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Spatial and temporal dynamics of Western Australia's commercially important sharks

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Abbreviations

AATAMS	Australian Animal Tracking and Monitoring System
ADMB	Automatic Differentiation Model Builder
AIC	Akaike Information Criterion
CI	Credible Intervals
CPUE	Catch per Unit of Effort
DoF	Department of Fisheries
EBFM	Ecosystem Based Fisheries Management
ESD	Ecologically Sustainable Development
EEZ	Australian Exclusive Economic Zone
FL	Fork Length
GLM	Generalized Linear Model
GPS	Global Positioning System
GVP	Gross Value of Production
ID	Identification Number
JASDGDLF	Joint Authority Southern Demersal Gillnet and Demersal Longline Managed Fishery
JANSF	Joint Authority Northern Shark Fishery
MCMC	Markov Chain Monte Carlo
MSF	South Australian Marine Scalefish Fishery
NSF	Northern Shark Fisheries
ONLF	Northern Territory Offshore Net and Line Fishery
OTN	Ocean Tracking Network
PCM	Post Capture Mortality
ROM	Rate of Movement
ROV	Remotely Operated Vehicle
SA	South Australia
SARDI	South Australian Research and Development Institute
SD	Standard Deviation
SE	Standard Error
SESSF	Southern and Eastern Scalefish and Shark Fishery
TDGDLF	Temperate Demersal Gillnet and Demersal Longline Fisheries
TEPS	Threatened, Endangered, or Protected Species
TL	Total Length

WA	Western Australia
WANCSF	Western Australia North Coast Shark Fishery
WCDGDLF	West Coast Demersal Gillnet and Demersal Longline (Interim) Managed Fishery
WC	West Coast (used as a synonym of WCDGDLF)
WTBF	Commonwealth managed Western Tuna and Billfish Fishery
YMB	Year-Month-Spatial Block
YMZ	Year-Month-Management Zone
ZN1	Zone 1 of the Joint Authority Southern Demersal Gillnet and Demersal Longline Managed Fishery
ZN2	Zone 2 of the Joint Authority Southern Demersal Gillnet and Demersal Longline Managed Fishery

Executive Summary

OVERVIEW

This project took advantage of an unprecedented deployment of acoustic receiver infrastructure around the Western Australian coast to monitor a large number of sharks implanted with acoustic tags. This research was undertaken to better understand the temporal and spatial dynamics of commercially-important sharks in Western Australia, which has enabled a re-evaluation of the risks of cryptic sources of catch and bycatch to dusky and sandbar shark stocks and development of population simulation models with which to test the implications of spatially-different histories of fishery management, as well as future spatial-management arrangements for whiskery and gummy sharks stocks.

The fishery biology (reproduction, growth, age, gear selectivity, fishing mortality, etc.) of Western Australia's four most commercially-important shark stocks (gummy, dusky, whiskery and sandbar sharks) are relatively well understood. However, uncertainty regarding their migratory and dispersal patterns remains a significant caveat to ensuring their sustainability and for the long-term viability of the fisheries that target them. Shark fishing has been prohibited in the north-west for more than a decade to protect adult dusky and sandbar sharks. However, the extent to which adults remain vulnerable to capture during their southerly natal migrations cannot be ascertained due to lack of knowledge about the timing, duration and pathways of those migrations. Gummy and whiskery shark movements between target-fishery management zones have significant implications for those stocks' continued recovery from historical periods of overfishing. In particular, the effects of gillnet fishing in the south east of the State during the previous seasonal closure of the fisheries west of 118° E and a previously-observed apparent westwardly emigration of gummy sharks from the south-eastern management zone are of interest to fishery managers and industry alike.

Aims and objectives

This project aimed to provide a better understanding of the dynamics of the four main commercial shark species as a basis for developing spatially and temporally-explicit stock assessment models and risk assessments. The specific project objectives were to:

1. Identify and describe the timing, duration and pathways of dusky and sandbar shark migrations
2. Quantify exchange rates of gummy and whiskery sharks among management zones
3. Reassess stocks' status with greater reference to their spatial and temporal dynamics

Methodology

Movements of sandbar, dusky, gummy and whiskery sharks were studied across Western Australia using acoustic telemetry. Acoustic receivers were located off Ningaloo Reef, from Tantabiddi Creek south to Coral Bay and in the south-west of the state, between Perth and the

Recherche Archipelago. Sharks were internally implanted with uniquely-coded acoustic transmitters from commercial demersal gillnet fishing vessels in the South and during fishery-independent longline and drumline fishing around the State.

For gummy and whiskery sharks, movement information was combined with catch history, standardised catch rate indices and biological information as a basis for development of several simulation models to represent population dynamics for future stock assessment. For dusky and sandbar sharks, movement information was used in a qualitative, consequence-likelihood risk assessment framework to re-evaluate remaining risks to their sustainability.

