an overtly precautionary TAC was determined, however there was some concern amongst regional communities that this reduced TAC had the potential to negatively affect regional socio-economics (Harrison, 2010). Data enabling a viable and sustainable shark fishery, while supporting the conditions for EPBC Act Wildlife Trade Operations (WTOs), were urgently required.

Significant investment by NSW DPI had been providing data on shark species composition, their biology, fishing gear details, and spatio-temporal catch information (Macbeth *et al.*, 2009). Although these data were substantially contributing to enabling suitable management protocols, NSW DPI fisheries managers called for more information on:

(1) stock structure and effective population size to enable sustainable TACs to be set; (2) methods to reduce unwanted catch thereby minimizing environmental impact; and (3) movements of target species to enable equitable State-wide access to the resource for fishers while providing temporal-spatial management options to improve risk-management of this fishery.

Considering the OTLF catch levels and historical collapses of other fisheries internationally that have targeted dusky and sandbar sharks, NSW DPI fisheries managers requested particular focus on these two whaler shark species. This research aims to address the management needs through innovative new techniques utilising linkages with several laboratories, national research programs and management agencies.

Objectives

Specifically, the objectives were to:

1. Genetically resolve the effective population size of dusky and sandbar sharks targeted in the OTLF to explore new ways to model sustainable catch levels for these species;
2. Determine the short-term and distance movements of sandbar and dusky sharks to assist in the development of potential spatial management options like time-area (spatio-temporal) closures;
3. Develop a fishing technique that will decrease mortality of unwanted species, particularly threatened and protected species, to minimise environmental impact of the fishery;
4. Assess the effectiveness of the NSW DPI shark field ID-guide through ground-truthing on-board shark identification between fishers and observers, plus via genetic testing;
5. Educate the fishers targeting sharks about field identification of the shark species they are catching to ensure an accurate long-term database to monitor fishing of the shark populations in NSW;
6. Evaluate assessment methods and management indicators for the main shark species that may provide a model for future national and/or international data-poor shark fisheries;
7. Provide scientific data-based advice for management to ensure the future sustainability of shark populations.

The research conducted to address each objective is presented as a stand-alone chapter as they are, for the most part, separate sub-projects connected by the overarching super-topic that is the NSW large shark fishery. By separating each objective in this manner the reader will hopefully better understand the various methodologies used and results obtained in addressing each component of this FRDC-supported project.

Objective 1: Genetically resolve the effective population size of dusky and sandbar sharks targeted in the OTLF to explore new ways to model sustainable catch levels for these species

1.1 Development and application of a genetic approach for modelling and monitoring shark populations

The key concept underpinning the genetics work undertaken as part of this FRDC Shark Futures project is 'Genetic Effective Population Size', a population parameter abbreviated here as 'Ne'. While Ne has no direct links to more conventional population estimation techniques (eg. such as catch- per-unit-effort or capture-mark-recapture), it does have similarities to the concept of 'effective number of spawners', which generally refers to estimates of the number or proportion of reproductively active adults in a distinct population and which is often used in fisheries literature.

In this project we focused on estimating Ne for populations of elasmobranchs (i.e. species of shark, skate, or ray). Population sizes and offspring numbers for these species are typically smaller than for other fisheries species such as teleosts (i.e. bony fishes), and hence are easier to work with. Specifically, we have applied the Ne estimation method to the two commercial elasmobranch species (dusky shark *Carcharhinus obscurus* and sandbar shark *C. plumbeus*) that represent the highest catch in the NSW large shark fishery and are therefore of relevance for practical management purposes.

In the scientific literature, there are two general categories of Ne. The first has a historical context (Historical Ne – 'H-Ne'), estimating the proportion of individuals reproducing over evolutionary timescales. H-Ne is not directly relevant to this project. The second is Contemporary Ne ('C-Ne'), which has the potential to provide recent information relating to demographic parameters and changes through time in these parameters for existing, exploited populations. Determining C-Ne is the focus of our work here and, in all reporting associated with this project, is simply referred to as Ne hereafter.

In simple terms, Ne-gene estimates are driven by the measurement of genetic associations among loci (technically two-locus gametic linkage disequilibrium) in the genomes of offspring. An increase in genetic association among loci arises due to their parents being a subset of the total number of mature individuals in the population. When this occurs in domestic animals it is called 'inbreeding' and is well understood and quite easily measured. In contrast, for much larger wild populations, the measurable amount of this property per individual is usually very small and more difficult to detect. For this reason, a sound sampling design is required to estimate Ne-gene in wild populations. It requires a large amount of genetic data to be collected per individual and from a considerable number of individuals.

For the genetics component of this project, our main hypothesis was that empirically derived estimates of Ne would provide information abundance for fisheries management and fisheries monitoring of the two most frequently caught species in the fishery. The targeted fishery for *Carcharhinus plumbeus* (sandbar shark) and *C. obscurus* (dusky shark) in NSW waters is in need of new information to assist with plans for sustainable future exploitation. The shark species co-occur across the fishing grounds off NSW and most likely would have experienced similar historical environmental fluctuations and catastrophes. Co-occurrence removes environmental effects as a major contributing factor to differences in Ne detected between the two species.

We used extensive computer simulations, produced by NeOGen software (specifically developed for this purpose in this project), to translate empirical Ne-gene estimates to estimates of abundance. We also used computer simulations to track the decline in Ne-gene over time in response to the decrease in population size due to harvesting. We used customised versions to the NeOGen software to explore this.

The life history characteristics of dusky shark and sandbar shark differ in two important ways that predicts disparities in the magnitude of empirical estimates of Ne- gene between the species. The key life history difference are their ages at reproductive maturity (or the youngest age at which they can reproduce) while the second is their longevity (or for how long they can live). While both species mature when quite old and are long-lived, the dusky shark becomes sexually mature later in life (at least 16 years old for females) compared to sandbar shark (at least 10 years old for females) and typically lives for longer (up to 34 years) compared to sandbar shark (up to 28 years). The two species are, however, similar in that on average only a few offspring per adult pairing per year will reach sexual maturity, thereby maintaining a population size regulated by the environment in which the population exists. In a given area, a longer-lived species with a slower rate of reproduction (e.g. older age at sexual maturity or few offspring) will have a smaller population size relative to a more short-lived species that reproduces earlier or more frequently. Thereby, population size is maintained primarily by the reproductive rate of a species in conjunction with the influence exerted by the surrounding environment (food availability, predation, competition). Thus, assuming the reproductive rates are relatively accurate, and the environmental influences are similar for both species, dusky sharks may naturally be less abundant than sandbar sharks in waters off NSW. Should this hypothetical difference be true, it may be detected by our study as a lower estimate of Ne-gene and abundance for dusky shark than for sandbar shark. Subsequent results from the study showed this to be supported.

To achieve objective #1, we explored the potential usefulness of Ne-gene for fisheries management and monitoring of elasmobranch species, the dusky and sandbar shark in particular. The first step was to undertake computer modelling to understand how Ne-gene relates to population parameters commonly used in fisheries stock assessments, such as the number of individuals in juvenile and adult cohorts. Second, genetic data were collected from substantial numbers of dusky shark and sandbar shark harvested from NSW waters, yielding empirical Ne-gene estimates for each species. Finally, the computer model generated as a result of the first step (i.e. 'NeOGen') was used to convert estimates of Ne-gene into abundance estimates and to assess the effect of harvesting on Ne-gene to inform fisheries and environmental managers (Blower *et al.*, 2019).

1.2 Description of the NeOGen model

A computer simulation model (NeOGen) was developed during this project to explore Ne-gene for populations of various elasmobranch species (Blower *et al*., 2019). NeOGen simulates the birth, growth and death of individuals in a population over many generations through time. It simulates the occurrence of multiple overlapping generations, the annual production of offspring, the effect of annual natural mortality and the longevity of the species.

In the simulated population, NeOGen represents each animal by its 'genotype'. A genotype is an individual's combination of genes (or alleles) across a range of genetic markers (referred to here as genetic loci). The software simulates reproduction of sexually mature individuals by mating them at each time-period step (one year or one generation) to produce offspring. Offspring are represented by a genotype that is a combination of the genotypes inherited from their parents. At each time-period step, a proportion of individuals are randomly selected to die of non-fishing-related causes (natural mortality) and fishing mortality (in a customised version of NeOGen). The software repeats these processes at each time-period step for multiple, overlapping generations through time, thereby tracking the pedigrees of families across the generations.

NeOGen simulates populations of various sizes (as determined by the user), with population size maintained as approximately constant across generations. After simulation stabilisation ('burn-in'), the software provides estimates of Ne-gene, as well as the number of individuals for each cohort category (neonates, juveniles, sub-adults and adults). The software calculates Ne-gene using the genetic data from a user-defined sample of simulated individuals. The development and testing of the software is described in detail in Chapters 2 and 3 of Blower (2020).

NeOGen was used in two ways in this project. It was used to link empirically determined estimates Ne-gene to total population size (N). A customised version of NeOGen, simulated artificial annual harvesting (i.e. fishing mortality, which contributed extra deaths in addition to natural mortality). This provided an avenue for exploring the demographic sustainability of the population at various rates of fishing and for exploring the predicted decline in Ne- gene associated with harvesting.

1.3 Results summary

This project developed and demonstrated the use of a novel method of population assessment for elasmobranch species based on genetic estimates of Ne. NeOGen software was used to infer population size, demography, and harvest vulnerability of two shark species from empirical estimates of Ne and life history characteristics.

Next-generation sequencing techniques were employed to develop species-specific microsatellite genetic markers and full mitogenomes for both species. Large tissue sample sets were genotyped under stringent quality control, after which population structure and the empirical Ne was estimated using the linkage disequilibrium method. Population structure, required to define the spatial limits of biological stocks for Ne estimation, was detected between western and eastern Australia for the sandbar shark, but none was observed for the dusky shark.

Populations of many sizes were simulated for each species using NeOGen software based on estimates of life-history traits that influence Ne (gestation, reproductive resting, polyandrous mating). The mathematical relationship between Ne and population size was determined for each species. This allowed the prediction of N from empirically derived Ne estimates.

For both species, the ratio between Ne and the number of sexually mature adults (Ne / Nc) $\approx$ 0.6. The population of sandbar sharks was estimated to be larger (N $\approx$ 105,000) than the population of dusky sharks (N $\approx$ 35,000).

To forecast sustainable harvest volumes and to evaluate relative harvest vulnerability, simulated populations of both species were subjected to depletion. Adult harvest exceeding the observed fishery harvest volumes in 2008 was found to be sustainable for both species, although juvenile harvest was predicted to be more sustainable than adult harvest.

A decline of Ne was detected within a decade after harvest commencement, around the first age at maturity for both species. Dusky sharks were found to be more vulnerable to exploitation than sandbar sharks; sustainable harvest volumes were smaller; Ne was lower and the decline in Ne was more pronounced.

The Ne-based population assessment process developed and demonstrated here for sandbar and dusky sharks allows researchers to forecast population size based on empirical estimates of Ne. It also allows evaluation of Ne / Nc relationships, likely demography and depletion vulnerability for elasmobranch populations.

Methods and results are described in detail in Chapter 4 of Blower (2020).

1.4 Application and limitations

Our vision for the application of Ne-gene and NeOGen is a cycle of consultation, sample and data collection, and then modelling, followed by the setting of harvest limits, fishery monitoring and further consultation. The practical application of this cycle begins with the collection of biological samples from a given fished population for the purpose of obtaining Ne-gene estimates. These, along with information about life history and sources of mortality, are provided to NeOGen, which estimates the size of that population. Different levels of simulated fishing mortality can then be evaluated using NeOGen, and sustainable fishing levels duly estimated. Using this information, suitable harvest limits can then be formulated in consultation with stakeholders. Following a period of fishing with these formulated limits (such as, for example, three to five years) with associated traditional fishery monitoring, the genetic sampling, modelling, and consultation cycle can then be repeated. If the modelling indicated that the new Ne-gene and population size estimates have reached the predicted equilibrium, no further action is required with respect to adjustment of harvest limits. If not, new limits can be set using NeOGen and the monitoring cycle repeated.

This process has similarities to the current process of fisheries stock assessment. Both use consultation, information about life history and modelling techniques. Both approaches have strengths and weaknesses. Regular fisheries models use CPUE and catchability to estimate biomass, while NeOGen uses Ne to estimate population size. However, NeOGen does not rely on catch reporting or estimation of fisheries catch to estimate biomass, it only requires tissue samples for genetic analysis. In the future, the two processes may be able to be integrated.

A major limitation is the validation of the abundance measures from genetic sources. For naturally occurring species, it is very difficult to ever know abundance with accuracy and thus validate the Ne-gene or any genetic abundance estimation method. Workers have had varied success comparing estimates of abundance from non- genetic sources such as fisheries assessments (Hauser *et al.*, 2002; Ovenden *et al.*, 2007; Jones *et al.*, 2019) and capture-mark-recapture (Dudgeon *et al.*, 2015). Here, instead, we have used population-simulation to ground-truth the inferred abundance of sandbar and dusky sharks on the NSW coast. The use of simulation in this study had additional goals, such as the effects of harvest on population size and rate of decline of Ne-gene under harvest conditions. However, the outcomes of the simulation approach are only as good as the model, which is only an approximation of population dynamics and demography. Interested readers can find an extensive discussion of limitations and caveats, as well as comparison to other genetic work from the literature, in Chapter 5 of Blower (2020).

Objective 2: Determine the short-term and distance movements of sandbar and dusky sharks to assist in the development of potential spatial management options like time-area (spatio-temporal) closures

Our shark tagging and tracking methodology utilised a combination of pop-up satellite archival tags (PSATs) and acoustic tagging technologies to collect data on the large- and smaller-scale movements of tagged sandbar sharks and dusky sharks in continental shelf waters off NSW and Queensland over an 18-month period. These methods provided detailed positional and environmental information (PSATs), along with a cost-effective and independent means for validating PSAT positional data and sporadically locating sharks over a much longer time period via internally deployed acoustic transmitter tags and Australia-wide 'listening station' arrays administered through the IMOS Animal Tracking Facility (ATF) to record movements of acoustically tagged animals (Steckenreuter *et al.*, 2016). Results of this component of our research have been published in a scientific peer-reviewed journal as Barnes *et al.*, 2015.

PSAT technology has been extensively used around the world to track many species, including sharks, to investigate a range of movement behaviours and environmental associations (Hussey *et al.*, 2015). Once attached to a shark, usually via a dart attachment into the surface skin and flesh just behind the dorsal fin, a PSAT collects and internally stores depth, temperature, light-level and time data at five-minute intervals. In our study, tag release from the sharks (i.e. detachment and 'pop-up' to the surface) was programmed to initiate after 100 days, or if the tag had been at a constant depth for four days (indicating likely death of the host shark), or if depth exceeded 1700 m (ensuring that the PSATs would detach before reaching damaging depths). Upon breaking the surface following detachment, a PSAT commences electronic transmission of the stored data via satellite to Advanced Research and Global Observation Satellites (ARGOS), which then transfer the data to researchers.

The light-level, depth and time data recorded by the PSATs are processed through data models to generate estimates of the position (latitude and longitude) of the shark through time, ultimately providing a two-dimensional 'track' representation of the most probable movements of the shark over the period between deployment and tag release. These 'most probable tracks' can reveal any large-scale movements or migrations, and/or can demonstrate that the shark stays in, or returns to the area in which it was tagged (known as 'site fidelity' or philopatry). Similarly, data recorded by PSATs provide insights into any associations (or 'preferences') that the shark may exhibit with respect to water temperature, depth and seabed habitat, and any movements up and down in the water column driven by the day/night cycle.

Long-lasting acoustic telemetry tags implanted in the body cavity of sharks (or any suitably sized aquatic animal) can be detected for over 10 years by arrays of strategically positioned, stationary listening stations throughout riverine, estuarine and continental shelf waters. The tags repetitively transmit a unique acoustic sequence at a set frequency of 69 kHz, with transmissions repeated after intervals of around one minute. If a shark moves to within around 500 m of one of the listening stations, depending on the location habitat & environmental conditions (Huveneers *et al.*, 2016), the unique acoustic sequence is detected and stored (along with the time of detection) by the listening station. Data stored by each listening station must be periodically downloaded *in situ* by SCUBA divers, after which it is transferred to researchers.

NSW DPI currently manages a substantial array of acoustic transmitter listening stations positioned throughout NSW inland and continental shelf waters which, in combination with the national network of listening stations of other researchers and agencies through the IMOS ATF, provide a useful matrix for low-resolution tracking of large-scale movements of tagged animals over a long period of time. In the context of our study, acoustic tags not only provide the potential to record long-term movement data via the IMOS ATF receiver network, but also potentially allows validation of PSAT data.

2.1 Movements of tagged sandbar shark and dusky shark

Targeted demersal longlining for large sharks was conducted from chartered commercial fishing vessels in waters within 20 km of the coast (just north of Coffs Harbour) over nine days between March and July 2013. Totals of 61 sandbar shark and 39 dusky shark were captured, with eight mouth-hooked individuals of each species (four female and four male sandbar sharks; three female and five male dusky sharks) fitted with a PSAT and an acoustic telemetry tag, and then released. In an attempt to maximise chances of survival and therefore yield of useful movement data, sharks used for our tagging and tracking research were selected only from the more active and animated of the sharks caught (i.e. those assessed as being likely to quickly recover from the capture/tagging process).

All 16 PSATs successfully recorded and transmitted data, with data from three indicating that the host sharks (two sandbar and one dusky) had died within 8 h of release and not far from the release location. Tracking data were recorded over periods of between 1 and 60 days for the remaining 13 sharks before unexplained, premature PSAT detachment, which is a technical issue not uncommon for these types of tags.

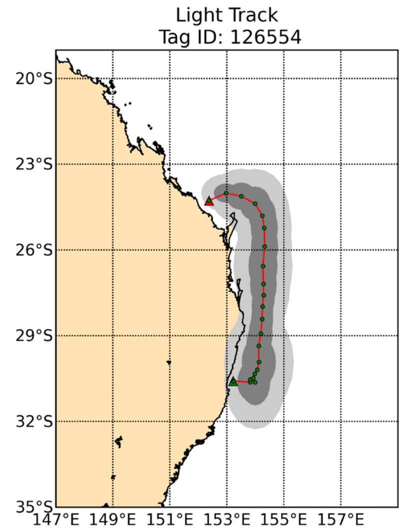
During the first 24 h following tagging and release, surviving sharks of both species first swam in an easterly, offshore direction to waters beyond the edge of the continental shelf, between 55 and 180 km from the coast – most likely as a behavioural reaction to capture. After the initial easterly movement, the most probable tracks estimated by PSATs prior to detachment (after 1 – 60 days) generally followed or remained in relatively close proximity to the edge of the continental shelf (i.e. within 50 km), possibly indicating a general preference for outer-shelf waters by these species, as has been previously reported elsewhere in the world. While both species generally remained in outer- shelf waters during the tracking period, the general patterns in direction of movements for the two species differed considerably.

Over at least two to five days following the initial easterly movement described above, all six surviving sandbar sharks moved through outer-shelf waters in generally southward directions to at least as far south as east of South West Rocks (around 100 km south), but in one case as far south as east of Newcastle (around 350 km south over 30 days). PSATs of four of the six surviving sandbar sharks detached after less than a week following release, while PSAT detachment occurred after 22 and 60 days for the remaining two sandbar sharks. Interestingly, most probable tracks estimated using PSAT data for these latter two sharks indicated that after 5 and 30 days, respectively, they stopped moving south and started moving back in a generally northward direction. The first of these two sharks ended up in outer-shelf waters east of Brisbane, Queensland, where its PSAT detached (total estimated track of around 725 km), while the second, after having moved around 350 km south, ended up back within approximately 13 km of the release location (total estimated track of around 969 km). Over an 18-month period following release of the tagged sandbar sharks, acoustic tag detections occurred for four of them, mostly within 30 km of the release location, suggesting a degree of site fidelity in that each year they may return to that general area in which tagging was undertaken.

In contrast to sandbar shark, following the initial easterly movement five of the seven surviving dusky sharks moved in generally northward directions to Queensland outer-shelf waters at least as far north as east of Tweed Heads (around 212 km north in 8 days until PSAT detachment), and in three cases as far north as east of Fraser Island (up to around 606 km north over 12 to 30 days until PSAT detachment). The remaining two dusky sharks moved relatively modest distances (up to 167 km) in a generally southward direction over less than five days until early PSAT detachment. Unlike sandbar shark, the most probable tracks estimated using PSAT data for tagged dusky sharks did not show any reversals in the direction of their large-scale, long-term movement pattern. However, acoustic tag detections, which occurred after PSAT detachment for five of the seven surviving dusky sharks, did indicate similar reversals in direction in four of those five cases, indicating the possibility of site fidelity in this species. Interestingly, two of the seven dusky sharks were detected by acoustic transmitter listening stations positioned on the continental shelf east of Sydney, with one of the two having been previously tracked by PSAT to waters off North Stradbroke Island in Queensland, demonstrating the very large geographical range in movements by the species through eastern Australian waters.