Results/key findings

This study internally implanted 397 sharks with acoustic transmitters and monitored the occurrence and movements of 207 of these individuals along the West and South coasts of Western Australia. Tagged sharks were monitored for periods of up to 1,453 days. Complex movement dynamics were revealed at very different temporal and spatial scales. Large male and female dusky sharks showed clear migratory displacements between northern and southern WA. The majority of tagged sandbar sharks were almost exclusively detected by receivers off Ningaloo Reef, with only two detected elsewhere. Gummy and particularly whiskery sharks showed relatively limited movements as a whole, although individuals showed that these species are nonetheless capable of relatively large-scale displacements.

For gummy and whiskery sharks, several population dynamics models were developed, from simple surplus production models to fully integrated size-based and sex-structured spatial models that make use of movement information derived from the acoustic and conventional tagging data generated by this and previous FRDC-funded projects. The calibration of these models and their future use for stock assessment required construction of relative abundance indices. An attempt was made to develop indices of abundance based on standardisation of the Temperate Demersal Gillnet and Demersal Longline Fisheries (TDGDLF) catch and effort data with imputation of missing temporal and spatial information. However, significant impediments to comparing monthly (1975-2006) and daily (>2006) effort data from the TDGDLF were encountered with this approach and these will require further resolution before these two incongruous time-series of data can be used to develop indices of stock abundance. For these reasons, a standardised catch rate index that confidently reflects stock abundance cannot currently be presented. Once these indices are developed, however, the population dynamics models developed in this study will be used to re-assess the status of whiskery and gummy shark stocks (and potentially other species, in the future).

For dusky and sandbar sharks, risk ratings for the majority of issues identified through risk assessments were at acceptable levels, including those relating to target TDGDLF fishing and for most other WA fisheries.

Implications for relevant stakeholders

The telemetry data collected through this project are likely to remain the best available source of information on dusky, sandbar, gummy and whiskery shark movements for many years to come. Although problems with standardising CPUE data across monthly and daily reporting periods could not be overcome before preparation of this report, the models that have been developed will be used to provide new gummy and whiskery shark stock assessment advice for management of the TDGDLF. By incorporating stock movement information, these models will be of particular benefit in assessing how these stocks may be impacted by potential future spatial management arrangements, e.g. marine reserves.

Confirmation of adult dusky shark movement patterns enabled a more refined assessment of Ecologically Sustainable Development (ESD) risks to this stock. Results of this assessment suggest that risks to adult dusky sharks are generally low, which should provide industry and fishery managers with confidence that existing management arrangements are providing adequate protection for the breeding stock, allowing it to recover from the previous level of depletion. The data collected on movements of adult sandbar sharks was less conclusive but still suggested that existing spatial management, especially the prohibition of commercial shark fishing off the Gascoyne and Pilbara coasts have resulted in generally low risks to the recovery of this stock. Risk assessments did however identify the resumption of fishing in the Northern Shark Fisheries (NSF), which have been inactive since 2009, would pose a medium to high risk to dusky and sandbar sharks, respectively. The internal implantation of acoustic transmitters with expected battery lives of up to ten years during this project provide an option for further studies of their distributional extent in NSF fishing grounds for several more years.

Recommendations

To further develop the research conducted in this study, the development of standardised CPUE indices that take into account the nature of commercial catch and effort data reporting and spatio-temporal resolution is required for calibrating the population dynamics models. In addition, species-specific reference points should be developed for improved stock assessments. Finally, consideration should be given to the potential medium to high Resource sustainability risks to dusky and sandbar sharks in determining future arrangements for the NSF and, consideration could be given to utilising internally-tagged sharks from the present project in further studying the spatial overlap of these species with future NSF fishing grounds.

KEYWORDS

Whiskery shark · Gummy shark · Dusky shark · Sandbar shark · Bronze whaler · Passive Acoustic Monitoring · Telemetry · Movement · Modelling

1. Introduction

The two Western Australian TDGDLF operate throughout a large area of continental shelf waters between the South Australia (SA)/ Western Australia (WA) border and Steep Point. Collectively, the fisheries are among Western Australia's largest commercial finfish fisheries, with annual catches of around 1500t, a Gross Value of Production (GVP) of $6.5M and a fleet of 30-40 active vessels, directly employing an estimated 85 skippers and crew (Braccini et al. 2014). As such, they are an important source of fresh fish, regional employment and income for the State. Due to the many similarities in their principal fishing method (overwhelmingly demersal gillnet), management plans and species composition of catches, the fisheries are often referred to and reported together. However, these fisheries are actually comprised of three distinct management 'zones' focused on different suites of target and byproduct species and age classes, as well as having disjunct histories of fleet development, research, management and sustainability issues.