PSAT data revealed that tagged sandbar and dusky sharks collectively spent around 85% of their time at depths in the water column between 0 m (i.e. the surface) and 100 m deep, although some short-term dives to depths of up to 287 m and 498 m, respectively, were recorded. The sandbar sharks spent only 9% of overall time in the 0–20 m depth zone and the highest proportion of time (32%) in the 20–40 m zone, but with few individuals approaching the surface. In contrast, time spent by dusky sharks among the shallowest four 20-m depth zones (0–20 m, 20–40 m, 40–60 m and 60–80 m) was quite evenly distributed (i.e. between16% and 22% for each zone, Fig. 2), with individuals readily swimming at the surface but also diving 200m deeper (498m) than sandbar sharks. General patterns in vertical movements between the depth zones by tagged sandbar sharks were also detected, with sharks showing a preference for deeper water during daylight hours and moving up to shallower zones at night (Fig. 3), although these patterns were not distinct for all individuals. There was less evidence for daily patterns of movement among depth zones in dusky sharks, with only one individual displaying similar behaviour.

(A)



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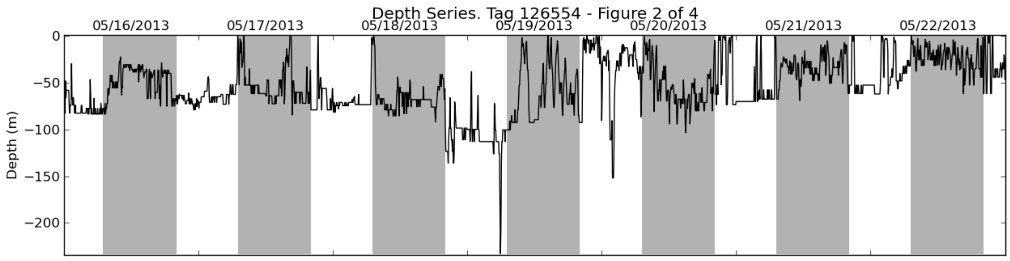

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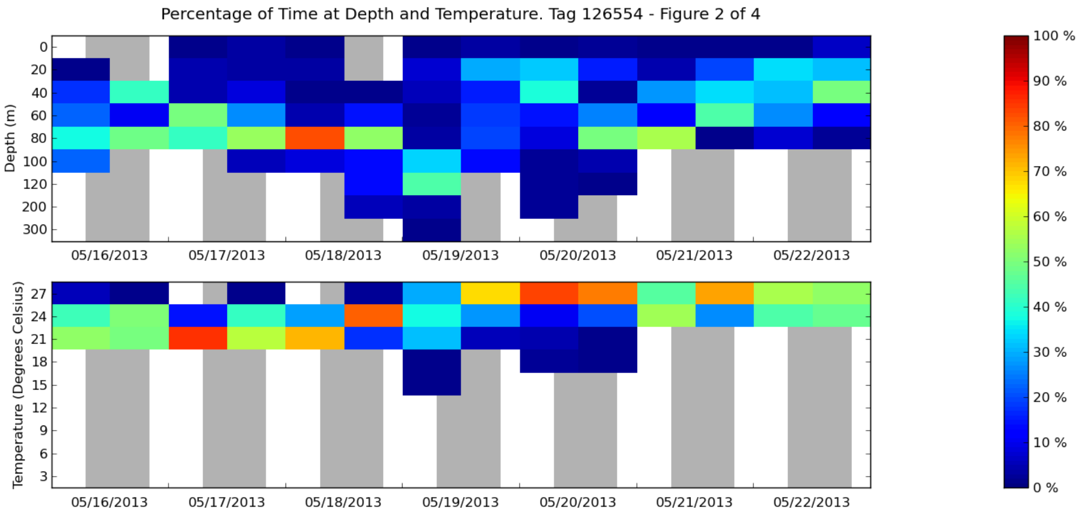
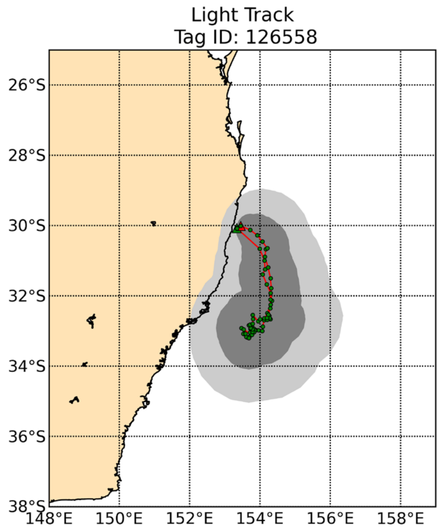


Figure 2 An example of dive data derived from a pop-up satellite archival tag (PSAT) for a dusky shark (*Carcharhinus obscurus*) released from longline fishing gear off northern New South Wales. (A) Calculated track of the shark; (B) Diel depth profile and (C) Percentage of time at depth and temperature over 1 week.

(A)



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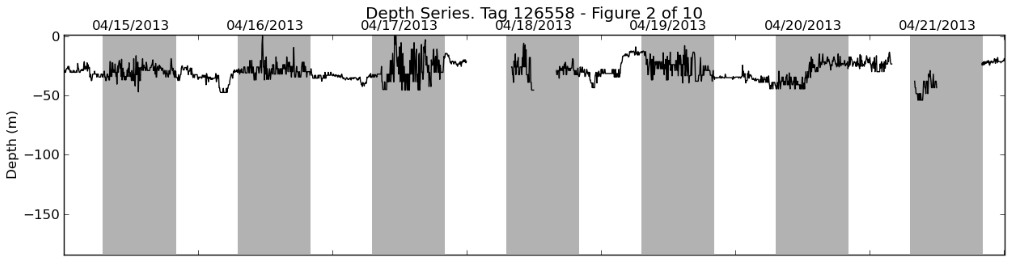

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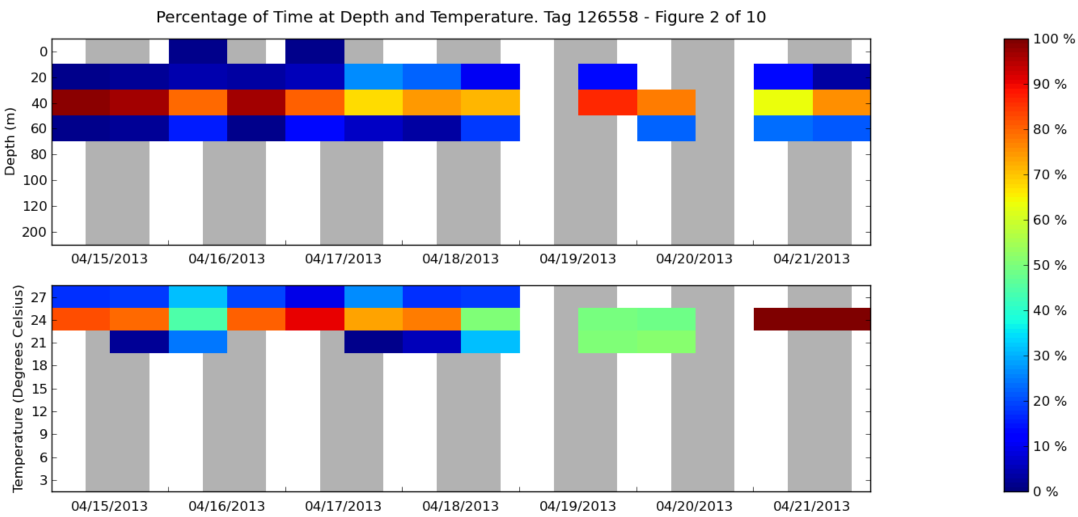


Figure 3 An example of dive data derived from a pop-up satellite archival tag (PSAT) for a sandbar shark (*Carcharhinus plumbeus*) released from longline fishing gear off northern New South Wales. (A) Calculated track of the shark; (B) Diel depth profile and (C) Percentage of time at depth and temperature over 1 week.

2.2 Post-release mortality in sharks caught by setline, tagged and then released

By using a commercial shark fishing vessel and typical commercial longline gear and fishing procedures to capture the sharks involved in the tagging research described above, we were able to collect data for preliminary investigations into the likelihood of tagged sharks dying following release (known as 'post-release mortality') and factors associated with their capture that may influence any mortalities detected. Such information provides some insight into post-release mortality in sharks released after surviving capture as part of normal commercial longline fishing activities, such as sharks that must be released once trip catch limits are reached. However, it is important to emphasise that the tagged and released sharks in our study cannot be considered truly representative of sharks released during commercial fishing activities for two reasons:

(1) only sharks displaying suitably active and animated behaviour were selected for tagging to maximise chances of successful tracking research outcomes, based on their condition scores (Table 2 in Butcher *et al.*, 2015). These would only represent the most 'active' end of the spectrum of conditions in which released (discarded) sharks would be in during normal commercial fishing, with the other end of the spectrum being dead or close to death.

(2) the on-deck blood sampling and tagging procedure (taking 5–10 minutes) would not be part of the on-deck, pre-release procedure employed during normal commercial fishing.

These two factors, combined with the very small sample size for each species (i.e. eight sharks) prevent us from making any definitive conclusions regarding mortality in large sharks released following capture during normal commercial longlining activities.

As outlined in previous sections, examination of PSAT depth data from three sharks (two sandbar sharks and one dusky shark) revealed a period of four or more days at constant depth within the general vicinity of capture and starting shortly following release (3.5, 6.0 and 7.5 hours respectively, Fig. 4). In each of these instances the constant depth readings were consistent with maximum water depths at PSAT location and that these animals were likely dead on the seabed and therefore represented post-release mortality. Vertical movement profiles prior to presumed mortality showed all three sharks diving to around 40 m immediately following release. The two sandbar sharks remained in the middle to upper portion of the water column before a sudden descent to the bottom (presumably upon death), while the dusky shark gradually descended to the seafloor.

Overall, the short-term post-release mortality rates for sharks caught on longlines, tagged and then released for the purposes of this study were 25.0% for sandbar shark and 12.5% for dusky shark. Notably, there was no apparent correlation of these presumed deaths with these individuals not spending longer time on the hook compared with the range for surviving sharks (respectively around 2, 5 and 11 hours on the hook compared to a range of 1 and 18 hours on a hook for surviving sharks). Further, as mentioned in section 3.4, none of the blood chemistry analyses suggested any patterns of difference in measured stress indicators between the tagged sharks that presumably died soon after release and those that apparently survived.

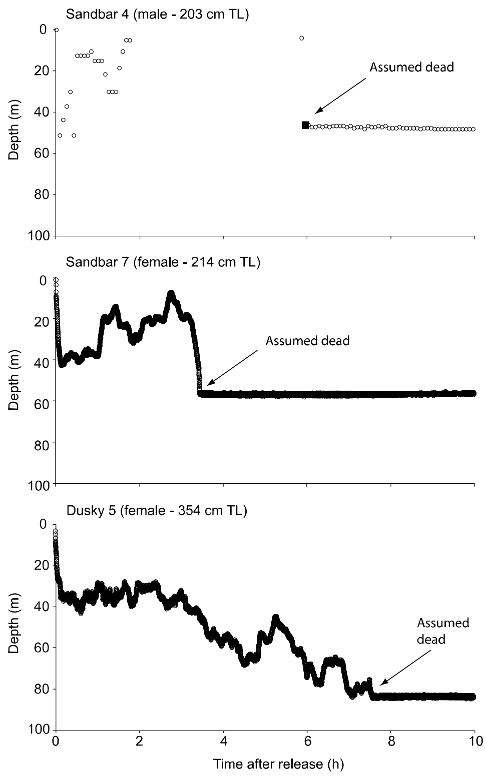


Figure 4 Depth profiles for two tagged *C. plumbeus* and one *C. obscurus* presumed to have died within 8 hours of release following capture and onboard tag attachment. Profiles produced using summary data (5 minute intervals) transmitted by PSATs.

Of concern, is that all sharks tagged were considered 'healthy' and exhibited apparently strong reflexes that deemed them likely to survive. The mortality rate of 25% and 12.5% for this cohort of animals suggests that any less vigorous animals released as a requirement of some catch-limit regulation imposed by fishery management, may exhibit considerably greater post-release mortality rates. Additionally, any level of mortality in sharks released (or discarded) at sea as a regulatory requirement represents a source of unreported or at least unconfirmed fishing mortality. Therefore, given the demonstrated vulnerability of species such as sandbar shark and dusky shark to heavy exploitation, such regulatory strategies may not be in the best interests of conservative fishery management for fisheries targeting large whaler sharks (Carcharhinidae).

Objective 3: Develop a fishing technique that will decrease mortality of unwanted species, particularly threatened and protected species, to minimize environmental impact of the fishery

3.1 Hooking patterns, stress and mortality rates in shark species caught by longline

The primary fishing method used to target large sharks in NSW involves bottom-set (or 'demersal') longlines, which are set on or near the seabed and comprise a 'mainline' that can be kilometres long, along which smaller secondary lines with attached baited hooks (termed 'gangions') are typically spaced around 20 m apart (Macbeth *et al*., 2009). The longlines are typically deployed at depths of 50−100 m to target various species of large whaler shark.

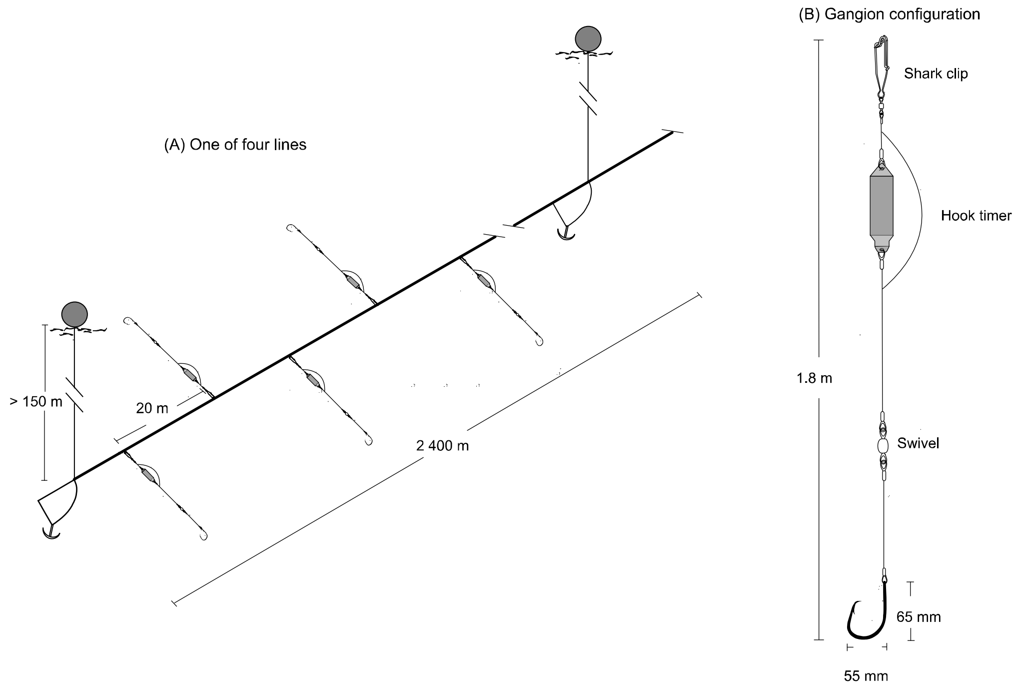


Figure 5 Schematic representation of (A) one of the four deployed lines and (B) expanded view of a gangion with hook timer attached

One concern about the large shark component of the OTLF is that, in addition to the targeted catches of species such as sandbar shark (*Carcharhinus plumbeus*), dusky shark (*Carcharhinus obscurus*), blacktip sharks (*Carcharhinus limbatus/tilstoni*) and spinner shark (*Carcharhinus brevipinna*), unwanted animals (collectively termed 'bycatch') are also sometimes caught and then released alive or discarded dead. These bycatches can include threatened, endangered or protected (TEP) species that are considered vulnerable in terms of their population status, including greynurse shark (*Carcharias taurus*), great hammerhead (*Sphyrna mokarran*) and scalloped hammerhead (*Sphyrna lewini*). Catches of TEP species should be minimised through appropriate, selective fishing practices, but unfortunately very little scientific data are available describing their interactions with fishing gears, or means by which these can be mitigated.

Deaths (i.e. 'mortalities') occurring directly as a result of commercial longline fishing in the forms of: 1) animals retained by fishers for sale; and 2) unwanted animals (i.e. 'bycatch') dead on the hook and subsequently discarded; can be determined through fisher catch reporting (plus validation via port monitoring) and thorough observer-based research (Macbeth *et al.*, 2009). Estimates of these sources of 'fishing mortality' are then used by fishery managers to help in determining appropriately sustainable annual catch (or bycatch) limits for the various species involved.

Bycatch animals released alive after capture, however, may have sustained levels of damage or physiological stress during capture such that their condition can quickly deteriorate upon release, ultimately resulting in impaired immune function, elevated risk of predation and possible death (i.e. 'post-release mortality'). Rates of post-release mortality in bycatch animals are typically estimated via tagging studies, as discussed in Section 3. Similarly, hooked animals escaping from hooks prior to (or during) gear retrieval may sustain injuries and/or stress, potentially resulting in undetected 'pre-retrieval mortalities' following escape. This category also includes hooked animals preyed upon and killed by other animals, commonly leaving no biological trace on the fishing gear. These sources of pre-retrieval fishing mortality apply to target and bycatch species alike, are perhaps the most difficult components of overall fishing mortality to detect and measure, and are very seldom quantified let alone included in total allowable catch calculations or total bycatch estimates for the fishery.

As part of the work undertaken by this FRDC Shark Futures project, we examined three aspects of the capture (hooking and landing) of targeted and bycatch species by commercial longline gear that may provide insights into ways of minimising unwanted hooking of bycatch animals (particularly TEP species). Additionally, we investigated ways of increasing their chances of survival once released.

Time of hooking will determine for how long animals are hooked prior to gear retrieval and therefore possibly influence their levels of physiological stress and chances of survival following release (see below). By recording and analysing data concerning environmental and/or operational factors that may influence the timing of hooking among and within species, strategies for avoiding hook-ups of certain species can potentially be formulated. Further to this, such hook-by-hook research methodology also provides the opportunity for a preliminary assessment of the frequency of hook-loss from 'bite-offs' which, as mentioned above, could be indicative of an unknown rate of pre-retrieval mortalities for unknown species.

The second aspect concerns levels of physiological stress experienced by individuals hooked by demersal longlines. Stress responses by sharks and fish to hooking and capture manifest as a series of biochemical and physiological processes that can be detected by measuring certain blood chemistry parameters. Therefore, by taking blood samples at the point of capture (i.e. upon retrieval of the catch to the vessel), potentially important insights into stress responses can be assessed for the subject species examined. Further, recording and analysing data concerning different environmental and/or operational factors that may influence stress levels might help explain any observed differences in stress responses (and rates of mortality) between those species. Such understanding may, in turn, help in revealing strategies to minimise stress and injury during capture and therefore, more importantly, potentially reduce rates of at-vessel and post-release mortality in bycatch animals, particularly TEP species.

The third aspect concerns rates of at-vessel mortality (i.e. confirmed dead upon retrieval to the vessel) for various targeted and bycatch species. Depending on species, certain operational (duration of gear deployment and time on hook), biological (size, sex, general physical condition and hooking damage) and environmental (e.g. water depth and temperature) factors may influence at- vessel mortality rates. As mentioned above, by estimating rates of at-vessel mortality and identifying factors that influence mortalities, potential strategies for reducing rates of at-vessel and post-release mortality in bycatch animals can be formulated.

This summary describes the research methodology we used to investigate patterns in hooking, at-vessel physiological stress and at-vessel mortalities associated with some selected target and bycatch species (including TEP species) caught during chartered longline fishing activities undertaken as part of the project. We also offer recommendations regarding possible management options for reducing captures of unwanted bycatch species, minimising post-release mortality in bycatch, and directions for future research.

3.2 Description of the commercial longline gear and fishing operation employed during the research

The test longline gear was designed to be representative of a typical commercial demersal longline used by fishers targeting large sharks in NSW waters. The gear comprised a 9600 metre mainline which was comprised of four, physically-separated sections (termed 'lines') for the purposes of our research. Each of the four lines had 120 gangions (baited 16/0 circle hooks attached to 1.8m monofilament lines) spaced around 20 m. Each gangion was rigged with a digital 'hook timer' designed to activate when an animal was hooked (Figure 5, Broadhurst *et al.*, 2014). By incorporating a digital hook timer with every baited longline hook, we were able to determine the amount of time that elapsed between hook deployment and a shark being hooked ('elapsed time until hooking'), and between a shark being hooked and being retrieved to the vessel ('time on hook'). In addition, during the seven- or-more hours that the longline gear was in the water on each sampling day (see below), water temperature was recorded every 30 minutes by eight loggers attached along the mainline and two to surface floats.

On each of 17 suitable fishing nights the longline gear was deployed in water ranging in depth between 45 m and 105 m. Retrieval of two of the four lines was commenced after 7 hours, while retrieval of the remaining two lines commenced 14 hours after deployment. This collectively provided a total of 8,160 set hooks for our study, with times of deployment and retrieval for each hook combining to provide a hook-specific 'soak time'. The staggered retrieval schedule, combined with inherent high variability in the speeds of gear deployment and retrieval, provided a wide range of 'soak time' and 'time on hook' measurements with which to investigate at-vessel physiological stress and mortality rates in captured animals.