Off the south and south-west coasts, the Joint Authority Southern Demersal Gillnet and Demersal Longline Managed Fishery (JASDGDLF) is split into two management zones. Zone 1 extends southwards from 33°S latitude off the west coast to 116° 30'E longitude off the south coast and Zone 2 extends eastwards from 116° 30'E to the WA/SA border (129°E). The West Coast Demersal Gillnet and Demersal Longline (Interim) Managed Fishery (WCDGDLF) extends northwards from 33°S latitude to Steep Point (26° 30'S), although the fishery was excluded from inside the 250 metre depth contour between latitudes 31°S and 33°S in November 2007 (Braccini et al., 2014), effectively making 31°S the fishery's southern boundary. The fisheries' primary target species are the gummy shark (*Mustelus antarcticus*) in Zone 2 and to a lesser extent in the south eastern part of Zone 1; the dusky shark (*Carcharhinus obscurus*) in Zone 1, the western part of Zone 2 and the WCDGDLF and the sandbar shark (*Carcharhinus plumbeus*) in the WCDGDLF. Whiskery sharks (*Furgaleus macki*) are also a major component of catches and have historically been targeted in all three management zones. All four of these species are known to be taken by a variety of other commercial and recreational fishing methods but in very low numbers (McAuley et al., 2015).

The biology of gummy, dusky, sandbar and whiskery sharks was extensively studied and their stocks' status assessed through a series of consecutive FRDC projects beginning in 1993 (Project no. 93/067, 96/130 and 2000/134). Management arrangements for the demersal gillnet and longline fisheries have been continually refined as new stock assessment results were derived, mostly through adjustment of permitted effort levels. While this previous research has provided a robust empirical basis for establishing sustainable harvest arrangements for the target fisheries, it also identified a number of information gaps and remaining sustainability risks relating to the stocks' spatial and temporal dynamics. Furthermore, differential management actions within the three management zones (McAuley et al., 2015) have raised further questions about these stocks' movements between management regimes and resulting implications for their sustainability.

In particular, while demographic analyses have demonstrated that current limits on demersal gillnet fishing effort should provide sustainable rates of dusky and sandbar shark fishing mortality, these assessments also highlighted that additional adult and sub-adult mortality rates of as little as 1–2% are sufficient to cause declining recruitment to these stocks. Despite State-wide measures to mitigate catches of older dusky and sandbar sharks (including a large area closure in the north-west of the State, commercial protection of all sharks and rays, maximum whaler shark size limit and gear restrictions), subsequent monitoring of the mainly neonate dusky shark catch rates in the gillnet fisheries have suggested that recruitment may, in fact, have declined through the 1990s and early 2000s as a result of additional, unidentified (cryptic) fishing mortality. Fishery independent survey data also indicated that the breeding stock of sandbar sharks was rapidly depleted by the development of targeted demersal longline fishing off the State's north coast between 1997 and 2005. The sustainability of demersal gillnet and longline fisheries' catches in the southern half of the State are therefore dependent on minimising further adult fishing mortality. Whiskery sharks were assessed as being overfished during the 1980s and early 1990s and below their (then) minimum acceptable limit of 40% virgin biomass. Although a decade of subsequent effort reduction measures slowed the rate of stock decline, the stock did not show signs of stabilisation until the mid-2000s and a two month closure of the WCDGDLF and JASDGDLF Zone 1 was therefore introduced in 2006 to protect pre-natal whiskery sharks and boost recruitment to the stock. Although subsequent catch rate trends have given cause for optimism that this stock is recovering, concerns have been raised, particularly by industry members, about the implications of permitting ongoing landings of whiskery sharks in Zone 2 during the seasonal closure of the fisheries, to the west of Albany. While previous age-structured stock assessment of gummy sharks suggested that the WA stock has been increasing above its minimum 40% biomass limit since the mid-1990s, this stock has not been formally-assessed since 1996. Thus industry and managers remain uncertain whether the increasing trend in gummy shark catch rates observed within both zones of the JASDGDLF is a result of increasing biomass and westwards re-population into Zone 1 or is a function of changes in fishing mortality, with possibly detrimental sustainability implications. Uncertainty regarding the movement and migratory patterns of these stocks, therefore, remains a significant impediment to ensuring their sustainability and for the long-term viability of their target fisheries.

Dusky and sandbar shark stocks are distinctly size-segregated, with juveniles targeted by demersal gillnet and longline fishers off the lower-west and south-west coasts, hundreds of kilometres to the South of adults' primary distribution. To maintain adequate recruitment to these stocks, shark fishing has been prohibited throughout most of the Gascoyne Bioregion (North of 26° 30's and West of 114° 06'E) since 1993 and in the western portion of the North Coast Bioregion (between 114° 06'E and 120° 00'E) since 2005, to protect adult sharks. However, the extent to which adults remain vulnerable to capture during their southerly migrations cannot be ascertained due to lack of knowledge about the timing and duration of those migrations. Gummy and whiskery shark movements between TDGDLF management zones also have potentially significant implications for those stocks' continued recovery from historical periods of overfishing. In particular, the effects of gillnet fishing in the south-east of the State during the seasonal closure of the TDGDLF west of 118 degrees longitude between 2006 and 2014 and an apparent westwardly emigration of gummy sharks from the south-eastern management zone during the early-mid 2000s are of interest to fishery managers and industry alike.

A unique opportunity to evaluate these and other spatial-temporal stock dynamics presented itself, via a significant deployment of acoustic telemetry infrastructure deployed around the State through various projects (McAuley et al., 2016). Together with improvements in the battery life of acoustic tags, the receiver infrastructure located between Ningaloo Reef in the North-West and the Recherche Archipelago off the South Coast of WA, enabled the collection of long-term information about these stocks' movements between TDGDLF management zones and within and between areas that are open and closed to commercial shark fishing (including the closed area off Metropolitan Perth). The acoustic monitoring data collected during the current study were therefore intended to provide a better understanding of the benefits and limitations of existing fishery management arrangements and a basis for developing spatially and temporally explicit population assessment models for TDGDLF-harvested (adult) gummy and whiskery shark stock components and to allow a more empirically-based evaluation of the remaining cryptic risks to adult dusky and sandbar sharks. In particular, this project was designed to collect the data to redevelop existing stock assessment models for gummy and whiskery sharks in order to provide more detailed advice about spatial and temporal aspects of the TDGDLF management arrangements (implications of seasonal and area closures, effort displacement/adjustment etc.), as they relate to movements of the study stocks (short-term, seasonal and long term movements, immigration/emigration between management zones, etc.).

2. Objectives

1. Identify and describe the timing, duration and pathways of dusky and sandbar shark migrations;
2. Quantify exchange rates of gummy and whiskery sharks among management zones; and
3. Reassess these stocks' status with greater reference to their spatial and temporal dynamics;

3. Methodology

3.1 Acoustic telemetry data

3.1.1 Data collection

Movements of sandbar, dusky, gummy and whiskery sharks were studied across Western Australia using acoustic telemetry data. Telemetry data were collected by receivers located between Tantabiddi Creek in the North-West (21° 53'S 113° 53.9'E) and Salisbury Island (34° 21'S 123° 33.1'E) in the South-East (Figure 1). Up to 138 Vemco[1] VR2W receivers were deployed in three cross-shelf lines and inshore clusters at Ningaloo Reef through the Australian Animal Tracking and Monitoring System (AATAMS; http://imos.org.au/aatams.html). Off Perth, a cross-shelf array of up to 57 VR2W receivers has been operated by the Ocean Tracking Network project (OTN) in collaboration with the WA Department of Fisheries (DoF), since 2009 (http://oceantrackingnetwork.org). A further 183 VR2W and VR4G (n=25) receivers were deployed and operated by DoF as a combination of cross-shelf and along-shore lines off Perth, around the South-West Capes region and off the South coast, though the WA Government's Shark Monitoring Network (SMN) Project (McAuley et al., 2016). Another 52 VR2W receivers have also been operated by DoF around Cockburn Sound off the southern Perth metropolitan coastline for various demersal scalefish studies since 2009. The majority of the telemetry data referred to in this study was recorded by the cross-shelf receiver lines off Ningaloo Reef (AATAMS array), Perth (OTN array) and the SMN arrays at Cape Leeuwin, Chatham Island and Bald Island (Figure 1). While these locations were not explicitly chosen for the purposes of the current study, they are nevertheless well-suited for the study of animals' distributions, movements and migration routes within and between Temperate Demersal Gillnet and Demersal Longline Fisheries (TDGDLF) management zones and areas 'closed' to shark-fishing off Perth and the North-West of WA.