All catches were either brought on board (retained) or alongside the vessel (e.g. TEP or unwanted individuals) where they were assessed for confirmation of species, their total length (TL) measured, and their sex and any signs of damage/injury recorded prior to on-board processing or release. Other technical and environmental data recorded included: the date, location, seabed depth, swell and sea conditions, current and direction, wind speed and direction, time of moon rise and set, sun rise and set, moon phase and the percentage visible, surface and bottom water temperatures, the presence or absence of rain, and the times of deployment and retrieval for each hook to provide total 'soak time'.

3.3 Patterns in hooking of shark species caught during demersal longline deployments

This component investigated how soon after longline deployment sharks became hooked ('elapsed time until hooking'). In turn, this allowed calculation of its 'time on hook' prior to gear retrieval and, therefore, how long it was subjected to elevated levels of physiological stress and the probability of physical damage to the shark. For unwanted bycatch (including TEP species), these data will likely influence their chances of survival prior to gear retrieval and following release (see following sections). Through correlation with various biological, environmental and operational parameters recorded during fishing operations, potential strategies for reducing or avoiding interactions with unwanted species can be determined and potentially enhance targeted fishing operations. Results of this research are published as Broadhurst *et al.* (2014) and a summary of these presented below.

Statistical analyses in the form of generalised linear mixed-effects models were used to examine the influence of a range of biological (e.g. species or taxonomic group – see below, sex and TL), operational (e.g. time of gear deployment and soak time) and environmental (e.g. seabed depth, bottom water temperature and time of hooking) factors (or 'predictor variables') on two separate 'response variables'. The first response variable, 'elapsed time until hooking', provided data for each shark caught with respect to when during the fishing gear deployment it was hooked. The second response variable, 'numbers caught (per line)', provided information about total numbers caught on the gear. These two analyses enabled us to investigate when sharks were caught during the overall soak time and examine patterns of variability in total catches among species and fishing days. More importantly, they provided the means with which to identify those factors that might explain any differences detected.

Twenty-two species comprising a collective total of 684 individuals were caught, with 72 individuals failing to activate the hook timers (mostly small sharks < 150 cm TL, such as gummy shark, *Mustelus antarcticus*, and wobbegong sharks, *Orectolobus* spp.). The numerically dominant retained species were sandbar shark (160 sharks), tiger shark (*Galeocerdo cuvier*; 123 sharks), blacktip sharks (113 sharks) and dusky shark (74 sharks). Non-target species caught included the following TEP species: scalloped hammerhead shark (52 sharks), greynurse shark (12 sharks), great hammerhead shark (11 sharks), and one loggerhead turtle (*Caretta caretta*). A total of 246 timers were activated without anything being on the hook at gear retrieval, including 65 hooks that were broken off.

To provide sufficient datasets for analysis of response variables, some species were combined together in logical groupings. For example, the '*Carcharhinus*' grouping comprised data for sandbar shark, dusky shark, blacktip sharks, spinner shark, bull shark (*Carcharhinus leucas*) and bronze whaler (*Carcharhinus brachyurus*), while the '*Sphyrna*' grouping comprised scalloped hammerhead, great hammerhead and smooth hammerhead (*Sphyrna zygaena*) sharks. These two groupings, along with two stand-alone species, tiger shark and gummy shark, provided four 'taxonomic group' categories for the statistical modelling. However, gummy shark was not included in the analysis of elapsed time until hooking as very few individuals activated hook timers, presumably mainly due to their relatively small size.

Analysis of elapsed time until hooking found that hammerhead sharks ('*Sphyrna*' grouping) were generally hooked later during gear deployments than tiger sharks and whaler sharks ('*Carcharhinus*' grouping), with the difference between hammerheads and whaler sharks statistically significant. Similarly, analysis of total catches found that the majority of hammerhead sharks were caught over significantly longer overall soak times than all other taxonomic groups, and typically when gear retrieval was during daylight hours. In fact, 50% of the hammerhead sharks (and mostly juveniles) were caught after sunrise, while proportionally fewer whaler sharks (< 15%) and tiger sharks (< 28%) were caught before sunrise.

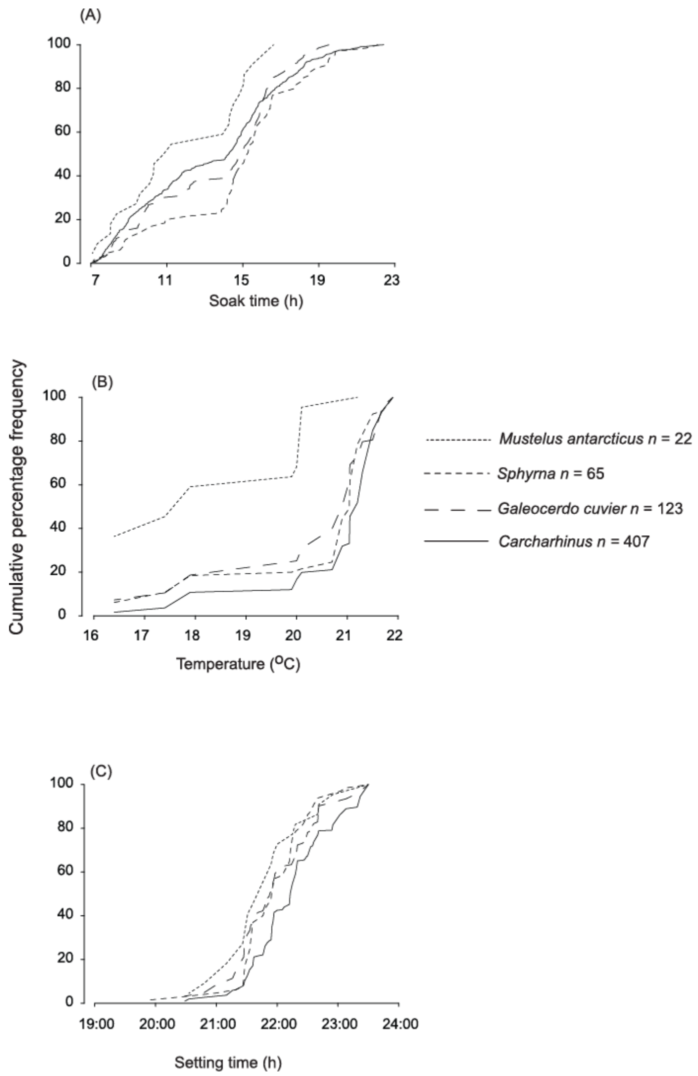


Figure 6 Cumulative percentage frequencies of *Mustelus antarcticus*, *Sphrna*, *Galeocerdo cuvier* and *Carcharhinus* caught plotted against (A) mainline deployment time, (B) bottom temperature and (C) mainline soak time.

Results from our analyses also indicated that hammerhead, whaler and tiger sharks (combined) generally took longer to take baited hooks after earlier longline sets (Fig. 6), suggesting that most of these sharks may not begin actively seeking food until well after sunset. In addition, the more full the moon was (disregarding cloud cover), the less time these species generally took to take baited hooks. In contrast, analysis of total catches found that the earlier in the evening the longline was set, the more gummy sharks were caught (Fig. 6), irrespective of moon phase. Furthermore, most gummy shark were caught during longline sets done in cooler bottom water (between 18 and 20^{o} C), while hammerhead, whaler and tiger sharks were mostly hooked when bottom temperatures were warmer than 20^{o}C (Fig. 6).

There were insufficient numbers of the two other TEP species caught (greynurse shark and loggerhead turtle) to enable analyses. Four of the 12 greynurse sharks were caught on the same line deployment (three within 120 m of each other), while another two were hooked within 60 m of each other on a different day. The remainder of the greynurse shark catch was distributed among the other 15 days. Most were caught during the night or close to dawn. None were caught in close proximity to a known aggregation site. The single loggerhead turtle was hooked in the flipper (without activating the timer) and still quite active, most likely indicating incidental capture through foul-hooking during line retrieval.

Given the above, the only identified variables that might be used to considerably reduce the catches of hammerhead sharks, while not greatly affecting catches of the target whaler shark species, were duration of longline deployment (soak time) and/or when the longline is retrieved, as just over half of hammerhead sharks caught were hooked during daylight. These results imply that restricting longline deployments to night fishing for less than 6 hours and retrieving the gear before dawn might reduce the incidence of overall hammerhead shark capture (particularly scalloped hammerhead), and especially juveniles (<150 cm TL). Restricting soak time in this way might also decrease post-release mortality rates of all animals released (including those of targeted species released/discarded due to trip limit restrictions), simply because all animals (and particularly juveniles more likely to die) would remain on hooks for less time. Restricting gear retrieval to pre-dawn hours may, as a consequence of reduced visibility, also reduce the probability of seabird interactions with baited hooks during retrieval.

Up to around a quarter of potential catches presumably managed to escape from hooks during gear deployment or retrieval (i.e. 246 activated timers without associated hooked animal), probably after incurring at least some level of stress and/or physical damage. This indicates that the issue of 'pre-retrieval mortality' for targeted and bycatch species (and particularly TEP species) should be of genuine concern as an unaccounted source of fishing mortality.

In summary, the large proportions of TEP species (~ 11% of the total catch) and juveniles of some of these species (e.g. 75% of the 52 scalloped hammerhead sharks) hooked in this study strongly support introducing management strategies to improve both species and size selectivity in the NSW large shark longline fishery. Future research should therefore investigate gear modifications for improving size and species selectivity, and/or operational procedures for reducing unwanted mortalities associated with demersal longlines used to target large sharks in NSW waters.

3.4 Physiological stress in longline-caught sandbar shark and dusky shark

In sharks captured by longlines and subsequently released alive, physical trauma and physiological stress caused by the hooking event can potentially result in eventual direct death from stress and/or exhaustion, or at least in a temporary increase in vulnerability to being preyed upon by larger sharks. Changes in blood biochemistry (e.g. 'blood plasma analytes': lactate, glucose, phosphate, urea, total protein, aspirate aminotransferase, creatine kinase, alkaline phosphatase, potassium, magnesium, calcium, chloride and sodium) can be good indicators for assessing physiological responses to (or 'stress' caused by) capture. There are clear relationships between how long the shark had been hooked prior to gear retrieval and their stress levels (Mandelman and Skomal, 2009; Marshall *et al.*, 2012). However, previous research has also found that susceptibility to physiological stress and/or post-release mortality are highly dependent on the species of shark (Gallagher *et al.*, 2014). A better understanding of the relationships between the duration of time hooked and stress levels in longline-caught sharks can help to identify methods to reduce stress-related post-release mortalities. Results of this research are published as Butcher *et al.* (2015) and a summary of these presented below.

Totals of 42 surviving sandbar shark and 23 surviving dusky shark of various sizes and sexes were selected for blood analysis. These two species were chosen because they: 1) are two of the four main target species for the fishery; 2) are known to be highly vulnerable to high fishing mortality; 3) are genetically distinct species (unlike blacktip sharks); and 4) were predicted to provide sufficient sample sizes of surviving sharks for assessing blood analytes across a wide range of capture variables. Within 60 seconds of landing each sandbar shark or dusky shark on deck, an 8 ml blood sample was taken, with part of the sample analysed immediately and the other part stored for later laboratory analysis (Butcher *et al.*, 2015).

While seabed water temperature was consistently found to be around 21°C during the 17 days of longline activities undertaken for our study, water depth ranged between 50 m and 105 m and surface current strength ranged between 0.3 and 2.0 knots. Approximate time on hook varied considerably for the live sandbar sharks (between 1 and 19 hours) and dusky sharks (between 1.5 and 18 hours) from which blood was taken. Generalised linear mixed- effects models were used to detect, for each blood plasma analyte, differences in concentration between the two species and within species (i.e. between sexes or among sizes), and to identify which environmental, biological or operational factors (e.g. time on hook, water depth, condition) might explain any such differences.

Overall, results from blood analysis indicated that the effect on levels of physiological stress in sandbar shark and dusky shark from the hooking and retrieval process was relatively benign, with few apparent trends in blood plasma analyte measurements. With one exception, there were no significant differences between the two species in blood plasma analyte measurements. The exception was a significantly higher average concentration of total protein in sandbar sharks than in dusky sharks. For those blood plasma analytes that were not different between species, data for the two species were combined for further modelling of potentially influential factors.

Very few significant correlations between blood plasma analyte measurements and potentially influential environmental, biological or operational factors were detected. Although correlations were not particularly strong, increasing concentrations of aspirate aminotransferase were detected with increasing water depth in which sharks were hooked, and increasing concentrations of potassium and lactate were detected with increasing time on hook. In contrast, concentrations of chloride decreased with increasing time on hook. Notably, all sharks that were alive upon retrieval to the vessel and assessed as having very low activity levels (i.e. not animated; low response to stimuli) had relatively high concentrations of potassium in their blood plasma.

Collectively, our results were generally similar to other studies and show that the longer sharks were hooked the more elevated their plasma potassium and lactate concentrations were. This has been surmised as a possible precursor to death in sharks subjected to capture and handling stress (Martini, 1974). While our blood chemistry study concentrated on sandbar shark and dusky shark, which would only be released alive (or discarded dead) as a potential consequence of management strategies involving size or trip limits, it is likely that our results may be indicative of stress responses in other species, including TEP species such as hammerhead sharks. Given this, perhaps the simplest way of reducing stress (and therefore mortalities) in hooked sharks would be via simple operational changes such as shorter deployments (< 5 hours), if this is a viable option for the fishers to adopt.

3.5 At-vessel rates of mortality in species caught during large-shark longline fishing

At-vessel rate of mortality refers to the proportion of animals of a given species dead upon retrieval to the vessel, and is known to be highly variable among species. Previous observer-based research in the NSW large-shark longline fishery found the highest at-vessel rates of mortality for spinner shark, blacktip shark, dusky shark and hammerheads (around 80–100% dead; including the recently listed TEP species scalloped hammerhead), with sandbar shark (around 60%) and tiger shark (< 10%) apparently better at surviving the capture process (Macbeth et al., 2009). The rarely captured, but critically endangered greynurse shark was observed to actively swim away from vessels upon release on 100% of occasions on which they were caught with an observer on-board.

As is the case for physiological stress, certain operational (duration of gear deployment and time on hook), biological (size, sex, general physical condition and hooking damage) and environmental (e.g. water depth, temperature and current strength) factors will influence at-vessel mortality rates, with the extent of influence dependent on species. Unlike the earlier, observer-based research, in our study many of these factors were carefully controlled and/or reliably measured, such as time on hook via different durations of deployment (i.e. 7 vs. 14 hours) and the use of digital hook timers, and general physical condition and hooking damage via scientific condition assessment methodology. By estimating rates of at-vessel mortality and identifying factors that influence mortalities, potential strategies for reducing rates of at-vessel and post-release mortality in bycatch animals can be formulated. Results of this research are published as Butcher *et al.* (2015) and a summary of these presented below.

The general operational methodology, profile of catches and summary of data collected during the 17 days of longline deployments are outlined in above sections. Generalised linear mixed-effects models were used to detect differences in at-vessel rates of mortality among species (or logical groupings of species) and within species (i.e. between sexes or among sizes), and to identify which environmental, biological or operational factors might explain any such differences (Butcher *et al.*, 2015). To provide sufficient data per 'taxonomic group' category for these analyses, only the five carcharhinid (whaler shark) species for which at least 10 individuals were caught and mortalities recorded were included as stand-alone categories (sandbar, dusky, blacktip, spinner and tiger sharks), while scalloped hammerhead, great hammerhead and smooth hammerhead sharks were combined as a '*Sphyrna*' grouping.

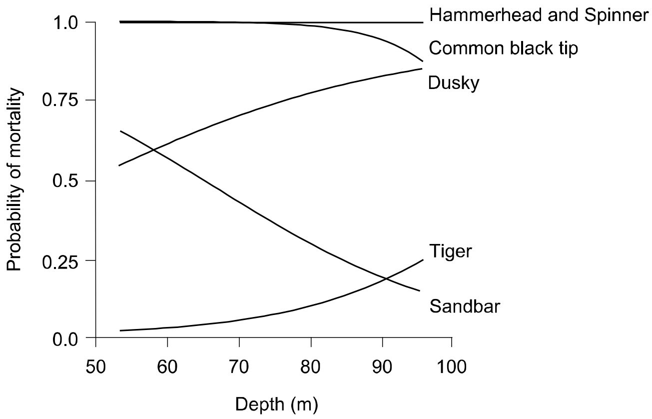


Figure 7 Fitted lines from the GLMMs for the probability of mortality against depth (m) of capture for tiger (n = 123), sandbar (n = 160), dusky (n = 74), common blacktip (n = 113), spinner (n = 50) and hammerhead (n = 65) sharks that were caught over the 17 days of fishing.

The seabed water temperature was consistently around 21°C throughout the 17 longline gear deployments, while water depth ranged between 50 m and 105 m and surface current strength ranged between 0.3 and 2.0 knots. The time on hook across all individuals caught ranged between less than 15 minutes and just over 20 hours. Very few animals exhibited any signs of damage after capture, indicating little depredation on hooked sharks, a general observation also made during previous observer-based research in the fishery (Macbeth *et al.*, 2009). Decreasing vigour (i.e. level of activity upon retrieval) was, as expected, highly correlated with increasing time on hook.

One hundred percent survivorship at retrieval to the vessel was recorded for only seven elasmobranch (sharks and rays) species: greynurse shark, bull shark, spotted wobbegong shark (*Orectolobus maculatus*), ornate wobbegong shark (*O. ornatus*), banded wobbegong shark (*O. halei*), eastern shovelnose ray (*Aptychotrema rostrata*) and smooth stingray (*Dasyatis brevicaudata*).

Notably, the greynurse sharks all survived times on hook ranging between 3 and 12 hours. In cases other than bull shark, this most likely is a fortunate consequence of their ability to 'pump' water over the gills, while whaler sharks and hammerheads require constant movement (or substantial current if stationary) to push water over their gills.

Generalised linear mixed modelling demonstrated that taxonomic grouping and time on hook were strong predictors of at-vessel mortality for the taxa included in the analyses, with longer times on hook generally correlated with a greater chance of mortality (Fig. 7). The variation in rate of mortality between long and brief times on a hook was dependent on taxonomic grouping. This is best illustrated by comparing at-vessel rates of mortality for the longer (14 hours) and shorter (7 hours) line deployments. In general, mortality rates were significantly higher for the 14-hour than the 7-hour deployments, though the extent of difference varied among taxonomic groupings. The difference was clear for sandbar shark (63% and 43% respectively) and dusky shark (80% vs. 53%). The difference was, however, relatively less in the case of blacktip sharks (95% and 86% dead for 14 hour and 7 hour deployments respectively), hammerheads (*Sphyrna* species combined: 90% vs. 87%) and spinner shark (97% vs. 94%), while very few tiger sharks were dead upon gear retrieval irrespective of deployment duration (7% vs. 4%).

The first signs of mortalities occurred after around 1 hour 20 minutes in blacktip sharks and scalloped hammerhead sharks, within 3 hours in spinner sharks, and between 3 and 6 hours in most other large shark species caught. At-vessel rates of mortality in sandbar and dusky shark began to increase more markedly 5 to 6 hours after hooking, but many individuals were still alive 12–18 h after becoming hooked.

Other key predictor variables that significantly explained variability in at-vessel rates of mortality (for taxa included in the analyses) were: 1) sex (males were more than twice as likely to be dead than females, irrespective of species); and 2) depth, depending on the shark species caught. Sandbar sharks caught in water 50 m deep were almost four times as likely to be dead as those caught in water 100 m deep irrespective of their time on hook, while mortalities of blacktip sharks also decreased slightly with increasing depth of gear deployment, especially at depths greater than 70 m. In contrast, dusky sharks caught in deeper water were more likely to be dead than those caught in shallower water. Almost all spinner and hammerhead sharks died on the hook irrespective of water depth.

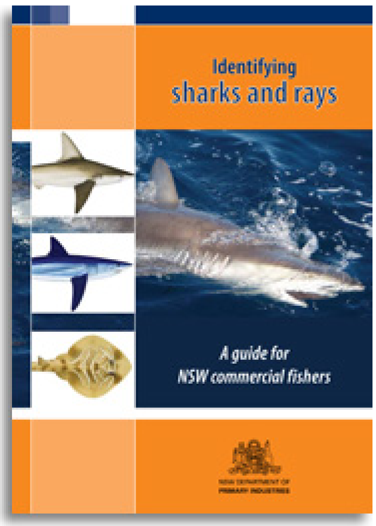
Objective 4: Assess the effectiveness of the NSW DPI shark field ID-guide through ground-truthing on-board shark identification between fishers and observers, plus via genetic testing

Prior to 2008, each OTLF fisher was required to submit a monthly catch report comprising combined monthly totals for fishing effort (in days) by method and catch weight by species or group, with little guidance or regulation with respect to the categories for each type of report entry. Review of summaries of the monthly catch records in 2008 revealed substantial elevations in retained catches of elasmobranchs (species combined) in 2006/07 and 2007/08 when compared with previous years (Macbeth *et al.* 2009). Records also showed that this increase coincided with sharp rises in catches of some large species of whaler (or ‘carcharhinid’) shark: sandbar shark (*Carcharhinus plumbeus*); blacktip sharks, (*C. limbatus* / *C. tilstoni*); and bronze whaler (*C. brachyurus*) (Macbeth *et al.*, 2009). More alarmingly, there were also very large increases for some more ambiguous species reporting categories, including ‘unspecified shark’ and ‘unspecified whaler shark’.

A subset of six OTLF fishers, later defined as the ‘NSW large shark sub-fishery’, were found to be responsible for those specific rises, which peaked in 2006/07 at a combined total catch weight of ~500 tonnes. This was more than three times the annual average for the nine-year period spanning 1997/98–2005/06 (154 t). Many large shark species are highly vulnerable to detrimental levels of fishing pressure, as demonstrated by the well documented and dramatic declines in stocks of sandbar shark and dusky shark (*C. obscurus*) in the US Atlantic large coastal shark fishery during the 1980s and 1990s (Morgan *et al.*, 2009). Deep concern in 2008 over the lack of verified knowledge of the species compositions of catches of large sharks in the OTLF led to a precautionary management approach involving a suite of new regulatory measures, adopted for 2008/09.

Catch-reporting reforms implemented in the OTLF in 2008 comprised measures primarily (but not exclusively) aimed at fishers targeting or incidentally catching large sharks. The goal was to obtain substantial improvements in the quality of data concerning species composition, catch quantities and fishing effort associated with targeting of sharks. Along with pre-declaring of planned fishing trips to fishery managers, daily catch reporting forms ('daily logs') were required to be submitted within 8 h of returning to port. These forms required detailed data concerning: gear use (longline length, number of hooks, number of deployments); fishing grounds visited; and catches (total number of individuals and total weight per species).

To improve the quality of the catch data with respect to the range of shark species being caught, a list of species codes was pre-printed on the inside cover of the logbooks (containing daily logs) that were distributed to fishers. To complement this, an OTLF shark species identification guide ('ID guide'; also available online https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0007/631384/Identifying-sharks-and-rays.pdf) was developed for use on deck prior to shark carcass processing, and distributed to all OTLF fishers in late-2008 (Fig. 8). The structure of the ID guide was designed to correspond with the list of logbook species and species codes (Fig. 9).



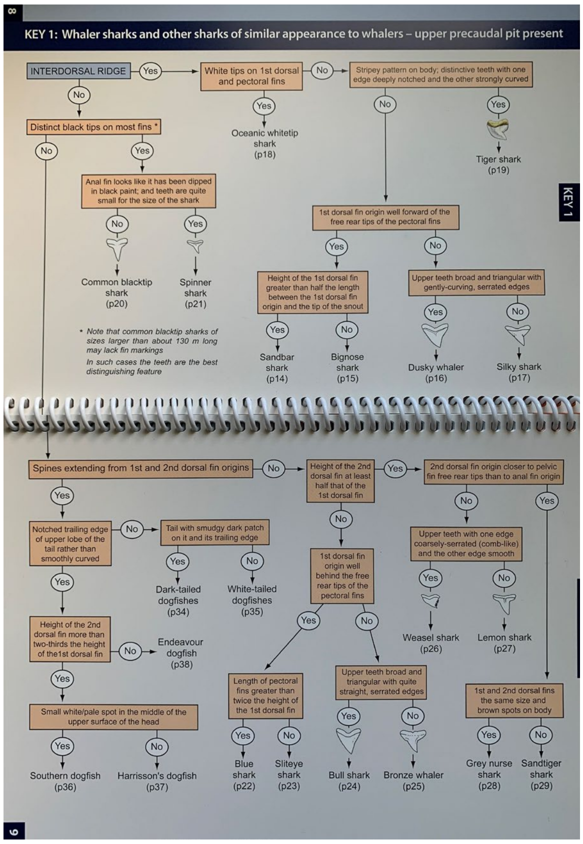
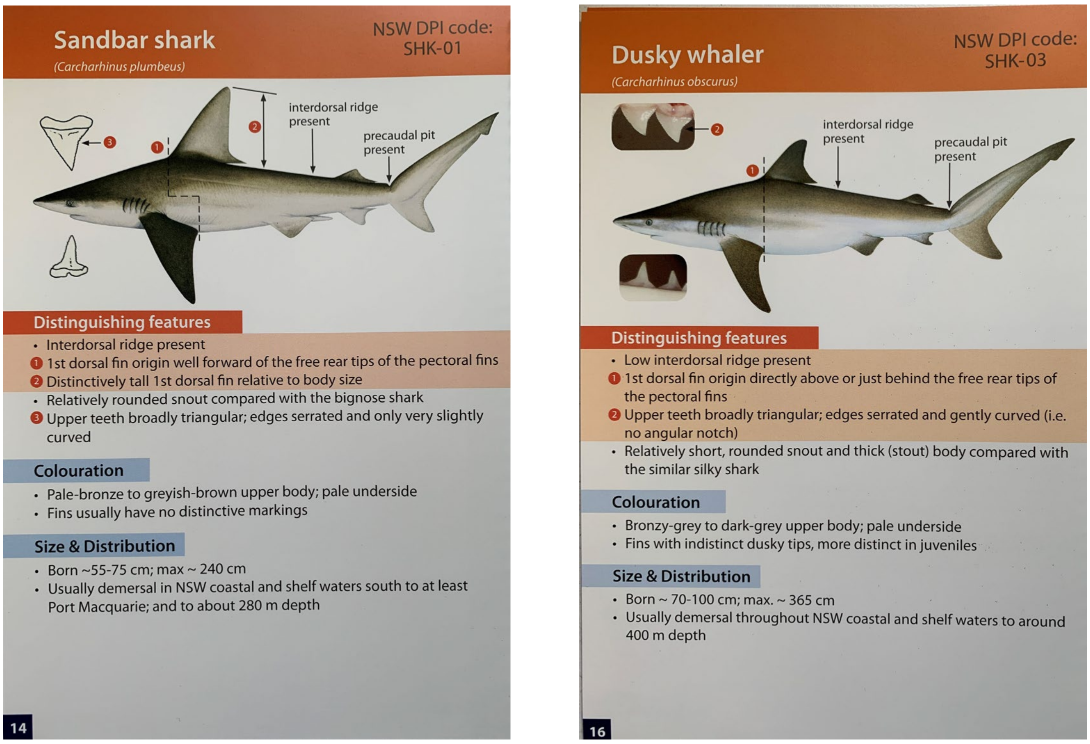


Figure 8 The "NSW DPI Guide for commercial fishers to identifying sharks & rays" and the key for identifying whaler sharks.


Sandbar shark
(Carcharhinus plumbeus)
NSW DPI code: SHK-01
interdorsal ridge present
precaudal pit present
Distinguishing features
- Interdorsal ridge present
- 1 1st dorsal fin origin well forward of the free rear tips of the pectoral fins
- 2 Distinctively tall 1st dorsal fin relative to body size
- Relatively rounded snout compared with the bignose shark
- 3 Upper teeth broadly triangular; edges serrated and only very slightly curved

Colouration
- Pale-bronze to greyish-brown upper body; pale underside
- Fins usually have no distinctive markings

Size & Distribution
- Born ~55-75 cm; max ~ 240 cm
- Usually demersal in NSW coastal and shelf waters south to at least Port Macquarie; and to about 280 m depth

14

Dusky whaler
(Carcharhinus obscurus)
NSW DPI code: SHK-03
interdorsal ridge present
precaudal pit present
Distinguishing features
- Low interdorsal ridge present
- 1 1st dorsal fin origin directly above or just behind the free rear tips of the pectoral fins
- 2 Upper teeth broadly triangular; edges serrated and gently curved (i.e. no angular notch)
- Relatively short, rounded snout and thick (stout) body compared with the similar silky shark

Colouration
- Bronzy-grey to dark-grey upper body; pale underside
- Fins with indistinct dusky tips, more distinct in juveniles

Size & Distribution
- Born ~ 70-100 cm; max. ~ 365 cm
- Usually demersal throughout NSW coastal and shelf waters to around 400 m depth

16

Figure 9 Species identification pages in the "NSW DPI Guide for commercial fishers to identifying sharks & rays" showing their species code in the top right of each page for logbook entries by fishers.

Finally, to obtain verified data concerning catch composition in the NSW large-shark sub-fishery and monitor the success of the new management arrangements, an intensive observer-based data collection program was undertaken during 2008/09 and has since continued on a less intensive basis. The program also provided the opportunity for direct, at-sea education of fishers in on-board identification of shark species and how to use the ID guide, thereby in theory improving the accuracy of the catch composition data being reported in daily logs. Important findings from this observer work included the significant prominence in catches of species either rarely reported (e.g. dusky shark) or completely unreported (e.g. spinner shark, *C. brevipinna*) prior to 2008 (Macbeth *et al.*, 2009).

This summary describes the results of research undertaken to examine whether the catch compositions (number of sharks for each species) in fisher-submitted daily logs match corresponding data collected by observers for fishing trips during which an observer was present. This, along with other related analyses, provides an indication as to whether the updated and improved fishery management measures led to improvements in the reliability of catch reporting by fishers targeting large sharks. Additionally, we present a summary of the results of a detailed questionnaire, distributed among all OTLF fishers to elicit feedback concerning industry usage or non-usage of the ID guide. These data have been published as Macbeth *et al.* (2018). Here we discuss our results in terms of future directions for further improvement in the reliability of fisher-reporting of catches of large shark species.

4.1 Reliability of logbook catch reporting in the NSW large-shark fishery

As part of the FRDC Shark Futures project, we aimed to assess the reliability of logbook catch reporting in the NSW large-shark fishery since the implementation of updated and improved fishery management arrangements and resources in 2008. Specifically, these improvements included: more detailed, daily catch reporting forms ('daily logs'); OTLF-wide distribution of an at-sea shark species identification guide; and direct, at-sea education of fishers in how to use the ID guide. Despite the higher resolution of the new daily logs, there was no guarantee that provision of the ID guide and associated attempts at fisher education during 2008/09 would translate into more accurate catch data submitted by fishers (compared to pre-2008 levels). Further, with the observer program scaled back to an average frequency of < 1 observed fishing day per month during the four-year period spanning 2009/10 to 2012/13, ongoing monitoring and reinforcement of education were substantially reduced, thereby potentially compromising the effectiveness of the new management measures. The results of our investigations into logbook catch reporting and factors affecting accuracy of these data have been published as Macbeth *et al.* (2018) and a summary of these presented below.

Data collected via the NSW large shark sub-fishery observer program between 2008 and 2013 provided the opportunity to test whether daily logs submitted by large shark fishers correlated with corresponding, species-specific catch data recorded by observers (and verified via genetic studies) (Macbeth *et al.*, 2018). These data comprised a total of 109 observed fishing trips (15 in 2008; 76 in 2009; 13 in 2010; 3 in 2011; and 2 in 2012), done by a pool of ten large shark fishers. If the correlation was strong, it would suggest that provision of ID guides and on-board education provided to large shark fishers by observers was effective, at least in the short term. However, if issues with species identification and/or daily logs were detected, potential reasons for these problems could be considered and solutions formulated.

Weighted linear mixed models were used to estimate rates of misreporting (i.e. the % difference of the number reported in daily logs by fishers from the number recorded by observers) for the 13 shark species (whaler, hammerhead and mako) caught by the fishery (Table 1).

Misreporting of total numbers of large sharks retained (i.e. all species combined) occurred for half of the 109 trips observed, with under-reporting (34% of trips) twice as common as over-reporting (16%). However, the mean extent of the over-reporting (~6 sharks trip) was greater than that of the under-reporting (~4 sharks trip), resulting in only a modest shortfall (~2.6%) in overall reported catch (1,481 sharks; daily logs combined) compared to corresponding observer data (1,520 sharks).

There were, however, some broad patterns in misreporting according to species, with some of the more commonly retained whaler shark species generally under-reported (dusky shark ~21%; spinner shark 10– 70%) or over-reported (bronze whaler ~18%; blacktip sharks ~21%) by fishers. While there was some inter-fisher variability in misreporting of sandbar shark, over- and under-reporting (which ranged among fishers between ~20% either way) balanced out such that there was general correspondence between observer and daily log datasets. In the cases of hammerhead sharks, catches of smooth and great hammerhead sharks were under-reported (~50% and ~41%, respectively), while scalloped hammerhead shark was over-reported by ~16%.

Deeper examination of misreporting patterns among fishers since 2008 confirmed that while some fishers appear highly skilled and diligent with respect to species identification and reporting, others have been characterised by problems, particularly with respect to mistaking similar-looking shark species for each other. For example, there appears to have been a problem in mistaking spinner and blacktip sharks for each other (both species usually have distinct black tips to some of their fins – Fig. 10). Similarly, smooth, scalloped and great hammerhead sharks also appear to have been commonly mistaken for each other, which is of particular concern given that in 2013 the latter two species were both declared threatened and protected species (and therefore prohibited from being retained by fishers). The mixing up of spinner and blacktip sharks and problems in identifying hammerhead sharks detected in fisher logbook entries were also both detected during the 2013 at-sea assessments of the shark identification skills of one large-shark fisher. This corroborated the apparent difficulty in species identification of large sharks by NSW commercial shark fishers.

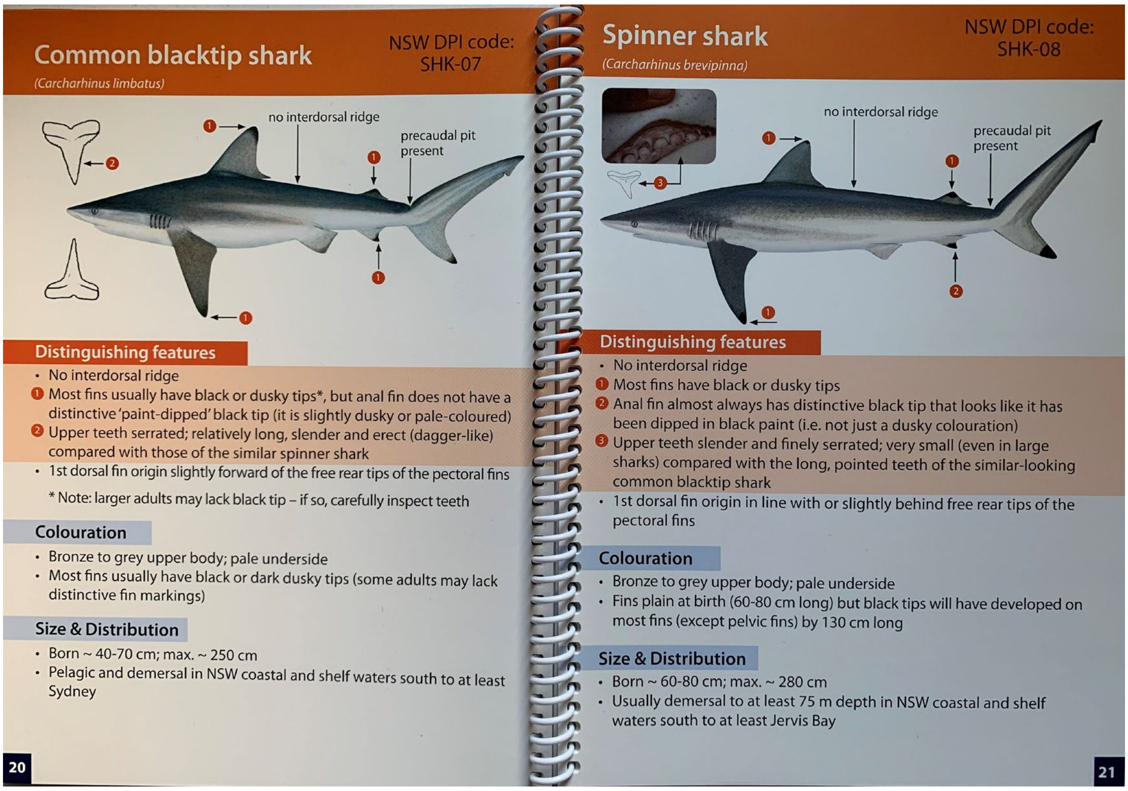


Figure 10 The "NSW DPI Guide for commercial fishers in identifying sharks and rays" pages showing identification features for the two commonly mistaken shark species: common blacktip shark (*Carcharhinus limbatus*) and spinner shark (*C. brevipinna*).

Of perhaps greatest concern was the overall level of ~21% under-reporting of captures of dusky shark. Severe depletion of USA east coast stocks prior to 2000 has led to a ban on retention of this species. Owing to its late maturation and low fecundity, dusky shark (like sandbar shark) is widely accepted to be particularly susceptible to stock collapse where larger individuals are being heavily exploited (Romine *et al.*, 2009). Given this assessment of the vulnerability of dusky shark to detrimental overfishing, the level of under-reporting detected by this study is arguably too high, potentially compromising confidence in any stock assessments attempted.

One potential confounding factor associated with the results described above is the 'observer effect'. This refers to the inherent potential for fishers to alter their fishing behaviour (e.g. choice of fishing grounds or other fishing methods that may influence catches), and/or vary their diligence in completing daily logs accurately, depending on the presence or absence of an observer. Such disparities would suggest that when an observer is absent, some or all fishers are, for some reason, not using the ID guide to assist in accurate catch reporting. This potential discrepancy can be retrospectively detected by appropriate comparison of daily logs from observed fishing trips against those from unobserved trips. If disparities were substantial, well-meaning management decisions based solely on data associated with observed trips might cause more harm than good in terms of monitoring and conservative control of catch quantities. We therefore compared daily logs from 78 observed fishing trips against those from 93 unobserved trips, across multiple fishers and years.

Genetic analysis has previously found the observers to have a high level of accuracy in species identification (Geraghty *et al.*, 2014b), therefore they were considered as 'correct' identification. Statistical analysis (Mann-Whitney test) revealed no conclusive evidence of an observer effect (Macbeth *et al.*, 2018).

To supplement the analyses described above, a study was undertaken onboard one large-shark fishing vessel in 2013 to test at-sea species identification skills of its skipper, years after last hosting an observer. This enabled a clear, first-hand assessment of the fisher's species identification abilities, as well as observations regarding the on-board processes associated with longline fishing for large sharks that might prevent reliable species identification and reporting. Similar to results from analyses described above, this assessment highlighted the mixing up of identifications of spinner and blacktip sharks, along with problems in correctly identifying hammerhead species.

Finally, a desktop analysis of some of the species identification traits prominent in the ID guide and/or commonly used by observers to superficially distinguish between large shark species was conducted to determine where misidentification problems may exist. The results from this desktop analysis supported the results from the other aspects to this study in that the misidentification between the more frequently caught species is most prominent in the cases of hammerhead species, and also between spinner and blacktip sharks.

Ongoing misreporting issues in the NSW large shark fishery (despite provision of species identification material and at-sea tuition) detected by this study appear to be a result of a combination of factors. While simple mistaken identity can be offered as a reason in the cases of some species (e.g. spinner and blacktip sharks), it seems that the most important factors are likely to be general unfamiliarity with the ID guide at the point at which species identifications, catch tallies and daily log duties are undertaken. Various sources of evidence indicate that these catch reporting tasks are commonly undertaken after catch processing duties, including trimming (removal of the head, guts and belly flaps), have been completed; and sometimes at the point of unloading the trimmed carcasses back at port. If species identification and tallying were diligently undertaken by suitably knowledgeable fishers (with or without species ID material) at sea during gear retrieval, it is likely that the current rates of misreporting could be greatly reduced. Real-time reporting of catch using electronic logbooks via a smart device could therefore substantially reduce such reporting error. Alternatively, a simple and logical reform to current management requirements would be to mandate that all retained sharks be returned to port with heads attached, and be available for random inspection by fisheries compliance officers prior to trimming. Effectiveness of such a measure would, of course, be dependent on a corresponding increase in targeted port monitoring by such officers.

Table 1 For each of the targeted large shark species: a) total number of observed trips during which it was recorded; b) total number of sharks (collectively across these trips) recorded by observers (Obs) and in logbooks by fishers; c) mean misreporting rate (%) by fishers (+ve = over-reported, -ve = under-reported) and 95% confidence intervals (CI); and d) variance component ratios associated with the Fisher, Year (nested within Fisher) and Observer (nested within Fisher) terms of the weighted linear mixed model comparing misreporting rates among trips. * = 95% CI do not include zero.

	a) Total	b) Total sharks		c) Misreporting rate (%)			d) Variance component ratio		
Family (common and scientific name)	Trips	Obs	Fisher	Mean	95% CI		Fisher	Year(Fisher)	Obs(Fisher)
Carcharhinids									
Sandbar shark (*Carcharhinus plumbeus*)	72	597	656	1	-26, 27		0.06	0.11	0
Dusky shark (*C. obscurus*)	64	273	230	-21	-39, -3	*	0	0.12	0.02
Spinner shark (*C. brevipinna*)	47	206	85	-42	-71, -12	*	0.09	0.06	0
Blacktip sharks (*C. limbatus/tilstoni*)	49	109	210	21	-3, 45		0.06	0.03	0.07
Tiger shark (*Galeocerdo cuvier*)	35	79	67	-5	-31, 21		0.06	0	0.05
Bronze whaler (*C. brachyurus*)	21	23	32	18	-14, 51		0	0.21	0
Bull shark (*C. leucas*)	12	17	20	16	-26, 58		0	0	0.13
Silky shark (*C. falciformis*)	11	16	9	-22	-79, 36		0	0.75	-
Bignose shark (*C. altimus*)	2	1	2	33	-61, 100		-	-	-
Sphyrnids									
Smooth hammerhead (*Sphyrna zygaena*)	27	91	30	-50	-84, -16	*	0.18	0	-
Scalloped hammerhead (*S. lewini*)	44	78	119	16	-8, 39		0	0.06	0
Great hammerhead (*S. mokarran*)	8	11	7	-41	-95, 13		0.28	0	-
Lamnids									
Shortfin mako (*Isurus oxyrinchus*)	13	19	14	-15	-45, 15		0	-	0

Objective 5: Educate the fishers targeting sharks about field identification of the shark species they are catching to ensure an accurate long-term database to monitor fishing of the shark populations in NSW

5.1 Fisher feedback on efficacy of the NSW Shark Species Identification Guide

As part of the FRDC Shark Futures project, we developed a questionnaire for OTLF fishers to provide anonymous feedback regarding their usage or non-usage of the ID guide and perceptions of the usefulness of various aspects of the guide in terms of identifying shark species and filling in daily logs. In 2014 the 19-question questionnaire was distributed to ~1,500 NSW commercial fishers, including all those with an OTLF endorsement. Key questions included:

‘Were you aware of the ID guide that was released by the NSW DPI in 2008?’;

‘Have you used the ID guide for identifying sharks and/or rays?’;

‘Do you find the ID guide useful to tell the difference between species?’;

‘Are the diagrams and descriptions in the ID guide accurate to real sharks and rays?’; and

‘Do you think that the ID guide helps you fill in the NSW DPI ‘catch record’ commercial log sheets more accurately?’