Acoustic receivers in OTN, SMN and DoF arrays were retrieved annually, although the timing of retrievals varied slightly each year. The receivers in AATAMS' Ningaloo array were generally retrieved bi-annually in autumn and spring. Shallow water (<30m) receivers in all arrays were retrieved and replaced by scuba divers. Deepwater receivers were retrieved using acoustic release mechanisms in the Ningaloo array, a Remotely Operated Vehicle (ROV) in the SMN arrays, and a combination of acoustic release and ROV in the OTN Perth array (acoustic releases were gradually retired in the OTN line as they failed and were replaced with ROV-serviced moorings). The development of ROV methods for recovering VR2W receivers from deep water during these projects improved recovery rates from around 81% in 2011 to above 98% since 2013. In addition, acoustic release-fitted receivers were retrieved by ROV on more than 70 occasions, after releases failed to operate due to battery or mechanical failures. Not only have these new ROV-recover techniques reduced the costs of replacing lost equipment but have also demonstrated that the associated costs of data-loss

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[1] VEMCO/ Amirix Systems Inc. Halifax, Nova Scotia. Canada.

from deep-water receiver deployments can effectively be negated. Following retrieval, all data were downloaded from VR2W receivers, their memories cleared, internal clocks re-set and batteries were replaced. The smaller amount of data from the 25 VR4G receivers deployed off Perth and the South and South-West of WA were remotely offloaded via satellite communication protocols on a weekly schedule (Bradford et al. 2011, McAuley et al., 2016).

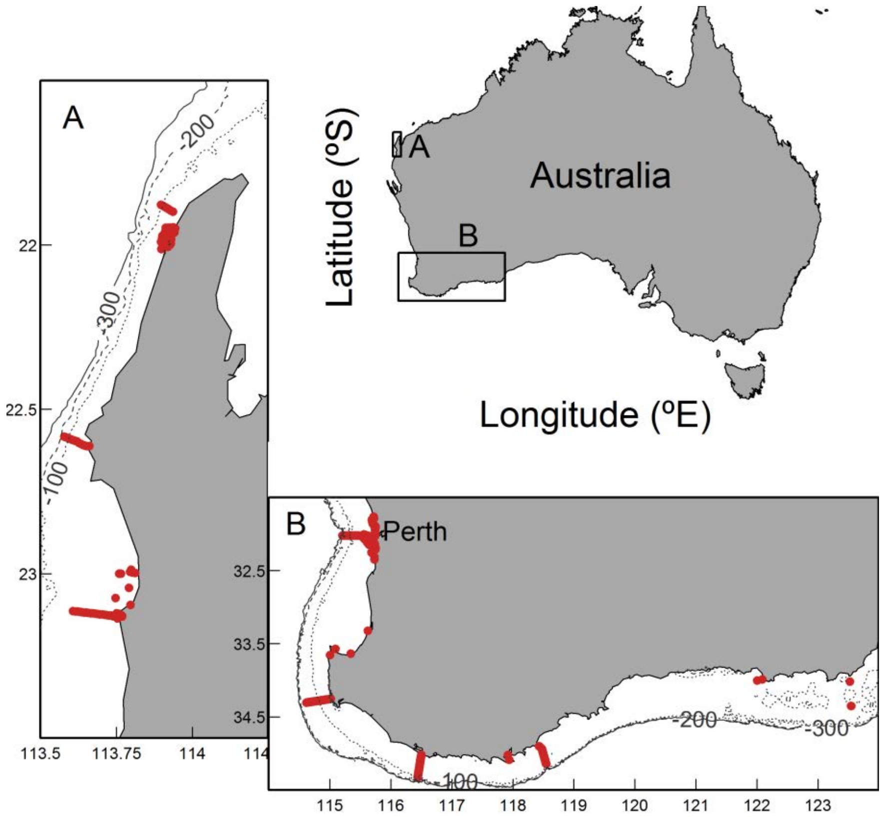

Figure 1. Location of acoustic receivers (red dots). A, Ningaloo array. B, Perth and Southern Lines arrays

A total of six fishery-independent research cruises (two per year) were conducted on-board DoF's Research Vessel Naturaliste between May 2011 and August 2013 during which adult and large sandbar and dusky sharks were tagged in northern WA. In addition, several days sampling with demersal longlines and drumlines were opportunistically conducted during receiver maintenance cruises in southern WA during 2012 and 2013. Gummy and whiskery sharks were mostly tagged during 51 trips (96 gillnet shots) on-board TDGDLF gillnet vessels operating from Albany, Bremer Bay and Augusta during their normal fishing activities between May 2012 and October 2013. To minimise tagged sharks' post-release mortality rates, gillnet-caught sharks were selected according to their apparent vigour and absence of obvious injuries. This selection process, together with lower than expected catch rates of healthy sharks, led to fewer whiskery sharks being tagged than were proposed (~100). The implications of the smaller-than-expected sample of tagged whiskery sharks are discussed in more detail elsewhere in the report. A smaller number (n=7) of gummy sharks were caught and tagged while targeting dusky sharks with demersal longlines during receiver maintenance cruises in southern WA in 2012 and 2013.

Similarly longline-caught sharks were only selected for tagging if they were apparently vigorous and lacked any obvious injuries (other than minimal hook entry/exit wounds).