Scale-based responses (i.e. choose a value 0 to 4) regarding the relative importance of various sections/aspects of the guide (e.g. ‘How to use this guide’, ‘Identifying parts of the shark’, ‘Identification keys’, and ‘Individual species and distinguishing features’) were also included. Various statistical analyses were applied where appropriate to interpret responses to the questions. Results of this investigation have been published as Macbeth *et al.*, (2018) and are summarised below.

Despite this questionnaire being posted to all of the OTLF fishers who had been posted a hard-copy ID guide in 2008, the proportion of OTLF fishers electing to respond to the questionnaire was extremely low (7.3%) and, of those that responded, almost two-thirds did not have a guide and half were not even aware of its existence. This indicates an insufficient level of extension education throughout the OTLF following distribution of relevant educational material. Initial, intensive extension efforts in the form of tuition in guide-use by on-board observers were justifiably directed towards those OTLF fishers targeting large sharks.

However, it seems that the full value of the resource with respect to generating consistent, reliable catch information from other OTLF operators who catch large sharks, albeit in relatively smaller quantities, was overlooked to a large degree. This was most likely (and understandably) due to limited resources. Any revision and re-issuing of the ID guide would provide the opportunity to amend this oversight and potentially dedicate more funding and resources to extension work.

Fishers that had used the guide (and responded to the questionnaire) found the ID guide useful when trying to differentiate between species, and indicated that the current format is accurate and sufficiently structured for easy species identification. Perhaps most importantly, the majority also stated that it aided them to fill in log books correctly. Interestingly, the most commonly used sections of the guide (and those deemed ‘more important’ by fishers) were: 1) the generic shark diagram pointing out the main morphological features that can be used to distinguish among species; and 2) the section of the guide that lists the distinguishing features of each species (one species to a page and with accompanying illustration, Figs. 9 and 10). This was despite the carefully designed dichotomous key for separating species within families being included in the guide with the intention of making species deduction an easier, step-wise process (Fig. 8). Perhaps further online resources in the form of a training module for using the species identification key might increase its utility by fishers.

Objective 6: Evaluate assessment methods and management indicators for the main shark species that may provide a model for future national and/or international data-poor shark fisheries

6.1 Relative importance of fishery variables for assessment of catch composition in a data-poor shark fishery

Fishers in the NSW large-shark longline fishery are required to record in their catch reporting 'logbook' the number of retained sharks and total trimmed weight (sharks combined) by species for each longline deployment. NSW fisheries managers rely on this logbook system as a basis source of catch and effort data used to monitor harvesting and, ultimately, stock assessment on a species-specific basis. The quality of logbook data is typically variable (Punt *et al.*, 2000, Macbeth *et al.*, 2018), with the consequential lack of useful catch and effort data resulting in a 'data-poor' fishery (Lack and Sant, 2006). Data-poor fisheries are very difficult to manage effectively due to inherent uncertainties concerning their impact on stocks of targeted species and any protected species at risk.

At-sea observer-based research is an effective means of gathering detailed and reliable information otherwise not available via mandatory reporting by commercial fishers. Observer sampling programs also provide an opportunity to 'ground truth' the information reported by fishers and hence can be an important fisheries management tool. However, observer programs typically only have limited spatial and temporal coverage of the fishery due to high costs, as has been the case for NSW fisheries.

Given the commonly prohibitive expense associated with observer data gathering for fishery monitoring purposes, it is essential for fisheries managers to understand which basic operational and/or catch data are most indicative of the catch composition across the fishery. This will provide guidance as to which data should be reported in fishers' logbooks and/or be recorded as part of more economical data collection at ports for effective monitoring of trends in catches within the shark fishery over time.

As part of the Shark Futures project, we analysed a range of operational, environmental and biological variables associated with the data-poor NSW large shark fishery to determine which of these 'predictor' variables were relatively more important than others with respect to describing key indicators ('response' variables) of catch composition for some of the most common shark species captured in this fishery. Data for our analyses were obtained from 104 fishing days across multiple fishers, observed as part of the large shark fishery observer program between 2008 and 2013. Data recorded by scientific observers were matched with total catch weight information reported by fishers in logbooks, excluding fishing days for which the numbers of sharks caught (per species) recorded by observers and reported by fishers did not sufficiently match up.

The key response variables (per species per fishing day) were mean total length ('mean TL' – determined using observer data) and total catch weight of 'trimmed' shark carcasses ('total catch weight' – sourced from fisher logbooks). A trimmed carcass is one that has had the head, viscera (guts and reproductive organs), fins and belly flap removed, as per normal commercial catch processing practices (Pleizier *et al.*, 2015). Operational predictor variables included in the analyses were the departure port, depth at which the bottom-set longline was set and number of hooks set on the day, while the environmental variable analysed was Austral season. Biological predictor variables included number of sharks (of that species) caught on that fishing day, proportion of those that were adult (i.e. sexually mature), proportion that were female, and the response variables as predictor variables for each other. Linear mixed-effects models were used to statistically examine relationships among variables and determine the more important predictor variables in explaining catch composition for the main species caught. Results have been prepared for publication in a peer-reviewed scientific journal and are summarised below.

In total, data pertaining to 1,165 sharks caught across the 104 fishing days were included in our analyses. More specifically, this total catch comprised: 598 sandbar sharks (*Carcharhinus plumbeus*) weighing (trimmed) a combined total of 12.4 tonnes (t); 235 dusky sharks (*C. obscurus*, 12.2 t); 91 spinner sharks (*C. brevipinna*, 3.1 t); 90 blacktip sharks (*Carcharhinus limbatus/tilstoni*, 2.6 t); 68 tiger sharks (*Galeocerdo cuvier*, 1.3 t); 60 scalloped hammerhead sharks (*Sphyrna lewini*, 1.7 t) and 23 bronze whalers (*C. brachyurus*). It should be noted that the scalloped hammerhead shark is now listed as a threatened, endangered or protected (TEP) species in NSW and are prohibited from being retained, so results here should be considered in the context of the closely related and very similar smooth hammerhead shark (*S. zygaena*), which has not been declared a TEP species in NSW.

Our results demonstrated the importance of accurate reporting of key biological variables such as species, size or age-class by commercial fishers within a shark fishery, while operational variables were found to be relatively less important. For accurate prediction of the total catch weight of sharks per fishing day for a given species, the number of sharks of that species in the catch was the most important variable to report for six of the seven species analysed (Table 2). For five of those six species the mean of total lengths of sharks of that species in the catch (mean TL) was the second most important variable. Unsurprisingly, to predict mean TL for a given species, the proportion of adults in the catch was the best predictor for all species analysed, while the relative importance ofthe remaining predictor variables varied among species. Austral season was quite an important predictor of both response variables only in the case of sandbar shark.

Table 2 The rank (and relative importance) of each variable from linear mixed effects models with mean total length (TL) as the response variable. The relative importance is the sum of the Akaike weights over all the models in which the variable of interest appears. The relative importance is between 0 and 1. A value of 1.00 shows that it appeared in all the models with an Akaike weight of greater than 0 (highly important variable) and a relative importance of 0.00 shows it didn't appear in any of the models with an Akaike weight of greater than 0 (not an important variable). "-" indicates that predicator variable was not included in that model. Models with port included as a fixed effect instead of number of hooks for bronze whalers, scalloped hammerheads and tiger shark the models did not converge.

Species	**Catch weight per shark**	**Proportion of adults**	**Proportion of females**	**Number hooks set**	**Season**	**Port**	**Mean depth**
Bronze whaler	2 (0.34)	**1 (0.95)**	4 (0.11)	3 (0.12)	6 (0.00)	-	4 (0.11)
Common blacktip	2 (0.65)	**1 (0.95)**	3 (0.44)	4 (0.19)	5 (0.12)	6 (0.10)	4 (0.19)
Dusky	**1 (1.00)**	**1 (1.00)**	**4 (0.99)**	6 (0.15)	**1 (1.00)**	7 (0.00)	5 (0.24)
Sandbar	4 (0.27)	**1 (1.00)**	**1 (1.00)**	4 (0.27)	6 (0.15)	7 (0.12)	3 (0.49)
Scalloped hammerhead	**1 (1.00)**	2 (0.84)	3 (0.33)	6 (0.18)	5 (0.20)	-	4 (0.25)
Spinner	**1 (1.00)**	2 (0.70)	3 (0.57)	4 (0.25)	6 (0.01)	7 (0.00)	5 (0.16)
Tiger	**1 (1.00)**	**1 (1.00)**	6 (0.08)	5 (0.18)	3 (0.39)	-	4 (0.19)

If restricted to morphological measurements from trimmed carcasses (e.g. via port monitoring rather than expensive observer research or unverified fisher reporting), an alternative body measurement may be used as a proxy for TL subject to statistical suitability. Irrespective of the type of length or proxy used, it is critical to obtain accurate measurements, as almost all of our models were extremely sensitive to any biological measurement error, with the relative importance of predictor variables changing significantly when extra error of only 10% was artificially introduced. Given this and the practical likelihood of fishers taking accurate measurements at sea, it may be more prudent to require fishers to estimate the proportion of adult sharks (i.e. sharks determined to be sexually mature by approximate size or genital morphology/anatomy) for each species in the catch for that fishing day (or trip) rather than take length measurements, with those data then used to estimate mean TL.

Our results also indicated that for four of the seven species there was significant variability in trimming practices among fishers and from trip-to-trip, which reduces the reliability of reported catch weight data with respect to fishery management (Pleizier *et al.*, 2015). To overcome this problem, legislative standards dictating shark trimming procedures and/or outcomes should be clear in their wording, such that fisheries managers and compliance officers could more effectively enforce them. This would improve fishery-wide consistency in trimming outcomes and, in turn, aid in improving the reliability of trimmed-carcass weight measurements used for conversion to whole weights and potentially to total lengths.

Objective 7: Provide scientific data-based advice for management to ensure the future sustainability of shark populations.

Other management issues for the NSW large shark longline fishery

In coastal waters off New South Wales (NSW), bottom-set (or 'demersal') longlines are used to target various species of large (mostly whaler) shark primarily for their fins and associated Asian export market. Current management legislation prohibits the landing (at port) of any fin detached from its host body. All sharks caught in NSW are initially processed at sea to remove and discard larger unmarketable components (head and internal organs). Upon returning to port some further trimming is commonly done (e.g. 'belly flaps' and unwanted fins) before the final 'trimmed' carcasses can be on-sold to the domestic shark-flesh market and target fins set aside for export.

Fishers in the NSW large shark longline fishery are required to record in their catch logbooks the number of retained sharks and total trimmed weight (sharks combined) by species for each longline deployment. Ongoing, near-real-time monitoring of these reported catches has mostly relied on the accuracy and consistency of measurements of total catch weights (all trimmed carcasses + marketed fins) undertaken back at port.

Total number of sharks caught and a combined trimmed weight of retained sharks per species per longline deployment is therefore the constraining detail in fisher catch reports. Average trimmed carcass weight per longline deployment is the only 'measure' of the size of sharks in the catch (per species) available for fishery managers to consider. Given the potential for variability in trimming practices among different species and particularly among size classes, these measurements do not indicate or describe the relative weight and value of fins or flesh, or the amount of wastage (discarded components) across the fishery very well. By first understanding relationships between whole body weight, at-sea processed (or 'landed') weight, trimmed carcass weight (i.e. the inverse of wastage) and the weight of retained fins, and then assessing variability in these relationships among species and size classes, more effective management strategies for catch regulation and wastage minimisation can be conceived and developed. Our investigations into determining these relationships have been published as Pleizier *et al.* (2015) and are summarised below.

A legitimate concern for consumers of shark meat caught by the NSW large shark longline fishery is the potential for high levels of certain metals and metalloids, such as mercury and arsenic, in the saleable products (fins and flesh). As long-lived apex predators, the shark species targeted in the fishery are inherently susceptible to bioaccumulation and/or biomagnification (i.e. steadily increasing concentrations over their lifespan) of some metals and metalloids in their tissues, primarily through sustained uptake over many years via their diet (Pethybridge *et al.*, 2010). The large sizes and old ages of sharks currently targeted in the fishery (specifically for the relatively high value of their fins), suggests that concentrations of metals and metalloids in their tissues may be quite high. As the fins and flesh are specifically for human consumption, concentrations of certain metals and metalloids in those tissues may be potentially harmful to human health. Given this, as part of the FRDC Shark Futures project we wanted to assess the level of metals and metalloids in the muscle, liver and fin-fibre tissues of the main commercial species and compare concentrations against Food Standards Australia New Zealand (FSANZ) standards for human consumption. The results of investigations into metal and metalloid concentrations in NSW-caught shark tissues has been published as Gilbert *et al.* (2015) and are summarised in the following sections.

This summary describes the results of research into relationships between fin weight and whole, landed or trimmed weights, and relative levels of wastage (discarding of unwanted body components) across species, between sexes and among sizes of sharks targeted in the NSW large-shark longline fishery. It also provides an outline of concentrations of metals potentially dangerous to humans in the fins and flesh of sharks caught in the fishery and comparisons against recommended maximum levels as per FSANZ standards. We also discuss our results in terms of possible management options to address issues uncovered and suggest directions for future research.

7.1 Relationships among catch weight components across species, sexes and sizes

As part of the FRDC Shark Futures project, we examined relationships between whole body weight, at-sea processed ('landed') weight (i.e. headed and gutted), trimmed weight (landed weight minus fins and belly flap) and total weight of retained fins across some of the most common shark species captured in the NSW large shark longline fishery. Sharks for the study were obtained via 17 days of chartered longline fishing undertaken primarily for shark tagging (Section 2) and hooking, physiological stress and at-vessel mortality (Section 3) research. Sharks retained during each of these days were measured for length (fork length) and stored in wet ice for 6–48 hours before being processed and trimmed back at port according to the standard at-sea and on-dock catch processing limitations (as per the requirements of the fishery regulations).

Whole body weights were measured at sea immediately following capture, while landed and trimmed carcass weights and combined weights of fins (first dorsal fin, right and left pectoral fins and lower caudal [tail- fin] lobe – Fig. 11) were obtained during processing at the dock. For our study we considered the discarded head, viscera (guts), body fat, belly flaps, and unwanted fins (pelvic fins, second dorsal fin, anal fin and upper caudal [tail-fin] lobe) as wastage, although it should be noted that the belly flaps and unwanted fins have a small value as bait. Given this, it follows that for a given individual the whole weight minus trimmed weight provides an index of wastage for that individual.

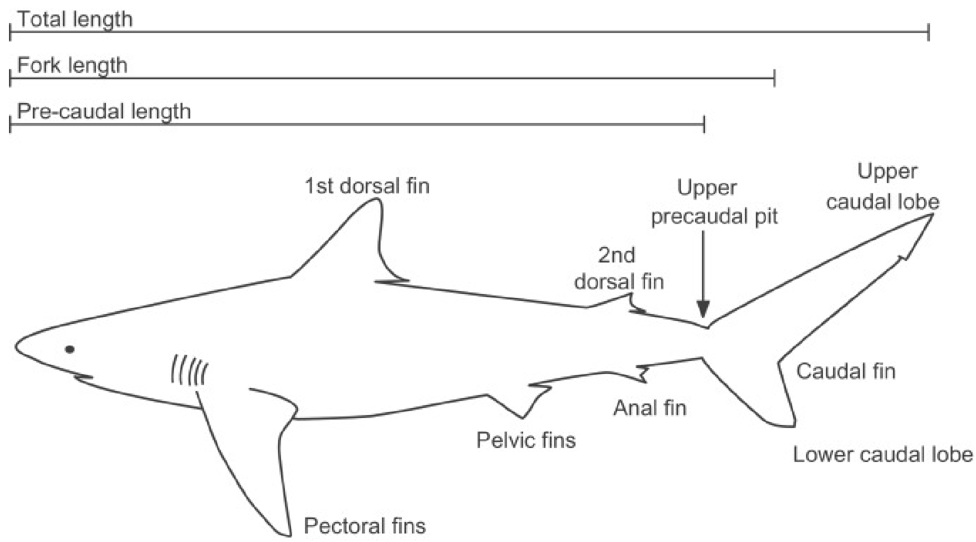


Figure 11 Length measurements and fin anatomy of sharks as used in this FRDC Shark Futures project.

In total, 337 sharks were processed and included in analyses as part of this study, consisting of 102 blacktip sharks (*Carcharhinus limbatus/tilstoni*), 82 sandbar sharks (*C. plumbeus*), 51 dusky sharks (*C. obscurus*), 47 scalloped hammerhead sharks (*Sphyrna lewini*), 44 spinner sharks (*C. brevipinna*) and 11 great hammerhead sharks (*S. mokorran*). It should be noted that both hammerhead species are listed as threatened, endangered or protected (TEP) species in NSW and are prohibited from being retained, so results are discussed here in the context of the closely related and very similar smooth hammerhead shark (*S. zygaena*), which has not been declared a TEP species by NSW authorities.

Statistical analyses in the form of generalised least squares models and associated techniques were used to examine relationships between trimmed weight and whole weight (i.e. index for wastage), between trimmed weight and landed weight, and between fin weight and each of the three body weights (data analysed as ratio per individual for each relationship pairing) (Pleizier *et al.*, 2015). Under the TACC management regulations, greater ratios of fin weight to trimmed weight might theoretically result in greater income for the fishery, as prices at first point of sale for fins (up to A$125/kg) far exceedprices for trimmed bodies (up to A$3.00/kg). On the other hand, ratios of trimmed weight to whole weight represent an index for wastage, where greater ratios of trimmed to whole weight would indicate that less trimmings (by weight) are discarded and a greater proportion of the shark utilised. Species, sex and length (in the form of 'centred FL' – i.e. all FL data shifted so mean FL = 0) were included in the models as 'predictor variables' in an attempt to identify differences among species and/or size classes, and/or between sexes for each of these five relationships. Results from these analyses will help to identify potential refinements to catch processing requirements that may improve yield efficiency in terms of maximising ratios of fin weight to body weight, and/or reduce wastage in the fishery.

Analysis identified that shark species, length and sex were all significantly important in explaining variability in ratios of fin weight to the three body weight measurements (whole, landed and trimmed) (Table 3). Perhaps unsurprisingly, the most sought after target species in the NSW large shark fishery, sandbar shark, was found to have by far the highest fin weight to body weight ratios (irrespective of size) ofthe species analysed. Specifically, the relative weight of fins to trimmed weight was greater in smaller sharks (i.e. shorter lengths) than in larger sharks in the cases of sandbar shark, dusky shark and hammerhead sharks, with the largest difference in ratios between size extremes apparent for sandbar sharks (Fig. 12). The opposite was the case for blacktip sharks and spinner sharks. Also, the relative weight of fins to whole weight tended to be greater in female sharks than in males for most species (Pleizier *et al.*, 2015).

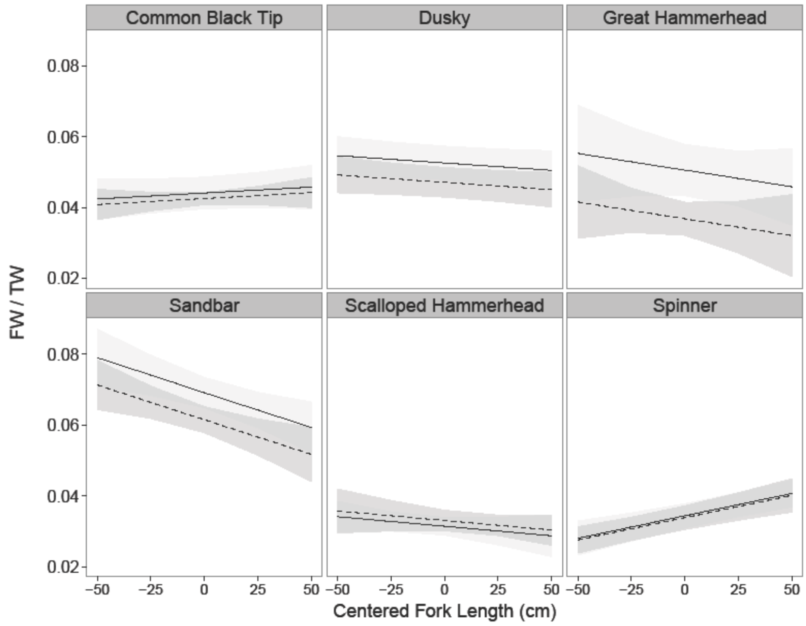


Figure 12 Model predictions for fin weight versus trimmed weight (FW/TW) (± 95% CI) for male (dotted line, dark grey confidence bands) and female (solid line, light grey confidence bands) shark species caught by commercial vessels off northern NSW, Australia.