Study sharks were ‘tagged’ with uniquely-numbered Vemco V16-5H and V16-6H acoustic transmitters. Acoustic tags were implanted into sharks’ abdominal cavities, via a small incision anterior to the pelvic girdle, using standard surgical procedures (e.g. Heupel et al. 2004). All personnel involved in tagging were previously experienced or trained by experienced taggers prior to conducting tagging procedures. Transmitters used to tag gummy and whiskery sharks were programmed to transmit at random intervals of between 75 and 150 seconds and 100 – 200 seconds for sandbar and dusky sharks. Sharks were also fitted with conventional Jumbo Rototags on their first dorsal fins, to allow their visual identification and reporting of any re-captures. Yellow-coloured tags were used during this study to distinguish acoustically-tagged sharks from the thousands of others that have previously only been tagged with (orange-coloured) conventional tags. Promotional materials (posters, pamphlets and fridge magnets, see ***Project materials developed***) were distributed to TDGDLF fishers and through DoF regional offices to explain what recapture data were requested for acoustically-tagged sharks and that rewards were offered for complete reporting of tag recaptures (i.e. tag identification numbers, recapture date and location). A few (<10) acoustic tags were returned to project staff, following sharks’ recapture and processing by commercial fishers.

Prior to tagging, sharks were measured to the nearest centimetre Fork length (FL), sexed and the release time, date and coordinates were recorded. Upon release, sharks’ conditions were observed and classified according to the criteria defined by McAuley et al. (2005) as: 1 (swam away strongly), 2 (swam away slowly) or 3 (sluggish or unable to swim away and/or bleeding heavily).

Although not an intended study species, 53 large bronze whaler sharks (*C. brachyurus*) were also opportunistically tagged with internal acoustic transmitters in Western Australian waters between Perth and Bremer Bay (120° E off the south coast) during this and other related WA Government-funded studies. Although this species was previously considered to be a minor component of TDGDLF catches (McAuley and Simpfendorfer, 2003), the more detailed catch data collected from the fisheries through daily logbooks that were introduced in 2006, indicate that bronze whaler sharks have become a more important component of commercial catches than was previously observed. As acoustic telemetry data for this species may therefore be of current or future benefit to the assessment and management of the TDGDLF, the detection data collected for this species are also summarised herein (although are not analysed in as much detail as the intended study species). Additional data for two dusky sharks were obtained from sharks tagged by the South Australian Research and Development Institute (SARDI) in Gulf St. Vincent off the South Australian (SA) coast.

All acoustic telemetry data are reported in accordance with the relevant data sharing agreements and policies between DoF, OTN, SARDI and IMOS.

3.1.2 Data analyses

Data collected from acoustic receivers were used to investigate the species' movement ecology (residency periods, fine-scale spatial use, distances travelled, rates of movement, etc.) and the extent and nature of stocks' overlap with fishing activities (proportion of time spent within management zones, exchange rates, depth preferences, etc.). All analyses and data manipulations were conducted in the statistical package R (R Development CoreTeam 2014).

3.1.2.1 Residence

Presence/absence timeline-plots were constructed to assess periods of residence/occupancy within and between receiver arrays, identify any evidence of regular coordinated movements between areas and evaluate variation in these measures between individuals and throughout the study period. For each individual, daily detections by one or more receivers within an array were plotted as a single detection event to show daily presence in an array and the recorded size at tagging was used to infer the stage of maturity (mature or immature) based on published information on each species' size at 50% maturity based on Braccini et al. (2015) and references therein. Daily presence was colour-coded to indicate the receiver array where detections were recorded, and to indicate whether the individual was tagged in the north or south of the state.

3.1.2.2 Spatial detection patterns

Bubble plots were constructed to graphically display species' overlap and area use. For each species, the size of the bubble represents P_r, i.e. the proportion of detections by receiver r, which was calculated as

$$P_r = \frac{\sum_n hits_{n,r}}{\sum_r \sum_n hits_{n,r}}$$

where $hits_{n,r}$ is the total number of detections from detected individual n in receiver r. For clarity, separate bubble plots are shown for the different arrays.

3.1.2.3 Rates of movement

As the configuration of the receiver arrays used in the current study was not designed to identify the precise position of tagged sharks within individual receivers' detection range (generally assumed to be 400–500m), movements were considered to be between receiver locations of consecutive tag detections (i.e. the centre of each receiver's detection range). Thus, over short distances (i.e. within arrays), movement (or displacement) distances were calculated as the minimum straight-line distance between two receivers. Over longer distances, displacement trajectories were forced around arbitrary turning points (off North West Cape, Shark Bay and Cape Leeuwin) to minimise biases associated with reconstructing straight-line movement trajectories across land. An example of the reconstructed trajectory is shown in Figure 2. For each displacement, a constant Rate of Movement (ROM) was calculated as the minimum displacement distance divided by the time between consecutive detections.