In summary, the fin weight analyses revealed that targeting and retaining smaller sharks, female sharks, and/or specifically dusky and sandbar sharks (the two primary target species), would increase fin weight relative to trimmed carcass weight (Fig. 12), in turn increasing the proportion of the TACC (by weight) sold in the more lucrative fin market. However, although fins are by far the most valuable portion of a shark carcass, at the first point of sale smaller fins (< 23 cm tall) are substantially less valuable by weight (A$6−40 per kg) than larger fins (> 60 cm tall; A$100−125 per kg). Therefore, increasing the proportion of smaller sharks comprising the shark TAC would also have consequences with respect to the economic viability of the fishery. Further, increasing the proportions of dusky and sandbar sharks, and/or females comprising the shark TAC would potentially have consequences with respect to population sustainability for those species, particularly given their well- known vulnerability to high levels of fishing mortality (see Section 1.3).

Our results also indicated that shark length was a significant predictor in explaining variability in ratios of trimmed weight to whole weight (i.e. predicting the proportion of the carcass that is wasted), but that the nature of this relationship depended upon species (Pleizier *et al.*, 2015). More specifically, for all but one of the species (scalloped hammerhead shark), modelling showed that a higher proportion of the carcass is wasted (i.e. the ratio of trimmed to whole weight decreases) with increasing shark length. Given that ethical concerns exist around wastage and under-utilisation of harvested sharks, it may be considered more ethically appropriate to target smaller sharks. Furthermore, from a sandbar and dusky shark population maintenance perspective, previous modelling (e.g. for Western Australia) has indicated that extracting only smaller, sexually-immature sharks according to a tailored sustainable harvesting regime might lower the risk of fishing mortalities leading to dangerous levels of decline in populations (McAuley *et al.*, 2007; Prince, 2005; Simpfendorfer, 1999). However, given documented rates of at-vessel fishing mortality, and the inferences of pre-retrieval and post-release mortalities in the NSW fishery target species presented in various sections of this report, adjustments in the permitted duration of longline sets and hook sizes used are likely required to improve the size selectivity and survivorship of captured sharks.

Notwithstanding demonstrated issues with respect to accurate species identifications (see Section 5), another area of justified concern for fishery managers is the known, but unquantified, variability in trimming outcomes among sharks, trips and fishers. Although there are broad legislated trimming guidelines, limited fishery management resources effectively prevents appropriately diligent compliance and monitoring with respect to trimming practices and accurate fisher reporting of shark species, numbers of sharks and catch weights. This likely leads to, at best, inaccuracies in catch weight estimates and therefore possibly significantly over- or under- estimated catches for some species. At worst, current output controls in the large shark longline fishery in the form of weekly catch limits, currently set at (750kg whole weight or 500kg landed weight) and the 85.9 tonnes TACC with a 'byproduct trigger limit' of 70 tonne may lead to systematic 'over-trimming' and under-reporting of retained and discarded catches of the target species. This could lead to a level of harvesting consistently exceeding that intended by the TACC. We recommend further review of the current management philosophies and framework underpinning the NSW large shark longline fishery with a view to reducing the risk of these sources of unaccounted fishing mortality.

Given the issues outlined above, detailed economic and population assessments involving various fishing and management scenarios would be required prior to formulating any new fishery management strategies. We recommend that managers carefully consider weight ratio data information presented here and undertake economic and population assessments as part of their decision making to promote a profitable but sustainable NSW shark fishery.

Table 3 Model coefficients of the optimal models to predict TW/WW, TW/LW, Waste/WW, FW/WW, FW/LW, and FW/TW. TW – trimmed weight, WW – whole weight, LW – landed weight, FW – fin weight, and CFL – centred fork length.

TW/WW	**Coefficient**	**Std. error**	**t-value**	**p-value**
Intercept	0.50148	0.00424	118.306	<0.001
Dusky	-0.0773	0.00737	-10.492	<0.001
Great Hammerhead	0.01492	0.01412	1.0561	0.2917
Sandbar	-0.0445	0.00633	-7.0227	<0.001
Scalloped Hammerhead	0.06666	0.00758	8.79657	<0.001
Spinner	0.00364	0.00776	0.46903	0.6394
FL	-0.0004	0.00021	-1.9282	0.0547
Dusky:FL	-0.0005	0.00023	-2.0292	0.0433
Great Hammerhead:FL	-0.0001	0.0007	-0.1906	0.849
Sandbar:FL	0.00011	0.00029	0.35802	0.7206
Scalloped Hammerhead:FL	0.00068	0.00035	1.95996	0.0509
Spinner:FL	-0.0003	0.00025	-1.0918	0.2757

Table 3 (continued)

TW/LW	Coefficient	Std. error	t-value	p-value
Intercept	0.7262430	0.004834065	150.23442	<0.001
Dusky	-0.0324732	0.008400710	-3.86553	<0.001
Great Hammerhead	0.0174922	0.016105492	1.08610	0.2783
Sandbar	-0.0340072	0.007221565	-4.70911	<0.001
Scalloped Hammerhead	0.0525161	0.008641562	6.07716	<0.001
Spinner	0.0289162	0.008846257	3.26875	0.0012
FL	-0.0002548	0.000233996	-1.08883	0.2770
Dusky:FL	-0.0007004	0.000261489	-2.67867	0.0078
Great Hammerhead:FL	0.0002784	0.000793092	0.35102	0.7258
Sandbar:FL	0.0008900	0.000336197	2.64715	0.0085
Scalloped Hammerhead:FL	0.0003163	0.000396051	0.79859	0.4251
Spinner:FL	-0.0007384	0.000282542	-2.61354	0.0094

Waste/WW	Coefficient	Std. error	t-value	p-value
Intercept	0.16846720	0.003940582	42.75186	<0.001
Dusky	-0.00356226	0.006848001	-0.52019	0.6033
Great Hammerhead	-0.01014607	0.013128704	-0.77282	0.4402
Sandbar	0.00603036	0.005886798	1.02439	0.3064
Scalloped Hammerhead	-0.02418712	0.007044337	-3.43356	<0.001
Spinner	-0.02077485	0.007211197	-2.88091	0.0042
FL	0.00003829	0.000190746	0.20074	0.8410
Dusky:FL	0.00052635	0.000213158	2.46930	0.0141
Great Hammerhead:FL	-0.00020019	0.000646504	-0.30964	0.7570
Sandbar:FL	-0.00073444	0.000274057	-2.67987	0.0077
Scalloped Hammerhead:FL	0.00004159	0.000322849	-0.12881	0.8976
Spinner:FL	0.00057309	0.000230319	2.48822	0.0133

Table 3. (continued)

FW/WW	Coefficient	Std. error	t-value	p-value
Intercept	0.04412945	0.002286558	19.299512	<0.001
Dusky	0.00848560	0.003323762	2.553011	0.0112
Great Hammerhead	0.00646423	0.004332464	1.492046	0.1367
Sandbar	0.02504024	0.003153196	7.941226	<0.001
Scalloped Hammerhead	-0.01269892	0.002615181	-4.855848	<0.001
Spinner	-0.00974503	0.002873208	0.0008	<0.001
Sex	-0.00156418	0.002450169	-0.638397	0.5237
Dusky: Sex	-0.00389857	0.004050447	-0.962504	0.3365
Great Hammerhead: Sex	-0.01217440	0.005081147	-2.395994	0.0172
Sandbar: Sex	-0.00608745	0.003786001	-1.607885	0.1089
Scalloped Hammerhead: Sex	0.00318966	0.003207395	0.994471	0.3208
Spinner: Sex	0.00104582	0.003503048	0.298546	0.7655
Common Black Tip:FL	0.00003350	0.000039718	0.843342	0.3997
Dusky:FL	-0.00004143	0.000027198	-1.523431	0.1287
Great Hammerhead:FL	-0.00009447	0.000100618	-0.938941	0.3485
Sandbar:FL	-0.00019579	0.000064235	-3.048072	0.0025
Scalloped Hammerhead:FL	-0.00005385	0.000045771	-1.176560	0.2403
Spinner:FL	0.00012556	0.000026749	4.693891	<0.001

LW/ FW	Coefficient	Std. error	t-value	p-value
Intercept	0.03240987	0.0009737889	33.28223	<0.001
Dusky	0.00297339	0.0015080835	1.97164	0.0495
Great Hammerhead	-0.00070501	0.0023436159	-0.30082	0.7637
Sandbar	0.01310531	0.0011622271	11.27603	<0.001
Scalloped Hammerhead	-0.00672389	0.0010356031	-6.49273	<0.001
Spinner	-0.00618027	0.0011162761	-5.53651	<0.001
Sex	-0.00155605	0.0008573001	-1.81506	0.0705

Common Black Tip:FL	0.00001071	0.0000302527	0.35413	0.7235
Dusky:FL	-0.00009239	0.0000228752	-4.03903	<0.001
Great Hammerhead:FL	-0.00000908	0.0001113149	-0.08161	0.9350
Sandbar:FL	-0.00008698	0.0000427007	-2.03689	0.0425
Scalloped Hammerhead:FL	-0.00000991	0.0000341293	-0.29044	0.7717
Spinner:FL	0.00005906	0.0000188989	3.12489	0.0019

FW/TW	**Coefficient**	**Std. error**	**t-value**	**p-value**
Intercept	0.04412945	0.002286558	19.299512	<0.001
Dusky	0.00848560	0.003323762	2.553011	0.0112
Great Hammerhead	0.00646423	0.004332464	1.492046	0.1367
Sandbar	0.02504024	0.003153196	7.941226	<0.001
Scalloped Hammerhead	-0.01269892	0.002615181	-4.855848	<0.001
Spinner	-0.00974503	0.002873208	-3.391689	<0.001
Sex	-0.00156418	0.002450169	-0.638397	0.5237
Dusky: Sex	-0.00389857	0.004050447	-0.962504	0.3365
Great Hammerhead: Sex	-0.01217440	0.005081147	-2.395994	0.0172
Sandbar: Sex	-0.00608745	0.003786001	-1.607885	0.1089
Scalloped Hammerhead: Sex	0.00318966	0.003207395	0.994471	0.3208
Spinner: Sex	0.00104582	0.003503048	0.298546	0.7655
Common Black Tip:FL	0.00003350	0.000039718	0.843342	0.3997
Dusky:FL	-0.00004143	0.000027198	-1.523431	0.1287
Great Hammerhead:FL	-0.00009447	0.000100618	-0.938941	0.3485
Sandbar:FL	-0.00019579	0.000064235	-3.048072	0.0025
Scalloped Hammerhead:FL	-0.00005385	0.000045771	-1.176560	0.2403
Spinner:FL	0.00012556	0.000026749	4.693891	<0.001

7.2 Concentrations of metals in large shark species in NSW waters

As long-lived apex predators, the shark species targeted in the NSW large shark longline fishery are inherently susceptible to bioaccumulation and/or biomagnification (i.e. steadily increasing concentrations over their lifespan) of some metals and metalloids in their tissues, primarily through sustained uptake over many years via their diet (Gilbert *et al.*, 2015). The large sizes and concomitant old ages of sharks currently targeted in the fishery (specifically for the relatively high value of their fins), suggests that concentrations of metals and metalloids in their tissues may be quite high. As the saleable products (fins and flesh) are specifically for human consumption, concentrations of certain metals and metalloids in those tissues may be potentially harmful to human health.

Given the above, we wanted to assess the levels of metals and metalloids (mercury, arsenic, cadmium, copper, iron, selenium and zinc) in the muscle, liver and fin-fibre (ceratotrichia) tissues of two of the main commercial species taken by the fishery: sandbar shark (*Carcharhinus plumbeus*) and dusky shark (*C. obscurus*). The main objectives of our assessment were to:

- enable comparisons of concentrations found in previous shark studies,
- compare the concentrations with Food Standards Australia New Zealand (FSANZ) standards for human consumption, and
- provide a baseline for future monitoring.

Muscle, liver and fin samples from 12 sandbar sharks and 12 dusky sharks were collected during the 17 days of chartered longline fishing undertaken primarily for shark tagging (Section 3.2) and hooking, physiological stress and at-vessel mortality (Section 3) research. Upon capture of each shark, total length (TL in cm), total weight (kg) and sex were recorded and samples of muscle (from in front of the dorsal fin), liver, and the whole lower caudal fin taken and then preserved on ice for up to 48 hours before being suitably preserved (frozen) in the laboratory. Duplicate sub-samples of individual shark tissues were taken from the stored samples for chemical analyses to determine concentrations of the seven aforementioned metals, which were undertaken at the Environmental Analysis Laboratory (EAL) at Southern Cross University (SCU). Non-parametric multivariate analysis techniques were used to: 1) test for differences in concentrations of metals between species and among tissue types; 2) test for differences in concentrations between males and females (species combined); and 3) test for correlations between metal concentrations and shark size (TL). Results from this study have been published as Gilbert *et al.* (2015) with a summary of our findings presented below.

Results of these analyses indicated that differences in concentrations of metals among the three types of tissue were greater than differences between species or sex. Irrespective of species, mercury and arsenic concentrations were both significantly higher in muscle and liver tissue than in fin fibres, while cadmium, copper, iron and selenium were significantly higher in liver tissue than in muscle and fin fibres (Gilbert *et al.*, 2015). Concentrations of zinc were similar among tissue types. Notably, arsenic concentrations were generally much higher than concentrations of other metals (except iron) across all three tissue types. However, while mercury, cadmium, copper, iron, selenium and zinc concentrations were generally similar between the species, both arsenic and cadmium concentrations were significantly higher in sandbar shark than in dusky shark. The only significant difference between sexes was higher concentrations of iron in males than in females.

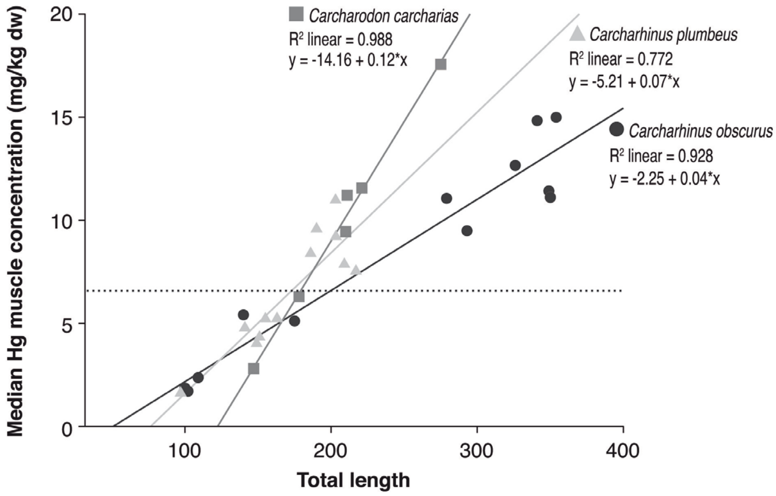


Figure 13 Relationships between median mercury (Hg) concentrations in muscle tissue and total length for dusky *Carcharhinus obscurus* (n = 12), sandbar *Carcharhinus plumbeus* (n = 12) and white *Carcharodon carcharias* sharks (n = 6). The dotted line indicates the Food Standards Australia New Zealand (FSANZ) maximum limit of 1.0 mg Hg kg^{-1} ww in fish tissues.

For both species there was a significant correlation between shark size (TL) and mercury in muscle tissue, with concentrations of mercury steadily increasing with increasing shark size (Fig. 13). Muscle concentrations of mercury in individuals of both species larger than around 150 cm TL, covering more than half of the 24 sharks sampled (7 sandbar and 9 dusky sharks), consistently exceeded FSANZ standards for human consumption. In dusky shark, concentrations in individuals larger than around 320 cm TL were more than double the standard. Similar significant correlations of increasing muscle concentration with increasing size were also found for cadmium and zinc. The age of the largest sandbar shark and dusky shark sampled for metal analysis was likely around 28 and 34 years old, respectively, (from Geraghty *et al.*, 2014a) highlighting the substantial time available for bio-accumulation of these metals.

In contrast to mercury, cadmium and zinc, muscle concentrations of arsenic steadily decreased with increasing shark size in both species. It is possible that differences between metals in patterns of concentrations is driven by ontogenetic shifts in diet and the differing patterns of metal concentration in concomitant prey species. All muscle, liver and fin-fibre tissue samples had arsenic concentrations at disconcerting levels (Fig. 14 with details below) well above the recently-withdrawn FSANZ maximum level of 2.0 mg kg-1 ww. Despite withdrawing the maximum limit for As because it was not possible to establish a safe level of exposure, FSANZ continues to issue a health warning regarding As exposure to people who consume large amounts of seafood (FSANZ 2011). One 120-gram serve of muscle tissue per week from any species in the present study would constitute between ~21–65 ug As kg-1 bw for a person weighing 70 kg. The previous provisional tolerable weekly intake (PTWI) for As was 21 ug kg-1 bw (FSANZ, 2002), highlighting the potential negative As-related health implications for ingestion of meat from NSW-caught sharks. Storelli *et al.* (2003) considered As concentrations in the muscle tissue of the smooth hammerhead sharks in their study to be ‘notable’, given that concentrations above 10 mg kg-1 ww were rarely reported in the muscle tissue of sharks. This makes some of the extremely high concentrations of As found in sharks in the present study quite remarkable, and identification of the ratio of organic:inorganic As and its potential toxicity will be important in further investigations (Glover, 1979).

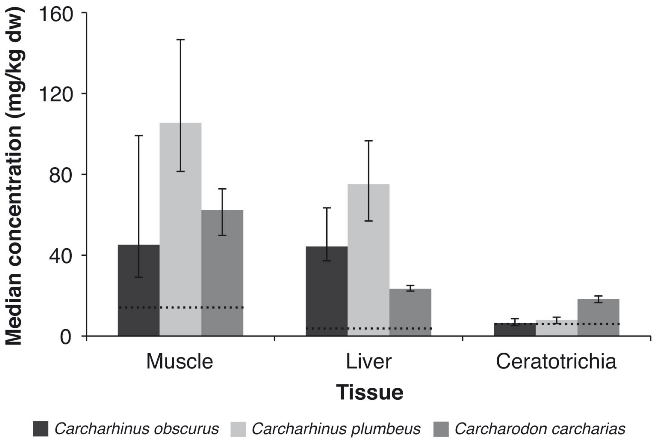


Figure 14 Median Arsenic (As) concentrations in muscle and liver tissue, and fin fibres (ceratotrichia) of dusky *Carcharhinus obscurus* (n = 12), sandbar *Carcharhinus plumbeus* (n = 12) and white *Carcharodon carcharias* sharks (n = 6 for muscle and liver tissue, n = 2 for fin fibres). The dotted line indicates the Food Standards Australia New Zealand (FSANZ) maximum limit in fish tissues. NB: dotted lines indicate the dry weight value equivalent to the FSANZ wet weight maximum limit or UL.

The high concentrations of As in most samples of fin fibres in the present study are also of concern, particularly since implications for regular consumers of these products (i.e. shark fin soup) are unknown. Considering the value of large Carcharhinid fins to the shark fin trade, the results of the present study imply that consumers of NSW shark fins may be exposed to high concentrations of As. These, and other recent findings of a highly potent neurotoxin (BMAA) in shark fins (Mondo *et al.*, 2012), highlight the requirement for further investigation into the effects of consumption of these products and the potential negative human health implications they pose.

FSANZ has developed guidelines for the consumption of shark muscle tissue based on what is considered a provisional tolerable weekly or monthly dietary intake (PTWI and PTMI, respectively) of individual metals and metalloids. Given that mercury concentrations in sandbar and dusky sharks sampled for this study approached the FSANZ recommended maximum standard for human consumption at around 150 cm, concentrations in trimmed carcasses of the majority of sandbar and dusky sharks caught and sold in the NSW large shark longline fishery are likely to be high enough to cause concern for regular consumers of flesh of large sharks, particularly children or pregnant women (Gilbert *et al.*, 2015). Using the highest concentration we found in muscle tissue in the two commercial species (because this is what consumers may ingest), we conclude that two 120 g serves per week of either dusky or sandbar shark flesh would be enough to exceed the FSANZ PTWI.

In the case of arsenic, review of the recently-withdrawn FSANZ recommended maximum standard for human consumption (withdrawn because it was not possible to establish a safe level of exposure) indicated that one 120-gram serve of flesh per week from any of the sharks sampled for this study would be enough to exceed that withdrawn PTWI, with the highest concentration being equivalent to triple that level. In addition, the high concentrations of arsenic in most samples of fin fibres in the present study are also of concern, particularly since implications for regular consumers of these products (i.e. shark fin soup) are unknown. FSANZ continues to issue a health warning regarding arsenic exposure to people who consume large amounts of seafood, highlighting the requirement for further investigation into the effects of consumption of these products and the potential negative human health implications they pose.

While management of the NSW large shark longline fishery has, to date, generally focused on sustainability and prevention of overfishing, it has assumed some guarantee of a high quality and safe product for human consumption. Our results clearly challenge this assumption and make it clear that health advisories and regulations on consumption of shark products need to be suitably conservative to account for disconcerting levels of potentially dangerous metals. In addition to recommending an expanded study to assess the potential impacts of shark consumption on human health, we recommend consideration of a 1.5 m total length size limit as a logical form of regulation given that concentrations of Hg in sharks in the present study and others from Australian waters approach or reach the FSANZ maximum limit at that size.

Conclusion

Genetic Population Modelling

NeOGen is a comprehensive software tool, developed through this FRDC Shark Futures project, which unifies genetic and demographic information to simulate small to large populations for species with overlapping generations. Its primary purpose is to convert empirical Ne-gene estimates to population size estimates for species of conservation or harvest interest, which was done here for two commercially harvested shark species on the eastern Australian coast. The population sizes estimated for sandbar shark and dusky shark provide a baseline for both predicting and monitoring the effects of fishing and environmental pressure on populations of these economically valuable and ecologically important apex predators.

The genetic population modelling facilitates rapid and informative Ne-based population assessments of fisheries species using the power of computer simulation. The framework can be useful at all points in the fisheries population assessment process: (1) when making initial predictions of Ne and population demography prior to experimental design; (2) when deciding on and budgeting for a sampling regimen for Ne estimation and genetic locus development; (3) for testing for appropriate Ne estimation power during sampling and locus development; (4) for population abundance and depletion predictions with Ne estimates.

Overall, this Ne-based population assessment process advances population evaluation and monitoring by allowing prediction of relationships between life history, demography, Ne and abundance as well as providing capacity to forecast contemporary demographic and genetic vulnerabilities of species and populations in response to depletion.

Movements and Mortalities of Tagged Sharks

Despite the problems associated with premature tag releases, short-term tracking of sandbar shark and dusky shark by PSAT in our study has contributed valuable and reliable broad-scale spatial information about movements and possibly migratory behaviour of these two species in waters off New South Wales and Queensland. Track lengths of >500 km in latitudinal directions consistent among individuals were estimated for both species and verified through detections by acoustic receivers. The large-scale horizontal movements indicates that a collective management approach by multiple jurisdictions (NSW, QLD and Commonwealth fisheries) would clearly be appropriate to develop a sustainable TAC for these two species and manage the fishing methods that catch them.

While the rates of post-release mortality in the tagged sharks in our study cannot be considered representative of rates for sharks released following capture during normal commercial fishing operations, it is clear that even seemingly vigorous sharks may still succumb to fatal effects from fishing-induced stressors soon after release. Further studies of post-release mortality of sharks discarded after being hooked by commercial demersal longline gears, using survivorship tags, could be an economical and effective method for resolving the viability of enforced discarding when TACs and trip or weekly limits are used as management tools.

Collectively, the results from our tagging and tracking study substantially enhances the knowledge available for effective management of commercially exploited stocks of sandbar shark and dusky shark along the east coast of Australia.

Capture, Stress and Mortality rates in longline-caught species

Our longline experiments indicated that in the cases of most of the targeted species of the NSW large-shark longline fishery, more than half are likely to be dead by the time the longline gear is retrieved after an overnight deployment. Given that a weekly catch limit is the predominant management option currently in force for the fishery, releasing (or discarding) any individuals of targeted species surplus to the weekly catch limit is a distinct possibility of at-sea activities on board fishing vessels. Assuming large proportions of these discards are dead, this highlights the real potential for unaccounted fishing mortalities, not to mention the unknown extent of post-release mortality in sharks released alive. Our research indicates that through reducing at-vessel rates of mortality of sharks and other bycatch species (particularly TEP species scalloped and great hammerhead), higher rates of survival of released sharks are likely to be achieved.

Our results also indicate that the greatest chance of increasing the survivorship of unwanted shark bycatch in the NSW large-shark longline fishery would be by addressing some of the operational (fishing) variables that might contribute mortality. The most obvious of these would be to shorten the duration of longline deployment. However, to ensure the majority of individuals survive, deployments would need to be less than 2 hours long (conservative) which is unfeasible for setting and retrieving demersal longlines. More realistically, our results indicate that setting demersal longline gear for no more than 5 hours may avoid significant rates of mortality for many large shark species. These timeframes are, however, considerably less than the 7–27 hour deployments previously observed in the fishery, and possibly difficult to achieve without significant losses in fishing efficacy and could be difficult to enforce. Nevertheless, consideration of ways of reducing the duration of deployments (< 5 h) would clearly considerably reduce some of the negative impacts associated with this fishery.

Fisher Catch Reporting in the NSW large-shark fishery

Our study has demonstrated that the considerable effort and resources invested by fisheries managers in improving the reliability of the fisher catch reporting system of the large shark catches within the OTLF yielded considerable success when measured against the monthly logbook reporting associated with the previous monthly system. Upgrades to the logbook design and requirements for increased frequency of reporting, along with provision of a useful species identification guide plus on-board extension education given by fishery observers, have all been contributing factors. Nevertheless, the relative lack of extension to OTLF fishers who target teleosts but still frequently catch sharks, but not in sufficient quantities to warrant being categorised as part of the large shark sub-fishery, has most likely offset some of this improvement.

Despite the overall improvement since 2008, there are still some systemic issues with respect to inversely-correlated misidentification of superficially similar-looking shark species, along with general misreporting of species tallies. The latter is most likely a result of fishers not dutifully identifying sharks and keeping tallies at sea prior to detachment/disposal of the shark heads, which are in most cases the most useful part of the shark with respect to identification. One solution to this may be to mandate that all retained sharks be returned to port with heads attached, and be available for random inspection by fisheries compliance officers prior to trimming.

Given the importance of effective and reliable monitoring of catches of potentially vulnerable species, future revisions and improvements made to the OTLF catch reporting system must place a greater emphasis on education and extension to maximise the intrinsic value of all system upgrades introduced.

Identifying variables for assessment of catch composition in a data-poor shark fishery

A range of operational, environmental and biological variables were assessed to determine whether there are any 'predictor' variables that can assist in identifying catch composition for the NSW large shark fishery. Recording of species and size or age-class (i.e. proportion of adults) were demonstrated to be the most important data in terms of predicting catch composition in this fishery. Operational variables were found to be relatively less important, while Austral season was an important environmental predictor in the case of predicting presence of sandbar shark in the catch. Therefore, in addition to their current requirements of recording total number of individuals and total trimmed weight (individuals combined) by species, we recommend that as a minimum standard of mandatory industry catch reporting all fishers should report a length measurement (preferably fork or pre-caudal length) and sex prior to trimming for each shark caught. If this is deemed impractical, our modelling indicates that recording the proportion of adults per species in the catch may be a suitable proxy for length measurements; however, this would be more complex for compliance without substantial training of both fishers and fishery compliance officers.

Our analyses indicate that, ideally, the legislative requirements should stipulate that sharks should not have their heads or pelvic fins removed at sea to ensure that accurate determination of species, sex and length can be undertaken by 'port observers' at the dock for compliance (logbook validation) and/or research (stock assessment) purposes. Alternatively, a comprehensive port-based scientific sampling program for collection of biological samples for genetic analysis could be introduced to validate logbooks and provide reliable catch data for traditional stock assessments and genetic data for population estimates using our recently developed modelling tool, NeOGen, however such a port-based monitoring and sampling program could be prohibitively expensive.

We show that to validate data integrity associated with any system of self-reporting by fishers, frequent and systematic assessments of catches by scientific observers, either during fishing or upon landing at the dock, must be implemented. Without a demonstrably reliable reference by which to determine the accuracy of logbook data, such as confirmation of species and/or size, measurement error could result in incorrect assessments of the fishery and, therefore, inappropriate management decisions being made and enacted.

Assessment of catch-weight variables and heavy metals in large sharks

The Ocean Trap and Line fishers targeting whaler sharks were primarily motivated by prices obtained for shark fin, although some meat was sold for human consumption. Under the belief that "large shark = large fin", fishers tend to keep the largest sharks caught, potentially leading to high-grading at sea and dumping of smaller carcasses when trip limits are reached. However, large sexually mature sharks are critical in contributing to population fecundity and potential for sustainable fishing of shark stocks. This led to an interest in determining whether there was a cost/benefit relationship between shark size, fin size, and wastage through carcass trimming, that would allow fishers to target smaller sharks whilst still being profitable and reducing wastage.

Our analyses highlight that the shark species, length and sex all contribute to variability in ratios of fin weight to the three body weight measurements recorded in our research (whole, landed and trimmed weights). Sandbar shark was found to have by far the highest fin weight to body weight ratios (irrespective of size) of the species analysed. Specifically, the relative weight of fins to trimmed weight was greater in smaller sharks (i.e. shorter lengths) than in larger sharks in the cases of sandbar shark and dusky shark, plus in hammerhead sharks. The largest difference in ratios between size extremes were apparent for sandbar sharks. Notably, the opposite trend was the case for blacktip sharks and spinner shark. While greater ratios of fin weight to trimmed weight might theoretically result in greater income for the fishery, disparity in prices across different fin sizes must also be considered via formal economic analyses in terms of assessing viability of the fishery if, for example, regulations were put in place regarding maximum size limitations on sharks landed.

Shark length was a significant factor influencing ratios of trimmed weight to whole weight, which represent the relative proportion of wastage, but this was dependent upon species. Most models showed that a higher proportion of the carcass is wasted (i.e. the ratio of trimmed to whole weight decreases) with increasing shark length. Given that ethical concerns exist around wastage and under-utilisation of harvested sharks, and that it is accepted that extracting only smaller, sexually- immature sharks according to a tailored sustainable harvesting regime might avoid ongoing population declines, it may be considered more ethically appropriate to target smaller sharks, despite above-mentioned economic considerations.

Another area of justified concern for fishery managers is the known, but unquantified variability in trimming (carcass 'dressing') outcomes among sharks, trips and fishers. Although there are broad legislated trimming guidelines, limited fishery management resources effectively prevents appropriate compliance and monitoring with respect to trimming practices and accurate fisher reporting of species, numbers of sharks and catch weights for landed catch. We recommend further review of the current management philosophies and framework underpinning the NSW large shark longline fishery with a view to reducing the risk of these sources of variability in catch reporting.

As apex predators, sharks accumulate pollutants from their prey. Such bioaccumulation can lead to unacceptable risk of pollutant poisoning through ingestion of affected shark product by humans. We examined concentrations of potentially dangerous metals and metalloids (i.e. mercury and arsenic) in shark muscle tissues (i.e. flesh), liver and/or fins for animals caught in the NSW large shark fishery. Results show that the large sizes, and hence old ages, of sharks targeted in this fishery has meant that concentrations of these analytes are quite high, with concentrations in larger sharks exceeding formally recommended levels for typical rates of human consumption of fish flesh. In addition to recommending an expanded study to assess the potential impacts of shark consumption on human health, we recommend consideration of a 1.5 m size limit as a logical form of regulation given that concentrations of Hg in flesh of larger sharks are above Food Standards Australia New Zealand maximum limit. Arsenic concentrations are also of concern, especially in fins of the larger sharks targeted by this fishery.

Implications

Losses of large apex predators like sharks can have substantial negative flow through cascading effects in marine ecosystems. Ensuring sustainable fishing of these ecologically important species is therefore imperative to ensure healthy coastal fish populations and concomitant fisheries.

Historically, targeted fishing for large sharks has occurred in low effort in NSW waters (Macbeth *et al.*, 2009), however a three-fold increase in targeting sharks with large, valuable, fins led to concern about sustainability of these shark stocks. Once overexploitation of such species occurs their populations can take years to recover (Baum *et al.*, 2003; Dulvy *et al.*, 2008).

The first population estimate for two target species of large shark, the sandbar shark *C. plumbeus* and dusky shark *C. obscurus* was calculated using our purpose-built new model now known as NeOGen (Blower *et al.*, 2019). It is estimated that there are approximately 36,500 dusky sharks in the Australian population, whilst there are approximately 105,000 sandbar sharks for the population residing in eastern Australia. These population estimates imply that particularly dusky sharks would be particularly prone to potential overfishing.

Substantial quality control and assurance tests indicated this new model provided genetically-based population estimates that were robust to the quality of genotype data. Validation work also provided a high level of confidence in NeOGen as a tool to interpret Ne-gene estimates with respect to the population demographics of these two shark species in eastern Australian waters. Using NeOGen to predict the effect of fishing mortality on Ne-gene and total population size suggested that detecting an unsustainable trend in fishing mortalities may be possible four years after fishing commences and becomes significantly more apparent after eight years of sustained fishing at those levels.

Our research suggests that fishing pressure throughout Australia should be taken into consideration when setting total catch limits or dusky sharks as the population appears to be genetically 'open'. Sandbar sharks, on the other hand, constitute an 'eastern Australia population' and quotas for this species could therefore be set at a more regional level.

Telemetry data indicated that these two whaler shark species preferentially occupy slightly different depths and water temperatures, implying that more targeted fishing activity may be plausible through setting gear at particular depths. However, the telemetry data also indicate that sandbar sharks showed evidence of philopatry (site/reef fidelity) which may lead to a higher susceptibility to over-exploitation in this species.

Analysis highlights the importance in accuracy of two life history characteristics to ensure the outputs from NeOGen are robust. Both require accurate details from the catch, including species identification and sizes of animals caught.

Our analyses of gear trials and catch rates suggest that to reduce unwanted catch fishers should set and retrieve their lines nocturnally and for short soak times of less than five hours. Due to logistical reasons, this is unlikely to be feasible; however, our data do indicate that fishers wanting to target large sharks should set their gear after dusk and retrieve it before dawn. Not only would this reduce catch of unwanted shark species (e.g. TEP species such as hammerhead sharks), but it would also likely reduce potential interaction with species such as sea birds.

Despite the overall improvement in reporting of shark catch since 2008, there are still some systemic issues with respect to inversely-correlated misidentification of superficially similar-looking shark species, along with general misreporting of species tallies. The latter is most likely a result of fishers not dutifully identifying sharks and keeping tallies at sea prior to detachment/disposal of the shark heads, which are in most cases the most useful part of the shark with respect to identification. One solution to this may be to mandate that all retained sharks be returned to port with heads attached, and be available for random inspection by fisheries compliance officers prior to trimming. This would have implications for both fishers and fish receivers as shark heads have no commercial value, except jaws and teeth, while the implication for fishery managers would be the legislative changes to be required.

Given the importance of effective and reliable monitoring of catches of potentially vulnerable species, future revisions and improvements made to the OTLF catch reporting system must place a greater emphasis on education and extension to maximise the intrinsic value of all system upgrades introduced. Therefore, in addition to their current requirements of recording total number of individuals and total trimmed weight (individuals combined) by species, we recommend that as a minimum standard of mandatory industry catch reporting all fishers should report a length measurement (preferably fork or pre-caudal length) and sex prior to trimming for each shark caught. If this is deemed impractical, our modelling indicates that recording the proportion of adults per species in the catch may be a suitable proxy for length measurements; however, this would be more complex for compliance without substantial training of both fishers and fishery compliance officers.

Our analyses indicate that, ideally, the legislative requirements should stipulate that sharks should not have their heads or pelvic fins removed at sea as this would enhance accurate determination of species, sex and length and can potentially be undertaken by 'port observers' at the dock for compliance (logbook validation) and/or research (stock assessment) purposes. Alternatively, a comprehensive port-based scientific sampling program for collection of biological samples for genetic analysis could be introduced to validate logbooks and provide reliable catch data for traditional stock assessments and genetic data for population estimates, however this is likely to be prohibitively expensive.

We show that to validate data integrity associated with any system of self-reporting by fishers, frequent and systematic assessments of catches by scientific observers, either during fishing or upon landing at the dock, must be implemented. Without a demonstrably reliable reference by which to determine the accuracy of logbook data, such as confirmation of species and/or size, measurement error could result in incorrect assessments of the fishery and potential for inappropriate management decisions being made and enacted.

Shark length was a significant factor influencing ratios of trimmed weight to whole weight, which represent the relative proportion of wastage, but this was dependent upon species. Most models showed that a higher proportion of the carcass is wasted (i.e. the ratio of trimmed to whole weight decreases) with increasing shark length. Ethical concerns exist around wastage and under-utilisation of harvested sharks. Other research has indicated that extracting only smaller, sexually- immature sharks according to a tailored sustainable harvesting regime might avoid population declines in fished shark species. These factors imply that a NSW whaler shark fishery should preferably target animals less than 1.5m total length.

To ensure accurate fisher reporting of species, numbers of sharks caught and catch weights, our research highlights that regulations should be refined to ensure shark catch is trimmed in a very specific manner to enable effective reporting and compliance of this fishery. This has legislative implications for fishery managers, reporting implications for fishers and fishery compliance staff, and implications for fish receivers regarding potential increased waste to contend with due to heads and other unwanted shark trimmings.

As apex predators, sharks accumulate pollutants from their prey. Such bioaccumulation can lead to unacceptable risk of pollutant poisoning through ingestion of affected shark product by humans. The levels of pollutants in NSW-caught sharks show that the large sizes, and hence old ages of sharks targeted in this fishery, have high concentrations of these analytes in their flesh and fins, with concentrations in larger sharks exceeding formally recommended levels for typical rates of human consumption of fish flesh. These results have implications for the fishery as they corroborate our suggestion that the fishery is limited to landing young whaler sharks less than 1.5m in length.

Recommendations

Regular fisheries models use CPUE and catchability to estimate biomass, while NeOGen, the new model developed through this FRDC Shark Futures project, uses Ne-gene to infer population size. NeOGen does not rely on catch reporting or estimation of fisheries catch to estimate biomass, it only requires tissue samples for genetic analysis. We recommend support for further development of the NeOGen method as this may then lead to its applicability to other fishery species characterised by much larger population sizes and different life histories.

The results regarding abundance of the sandbar and dusky sharks need extensive sensitivity testing to provide confidence in the outcomes. The uncertainty in the estimates generated here is relatively high and there is also the question of whether the input parameters (such as age at maturity, characteristics of reproduction and natural mortality) are correct, and whether uncertainty effects the abundance estimates. For example, the age and growth work that these estimates are based on (Geraghty *et al.*, 2014a) produced estimates of age at maturity that are quite different than those produced by every other study globally, including those from Western Australia. Embracing this uncertainty, as we do with regular stock assessments, is an important part of the process of bringing this type of genetic approach into the mainstream.

This research has highlighted the benefit of using pop-up satellite archival tags (PSATs) to understand levels of post-release mortality in unwanted sharks from commercial fishing operations. We therefore recommend that support should be provided to including this technology to estimate survivorship of released animals from other fisheries. Unfortunately, it appears that in some cases even apparently healthy-looking and vigorous sharks still do not survive capture. We therefore propose that total catch should incorporate a percentage of animals likely succumbing to post-release mortality to ensure all fishery related removals from the population are accounted for in modelling TACs and/or other fishery management measures.

Determining the post-release survivorship for other shark species caught on demersal long-lines requires further research to ensure all fishery-related mortalities are incorporated in population modelling to ensure sustainable shark fisheries.

This study suggested some philopatry for sandbar sharks. Almost all shark species that have been tracked through various forms of telemetry have exhibited philopatry in some form. As this behavioural trait may impact subjection to localised fishing pressure, more effort should be initiated into telemetry of commercially valuable shark species to determine movements, habitat use and philopatry. Researchers should be encouraged to participate in the Australian tagging database administered by the IMOS Animal Tracking Facility if their project is funded through the FRDC.

Fishery models incorporating animal movement need to be developed.

Our research has highlighted how catch reporting accuracy can be affected through belated reporting by fishers. Electronic logbooks need to be considered for fishers and, in the case of sharks, should include fields for length and sex for individual sharks caught.

Considering how our research has underlined the importance of landing sharks of less than 1.5m total length, further experiments should be conducted to establish size-selective fishing measures.

Further development

The promise of rapid and efficient Ne-based population assessments that can evaluate both the genetic health of a population and a population's size, productivity, and vulnerability to depletion can be realised with effective tools, thoughtful experimental design, and commitment to genetic population assessment.

The methodology and tools developed here address some major hurdles to understanding the general relationships between the life history of fisheries species, Ne and abundance. They have the potential to facilitate rapid and consistent population-specific analyses when reliable life history and demographic information is available.

The field of population assessment with genetic Ne is progressing rapidly with new sampling techniques, cost-effective genome-wide DNA analyses, and the increasing availability of high-performance computing resources and simulations. However, uptake and refinement of *N*e-based population assessment also relies upon recognition of the value of genetic analyses and commitment to genetically assessing and monitoring populations of conservation or sustainability concern. To realise the promise of Ne-based population assessments, the number one priority should be to ensure that genetic samples are obtained whenever possible, which requires funds and dedication to sampling populations as widely as possible. In the case of fisheries, commitment to ageing and genetically sampling large proportions of catches would go a long way towards effective and efficient *N*e-based population management.