3.1.2.4 Daily patterns and co-detections

Daily patterns were studied by plotting the proportion of detections by hour for each array and aggregating the observations from all detected sharks by all receivers. Co-detections of different individuals of the same and of different species were studied by calculating the number of individuals that were detected by the same receiver at the same date and hour.

Where sharks moved between arrays, ROM estimates were used to estimate the proportional amount of time that sharks spent within the different management areas (zones, open and closed areas), between detections and quantification of movement rates between adjacent and non-adjacent zones. As the precise position of a detected shark within a receiver's detection range is unknown and to reduce the bias caused by sharks being detected near the detection boundary of two closely positioned receivers, ROM estimates based on displacements of less than one hour duration were excluded from analyses. For example, if a shark was detected near the edge of a receiver's detection range before moving a short distance (e.g. 100–200m) to be detected within the proximal detection range of a second receiver, its estimated ROM would be artificially exaggerated. Different scales of observation were considered to detect possible difference in movement behaviour (e.g. more random movement at a smaller scale vs more directed movement at a larger scale). Hence, ROM was calculated for detections ≤ 10km, > 10km, ≤ 50km and > 50km.

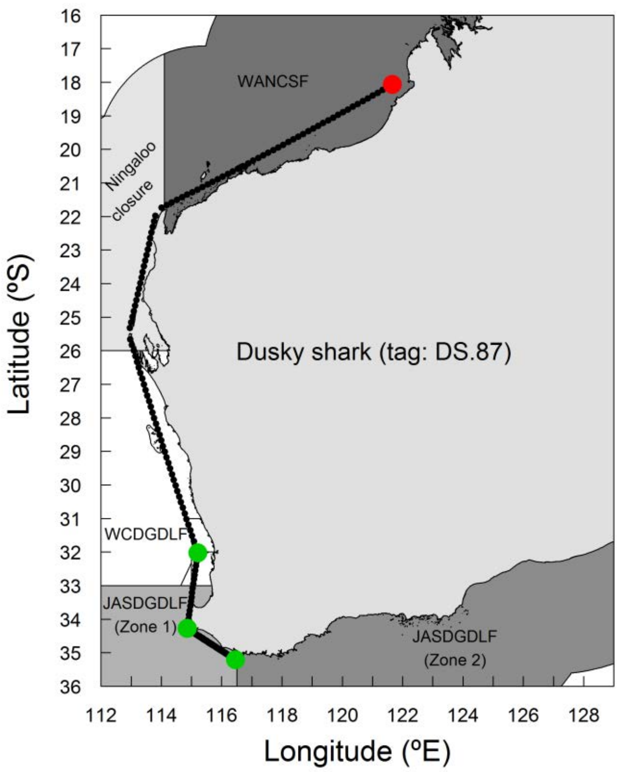

Figure 2. Example of an interpolated displacement trajectory (black dots) for a tagged dusky shark (DS.87) through different fishery management areas, between the release location (red dot) and detection locations (green dots).WANCSF: WA North Coast Shark Fishery; WCDGDLF: West Coast Demersal Gillnet and Demersal Longline (Interim) Managed Fishery; JASDFDLF: Joint Authority Southern Demersal Gillnet and Demersal Longline Managed Fishery

3.1.2.5 Proportion of time per area

The proportional amount of time per area was calculated as the ratio of time spent in a defined area over the monitored period (i.e. between release and last detection). The reconstructed trajectories (e.g. Figure 2) were used to quantify the time spent in each area. As this analysis assumes straight-line movement between consecutive detections, sharks detected within an array, then not detected for a period of time before being re-detected within the same array, are assumed to have remained within that area.

3.1.2.6 Seasonal migration of dusky sharks

Migration was quantified for each sex separately using a sigmoidal Bayesian model fitted in JAGS (Plummer 2003), using the equation

$$P_{l,s,m} = \alpha_{s,m} \Big/ 1 + e^{(l-\beta_S)\varphi_S} + \tau_t$$

where $P_{l,s,m}$ is the proportion of sharks of length l and sex s detected in the Ningaloo Reef array in month m; $\alpha_{s,m}$ is the maximum proportion migrating; β_s is the estimated length at which 50% of $\alpha_{s,m}$ sharks migrate; φ_s is the predicted rate of change (slope) in sharks' growth increments and was used to define the probability that a shark would or would not migrate; and τ_t is a random effect of shark t, used to account for multiple observations being derived from the same individuals. β_s and φ_s varied between sexes but not between months since we considered it unlikely that the size at which sharks migrated would change markedly between months. Data were pooled to one record per individual per month. If an individual was detected at Ningaloo Reef in a month, it was considered to have migrated (assigned a response value of 1), whereas if all detections for that shark in that month were recorded to the south of Ningaloo, it was considered not to have migrated (assigned a response value of 0). This included the original tagging observation, i.e. if a shark was tagged in the north it was considered to have migrated in that month. For each sex the model was run with 2,000,000 iterations, three chains and a thinning rate of 5. The models achieved good mixing between chains and the Gelman-Rubin statistics indicated model convergence. For both models, the standard deviation associated with the random effects was relatively small when compared to those from the other model terms. This indicated that individual sharks displayed unique behaviour, which therefore did not have to be accounted for in the model. Therefore, the random effects were removed.

3.1.2.7 Exchange rates of gummy and whiskery sharks

Exchange rates of gummy and whiskery sharks between management zones (Figure 3) were quantified using an individual based model fitted to conventional tagging generated by previous FRDC projects (Simpfendorfer et al. 1996; Walker et al. 2000) and to the acoustic tagging data collected in this project.

For conventional tag data, movement parameters were estimated based on release and recaptures only. By conditioning the analysis only on recaptures, the typical difficulties for conventional tagging studies of tag non-reporting, tag shedding, and the effect of natural and fishing mortality are minimized, as the models are not fitted to the numbers released but to numbers recaptured (McGarvey and Feenstra 2002). An individual-based model was therefore constructed to calculate the probability of recapturing a shark in a given zone and time considering the time this individual was at liberty.

For the conventional tagging data, a movement transition matrix, Θ, which represents the probability of moving from one zone to another zone, was constructed as

$$\Theta = \begin{pmatrix} p_{11} & p_{12} & p_{13} \\ p_{21} & p_{22} & p_{23} \\ p_{31} & p_{32} & p_{33} \end{pmatrix}$$

where each element p_{ij} represents the probability of moving from zone i to zone j, with zones 1, 2, and 3 representing the 'West Coast', 'Zone 1' and 'Zone 2' management zones, respectively. Note that each row sums to one.

Based on Θ and the time at liberty *t*, P_n was defined as the product matrix taking Θ and multiplying it by itself *t*-times. Then, the predicted probability of recapture zone and time ($\hat{p}_{ij}$) was extracted from the P_i row and column corresponding to the release and recapture zone.

Very few gummy sharks were released in the West Coast so the movement rates for individuals released in the West Coast could not be estimated. Hence, as neither the West Coast nor Zone 1 are not core habitat areas for this species (Simpfendorfer et al. 1996), movement rates from the West Coast were set equal to the movement rates of sharks released in Zone 1. An annual time step was used for the analysis of conventional tags.

A similar approach was adopted for the acoustic tagging information obtained from the network of acoustic receivers. Unlike most conventional tagging studies, where tagged individuals are released and recaptured only once, acoustic monitoring allows the detection of tagged individuals multiple times. In such a case, tagged sharks could be modelled as random effects to remove the natural variability in movement among individuals. Initially, this was attempted but due to the limited data set and the small proportion of tagged sharks with detections over multiple days the models failed to converge. Hence, rather than fitting each shark as a random effect, the contribution of each shark to the likelihood was down-weighted by the number of observations per shark.

A daily time step was used for the analysis of acoustic tagging data (acous) so the movement transition matrix, Θ_{acous}, of species s was constructed as

$$\Theta_{acous} = \begin{pmatrix} p_{11} & 1-p_{11} & 0 \\ 0.5(1-p_{22}) & p_{22} & 0.5(1-p_{22}) \\ 0 & 1-p_{33} & p_{33} \end{pmatrix}$$

The p_{13} and p_{31} elements were set to 0 as it is highly unlikely that a shark moves to a non-adjacent zone in 1 day.

For the West Coast receivers, there were no or very few detections of whiskery and gummy sharks. Hence, for whiskery sharks p_{11} was set equal to p_{33} as the West Coast and Zone 2 are not core habitat areas for this species, whereas for gummy sharks p_{11} was set equal to p_{22} as the West Coast and Zone 1 are not core habitat areas for this species (Simpfendorfer et al. 1996).

To estimate the movement parameters, the model was fitted to the conventional and acoustic tagging data by minimizing an overall objective function, λ, which contains three terms

$$\lambda = \lambda_1 + \lambda_2 + Tag_{pen}$$

where λ_1 and λ_2 are the negative log-likelihoods for the conventional and acoustic tagging data, respectively; and Tag_{pen} is a penalty used to maintain all p_{ij} parameters between 0 and 1. λ_1 and λ_2 are calculated as

$$\lambda_1 = -\sum_n \hat{p}_{conv,ij} \quad ; \quad \lambda_2 = -\sum_n \hat{p}_{acous,ij}$$

where $\hat{p}_{conv,ij}$ and $\hat{p}_{acous,ij}$ are the predicted recapture probabilities for individuals tagged with conventional or acoustic tags, respectively.