This project has highlighted the importance of accurate reporting and the discrepancies that can arise if fishers wait until arriving back at the dock before completing their catch logbooks. We therefore believe that use of electronic logbooks for instantaneous catch reporting would provide far more accurate data to enable development and maintenance of sustainable fisheries. Further development of electronic reporting and monitoring is therefore warranted.

Several components of this FRDC Shark Futures project have indicated the benefits of retaining and landing whaler sharks less than 1.5m total length. To reduce catch of unwanted species and size classes, further gear experiments using different hook characteristics are recommended.

Additionally, gear modifications should consider the feasibility of developing shark fishing gear that would allow deployment and retrieval with soak times of around 5 hours, or at minimum during nocturnal hours, to reduce catch of TEP species such as hammerhead sharks.

The investigations completed during this project have also underscored the importance of ensuring accurate species identification and size measurements if sustainable shark fisheries are to be developed. Our research indicates the value of inclusion of the heads and all fins on shark carcasses when landed. We therefore propose management changes that will lead to shark carcasses being landed with minimal and carefully worded trimming/dressing guides including prohibition of beheading sharks at sea.

Extension and Adoption

In order to effectively deliver on Objective 5, we dedicated considerable effort to identifying the problems fishers were experiencing with shark identification to ensure an accurate long-term database to monitor fishing of the shark populations in NSW and to educate them on correct field identification and logbook recording, whilst also determining the value of the use of a field-identification booklet in ensuring correct records.

We developed a questionnaire for OTLF fishers to provide anonymous feedback regarding their usage or non-usage of the ID guide and perceptions of the usefulness of various aspects of the guide in terms of identifying shark species and filling in daily logs. This 19-question questionnaire was distributed to ~1,500 NSW commercial fishers, including all those with an OTLF endorsement.

Scale-based responses (i.e. choose a value 0 to 4) were requested and various statistical analyses were applied where appropriate to interpret responses to the questions (Macbeth *et al.*, 2018).

Despite this questionnaire being posted to all of the OTLF fishers who had been posted a hard-copy ID guide in 2008, the proportion of OTLF fishers electing to respond to the questionnaire was extremely low (7.3%). Our research highlighted a historically insufficient level of extension education throughout the OTLF following distribution of relevant educational material.

Fishers that had used the guide (and responded to the questionnaire) found the ID guide useful when trying to differentiate between species, and indicated that the current format is accurate and sufficiently structured for easy species identification. Perhaps most importantly, the majority also stated that it aided them to fill in log books correctly. Interestingly, the most commonly used sections of the guide (and those deemed 'more important' by fishers) were: 1) the generic shark diagram pointing out the main morphological features that can be used to distinguish among species; and 2) the section of the guide that lists the distinguishing features of each species (one species to a page and with accompanying illustration). This was despite the carefully designed dichotomous key for separating species within families being included in the guide with the intention of making species deduction an easier, step-wise process.

Nevertheless, there was relative lack of extension to OTLF fishers who target teleosts but still frequently catch sharks, but not in sufficient quantities to warrant being categorised as part of the large shark sub-fishery. This has likely offset some of the improvement in shark catch records experienced since the ID Guide and shark fisher training was completed.

It is clear that any educational materials developed for use by fishers requires substantial follow-up including *in situ* training and tuition in guide-use.

Communication and Extension outputs

Face-to-face presentations

Face-to-face dissemination of information was identified as the commercial fisher's most preferred method of information delivery. Nine observers worked with ten large shark fishers during the course of this FRDC Shark Futures project and assisted fishers with training in use of the Shark & Ray Identification Guide, plus any questions the fishers had about their catches, the research project and/or logbook entries.

In addition, the project executant, Dr Butcher, has discussed the project with shark fishers operating from several of the major ports on the NSW north coast.

Three formal project partner meetings were conducted during the course of this project. These face-to-face presentations provided an opportunity to maintain relationships with project partners, discuss project aims, inform partners of the project's progress, and discuss any queries:

(1) Project Research Meeting, Sydney Institute of Marine Science, 07 October 2014.

Invitees included NSW DPI scientists (fisheries and biometrics), NSW fisheries managers, University of Queensland, independent consultant.

Presentations were delivered by all project co-investigators.

(2) Project Update Meeting, Sydney Institute of Marine Science, 07 July 2014

Invitees included FRDC, Australian Marine Conservation Society, Humane Society International, Professional Fishermen's Association, NSW DPI fishery managers, NSW DPI Threatened Species Unit, independent consultant re fishery observer programs, and all co-investigators.

Presentations included:

Vic Peddemors (Introductions and welcome)

Paul Butcher (overview of project objectives)

Jenny Ovenden and Dean Blower (genetics) – objective 1

Paul Butcher (tagging data) – objective 2

Vic Peddemors (bycatch mitigation techniques) – objective 3

Will Macbeth (ID guide efficacy) – objective 4

Vic Peddemors (data poor modelling) – objective 5 and 6

Vic Peddemors (concluding remarks synthesising the presented results and highlighting management options to develop sustainable large shark fisheries.

Fiona McKinnon (NSW DPI fishery management – comments and concerns)

Discussion with stakeholders regarding future management options for the capture of large whaler sharks within NSW fisheries.

(3) Final Project Meeting with shark fisher stakeholders, National Marine Science Centre, Coffs Harbour 27 July 2014.

The purpose was to present the final outcomes of this FRDC-supported project on the large whaler shark fishery in NSW to stakeholders. The workshop presented an overview of the project and all associated chapters/papers. This presented an opportunity for stakeholders to participate in discussions regarding the outcomes prior to the preparation of the Final Report.

Invitees included the ten historically most active large shark fishers, Professional Fishermen's Association, NSW DPI fishery managers, and all co-investigators.

Presentations included:

Vic Peddemors (Introductions and welcome)

Paul Butcher (overview of project objectives)

Jenny Ovenden and Dean Blower (genetics) – objective 1

Paul Butcher (tagging data) – objective 2

Vic Peddemors (bycatch mitigation techniques) – objective 3

Paul Butcher (ID guide efficacy) – objective 4

Vic Peddemors (data poor modelling) – objective 5 and 6

Discussion with stakeholders regarding future management options for the capture of large whaler sharks within NSW fisheries.

Project materials developed

Project materials developed are described in detail in the Extension and Adoption Section (above). Other project materials can be found in the Appendices.

The following manuscripts have emanated from this research and hyperlinks are included to assist readers in accessing these peer-reviewed scientific publications. If you are unable to gain access, please do not hesitate to contact the Principal Investigator, Dr Vic Peddemors at: vic.peddemors@dpi.nsw.gov.au

Objective 1: Genetically resolve the effective population size of dusky and sandbar sharks targeted in the NSW Ocean Trap and Line Fishery.

Blower, D. C. 2020. Estimating contemporary abundance, demography, and vulnerability to change for long-lived species with effective population size and population simulation. PhD thesis. School of Biological Sciences, p. 257. The University of Queensland. DOI https://doi.org/10.14264/uql.2020.760

Blower D, Hereward J and Ovenden J (2013). The complete mitochondrial genome of the dusky shark *Carcharhinus obscurus*. *Mitochondrial DNA* **24**: 619-621. https://www.tandfonline.com/doi/abs/10.3109/19401736.2013.772154

Blower D and Ovenden J (2016). The complete mitochondrial genome of the sandbar shark *Carcharhinus plumbeus*. *Mitochondrial DNA* **27**: 923-924. https://www.tandfonline.com/doi/abs/10.3109/19401736.2014.926487

Blower D. C., Corley S. W., Hereward J., Riginios C., Ovenden J. R. (2015). Characterisation and cross-amplification of 19 novel microsatellites for the sandbar shark, *Carcharhinus plumbeus*. *Conservation Genetics Resources* **7**: 913-915. https://link.springer.com/article/10.1007/s12686-015-0500-0

Blower D. C., Corley S. W., Hereward J., Riginios C., Ovenden J. R. (2015). Characterisation and cross-amplification of 21 novel microsatellite loci for the dusky shark, *Carcharhinus obscurus*. *Conservation Genetics Resources* **7**: 909-912. https://link.springer.com/article/10.1007/s12686-015-0499-2

Blower D.C., Riginos C. and Ovenden J.R. (2019). NeOGen: A tool to predict genetic effective population size (Ne) for species with generational overlap and to assist empirical Ne study design. *Molecular Ecology Resources* **19**: 290-271. https://onlinelibrary.wiley.com/doi/full/10.1111/1755-0998.12941

Blower D.C., Butcher P.A., Geraghty P.T., MacBeth W.G., Peddemors V.M. and Ovenden J.R. (*in prep*). The Australian population structure of two commercially harvested shark species, *Carcharhinus plumbeus* and *Carcharhinus obscurus*.

Blower D.C., Butcher P.A., Peddemors V.M. and Ovenden J.R. (*in prep*). The genetic current effective population size (Ne) and census size (Nc) for two commercially harvested shark species and predictions of population size under future mortality scenarios.

Objective 2: Determine the short-term and distance movements of sandbar and dusky sharks to assist in the development of potential spatial management options like time-area (spatio-temporal) closures.

Barnes C.J., Butcher P.A., Macbeth W.G., Mandleman J.M., Smith S.D.A. and Peddemors V.M. (2016). Movements and mortality of two commercially exploited carcharhinid sharks following longline capture and release off eastern Australia. *Endangered Species Research* **30**: 193-208. https://www.int-res.com/abstracts/esr/v30/p193-208/

<u>Objective 3:</u> Develop a fishing technique that will decrease mortality of unwanted species, particularly threatened and protected species, to minimize environmental impact of the fishery.

Broadhurst M., Butcher P., Millar R., Marshall J. and Peddemors V. (2014). Temporal hooking variability among sharks on south-eastern Australian demersal longlines and implications for their management. *Global Ecology and Conservation* **2**: 181-189. https://www.sciencedirect.com/science/article/pii/S2351989414000365

Butcher P.A., Peddemors V.M., Mandleman J.W., McGrath S.P. and Cullis B.R. (2015). At-vessel mortality and blood biochemical status of elasmobranchs caught in an Australian commercial longline fishery. *Global Ecology and Conservation* **3**: 878−889. https://www.sciencedirect.com/science/article/pii/S2351989415000487

<u>Objective 4:</u> Assess the effectiveness of the NSW DPI shark field ID-guide through ground-truthing on-board shark identification between fishers and observers, plus via genetic testing.

Macbeth W.G., Butcher P.A., Collins D., McGrath S.P., Provost S.C., Bowling A.C., Geraghty, P.T. and Peddemors V.M. (2018). Improving reliability in species identification and logbook catch reporting by commercial fishers in an Australian demersal shark longline fishery. *Fisheries Management and Ecology* **25**: 186-202. https://onlinelibrary.wiley.com/doi/full/10.1111/fme.12276

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<u>Objective 5:</u> Apply and evaluate assessment methods and management indicators for data-poor species that may provide a model for future national and/or international data-poor shark fisheries.

Lee K., Butcher P., Peddemors V., and Macbeth, W. (*in prep*). Relative importance of biological and operational variables to accurately assess the catch composition in a 'data poor' multi-species shark fishery in Australia.

<u>Objective 6:</u> Provide scientific data-based advice for management to ensure the future sustainability of shark populations.

Pleizier N., Gutowsky L., Peddemors V., Cooke S. and Butcher P. (2015). Variation in whole-, landed - and trimmed-carcass and fin-weight ratios for various sharks captured on demersal set-lines off eastern Australia. *Fisheries Research* **167**: 190-198. http://www.fecpl.ca/wp-content/uploads/2015/02/pleizier_et_al_2015_shark_ratios.pdf

Gilbert J, Reichelt-Brushett A., Butcher P., McGrath S., Peddemors V., Bowling, A and Christidis L. (2015). Metal and metalloid concentrations in the tissues of dusky *Carcharhinus obscurus*, sandbar *C. plumbeus* and white *Carcharodon carcharias* sharks from south eastern Australia, and the implications for human consumption. *Marine Pollution Bulletin* **92**:186−194. https://www.sciencedirect.com/science/article/pii/S0025326X14008388

Gilbert J.M., Baduel C., Li Y., Reichelt-Brushett A.J., Butcher P.A., McGrath S.P., Peddemors V.M., Hearn L., Mueller J. and Christidis L. (2015). Bioaccumulation of PCBs in liver tissue of dusky *Carcharhinus obscurus*, sandbar *C. plumbeus* and white *Carcharodon carcharias* sharks from south-eastern Australian waters. *Marine Pollution Bulletin* **101**: 908-913. https://www.sciencedirect.com/science/article/pii/S0025326X15301442

Appendix A - List of researchers and project staff :

- Dr Victor Peddemors – NSW DPI Fisheries scientist and project Principal Investigator.
- Dr Paul Butcher – NSW DPI Fisheries scientist and project coordinator.
- Dr. Will Macbeth – NSW DPI Fisheries scientist and specialist in fisheries observer programs. Currently at FERM Services.
- Dr Damian Collins – NSW DPI biometrician with statistical expertise is in mixed models, especially generalized linear mixed models (GLMMs).
- Dr Jennifer Ovenden – Geneticist specializing in fishery-related techniques. Previously at Queensland DAF and currently at the University of Queensland.
- Mr. Andrew Goulstone – NSW DPI Director of Commercial Fisheries (retired).
- Dr Mathew Ives - NSW DPI Fisheries scientist specialising in fisheries modelling and assessment, particularly data-poor fisheries risk assessments. Currently at Oxford University, U.K.

Researchers and staff that became associated with the project through various sub-projects and/or due to their expertise relevant to this project:

- Dr Christine Baduel – University of Queensland, Australia
- Mr Christopher Barnes - fisheries technician in NSW DPI
- Mr Dean Blower – genetics PhD candidate developing SharkSIM (University of Queensland)
- Dr Alison Bowling – Southern Cross University, Australia
- Dr Matt Broadhurst – NSW DPI Fisheries scientist specialising in gear technology and reducing bycatch in fisheries.
- Prof. Steven Cooke – specialist in fish and aquatic ecosystem research, particularly conservation physiology (Carleton University, Canada)
- Prof. Les Christidis – Southern Cross University, Australia
- Prof. Brian Cullis –applied statistician (University of Wollongong).
- Dr Pascal Geraghty – fisheries technician in NSW DPI
- Ms. Jann Gilbert – MSc student in marine pollution, Southern Cross University, Australia.
- Dr Lee Gutowsky – biotelemetry specialist (Carleton University, Canada)
- Dr Laurence Hearn – University of Queensland, Australia
- Dr Katherine Lee – Macquarie University, Australia
- Dr Yan Li – University of Queensland, Australia
- Prof. John Mandelman – academic (New England Aquarium, USA) for analysis of PSAT data from tagged and released sandbar and dusky whaler sharks, plus blood chemistry analysis of caught sharks.
- Ms. Jen Marshall – fisheries technician in NSW DPI
- Dr Shane McGrath – fisheries technician in NSW DPI
- Assoc. Prof. Russell Millar – statistician specialising in ecology and fisheries research (University of Aukland, New Zealand).
- Prof. Jochen Mueller – University of Queensland, Australia
- Ms Naomi Pleizier – Carleton University, Canada
- S.C. Provost – fisheries technician in NSW DPI
- Assoc. Prof. Amanda Reichelt-Brushett – Southern Cross University

Appendix B - Intellectual Property:

NeOGen

The Microsoft Windows (64-bit ver. 7 or later) program, user manual and associated documentation (e.g. README.txt) are available from the Molecular Fisheries Laboratory web site (https://www.molecularfisherieslaboratory.com.au/neogen-v1-3-0-6-a1-software).
A GNU General Public License (GPL) licence applies to the NEOGEN software, and the code (written in PYTHON v2.7 and SIMUPOP v1.1.3) is available on request.
Example data for zebra shark, *Stegostoma fasciatum*, is included and accessed from within the NEOGEN program, and the documented analysis is available upon request. Note that these example data for zebra shark were not collected as part of this FRDC Shark Futures project.

Scientific outputs

All results will be published in scientific and non-technical literature.
Manuscripts published in peer-reviewed literature to date are provided in the section Project Materials Developed (pages 56-57). These publications should be cited as papers rather than as part of the report.

Fishery Data

The raw data from compulsory fishing logbooks remains the intellectual property of NSW DPI. Raw catch data provided by individual fishers remains the property of the fishers. Intellectual property accruing from the analysis and interpretation of raw data rests jointly with NSW DPI, SCU and UQ.

Appendix C - References:

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Appendix D - Conference Presentations

Sharks International – Durban, South Africa 2014

Why do they die? Mortality indices of elasmobranchs caught on demersal long lines in a south-east Australian commercial shark fishery.

Paul A. Butcher[1]*, Shane P. McGrath[1] and Victor M. Peddemors[2]

The high mortality of captured sharks in the commercial large shark fishery off northern New South Wales, Australia, initiated research to investigate methods of reducing mortality of unwanted catch. Over 17 days between January and June 2013, setlines with 480 gangions were deployed from a commercial fishing vessel in 45–105 m of water. To quantify the length of time between initial hooking and capture, all gangions were fitted with 'hook timers'. On each day, the start of the long line was retrieved after a minimum deployment of seven hours and depending on catch, retrieval took up to 13 hours . All animals were assessed for their condition with respect to activity, wounds, sea lice and skin. A total of 689 animals (22 species – 18 elasmobranchs) were landed. All wobbegong (ornate, spotted and banded), smooth stingrays, eastern shovelnose ray, grey nurse and bull sharks survived capture. Tiger sharks, white-spotted guitar fish and gummy sharks exhibited some deaths (6%, 13% and 23% respectively). However, whaler and hammerhead sharks experienced substantial mortality rates ranging from: 51% – sandbar, 67% – bronze whaler, 69% – dusky, 90% – scalloped hammerhead, 92% – common black tip, 96% – spinner and 100% for great and smooth hammerhead. Mortality rates were correlated to activity, wounds and time spent on the line after initial hooking. Most spinner, common black tip and hammerhead shark mortalities occurred within three hours of being hooked. However, some sandbar, dusky, bronze whaler and tiger sharks were still alive >15 hours after initial hooking. Given the high mortality rates seen for protected species (scalloped and great hammerheads) in this jurisdiction and the 500 kg weekly trip limit that is currently in place for this fishery, concern exists about the number of animals that would be returned dead to the water after capture.

Quantifying metal and metalloid concentrations in the muscle, liver and ceratotrichia of dusky, sandbar and great white sharks from south-eastern Australian waters

Jann Gilbert[1*], Paul Butcher[3], Les Christidis[1], Shane McGrath[3], Victor Peddemors[4], Alison Bowling[5] and Amanda Reichelt-Brushett[2].

As apex predators, sharks are known to bioaccumulate metals and metalloids in their tissues, and because of their high trophic level they are also vulnerable to biomagnification. In this study, metal and metalloid concentrations in the muscle, liver and ceratotrichia of dusky, sandbar and great white sharks from south-eastern Australia were quantified. Approximately 70% of all muscle tissue had mercury concentrations above the FSANZ maximum limit (1.0 mg kg^{-1} ww). Liver tissue generally had the highest mean concentrations of analytes, with the exception of arsenic, which was found in higher concentrations in muscle tissue. The highest mean (±SE) mercury concentration in muscle tissue was found in great whites (9.7 ± 2.0 mg kg^{-1} dw), followed by dusky (8.5 ± 1.4 mg kg^{-1} dw) and sandbar (6.71 ± 0.9 mg kg^{-1} dw) sharks. Mean liver tissue concentrations of mercury were comparable between dusky (11.6 ± 4.3 mg kg-1 dw) and sandbar (11.5 ± 4.7 mg kg^{-1} dw) sharks but significantly lower in great whites (0.9 ± 0.2 mg kg^{-1} dw). Concentrations of analytes in ceratotrichia were lower than all other tissues with the exception of zinc. There was a general trend for higher concentrations in muscle tissue of juvenile sharks, whereas liver concentrations tended to be higher in adults. Mean mercury concentrations in muscle tissue were significantly correlated with total length for all species, and generally higher in males. A positive correlation was found between mercury and selenium in shark liver tissue, and a molar ratio approaching 1:1 indicated a physiological response to high mercury concentrations. The concentrations reported here are higher than many other studies and could cause potential health concerns for regular consumers of shark flesh and shark products, and warrant further investigation.

Appendix E – Extension Presentations

Data and slides from various components this project have been used in several presentations:

- University of La Reunion (2019), Isle de la Reunion
- SIMS Master in Marine Sciences lecture series (annual 2014-2020), Sydney
- University of Technology Sydney 3rd year course (annual 2010-2020), Sydney
- **Stakeholder Workshop** (2015), National Marine Science Centre, Coffs Harbour
- **Stakeholder Workshop** (2015), Sydney Institute of Marine Science, Sydney
- AusAID Sustainable Islands Program (2015), Sydney
- SBEEL VIII plenary lecture (2014), Recife, Brazil
- Taronga Conservation Society (2014), Sydney
- University of NSW 3rd year course (annual lecture 2010-2014)
- Mosman Council Environmental Sustainablity Program (2013), Sydney
- Sydney Institute of Marine Science, Public Education lecture series (2013), Sydney
- Shark Futures research team workshop (2013), Brisbane

NSW DPI Guide to identifying hammerhead sharks

Due to commercial fishers shown difficulty in correctly identifying the species of hammerhead shark, a new hammerhead-specific identification brochure was developed in consultation with the Threatened Species Unit of NSW DPI Fisheries: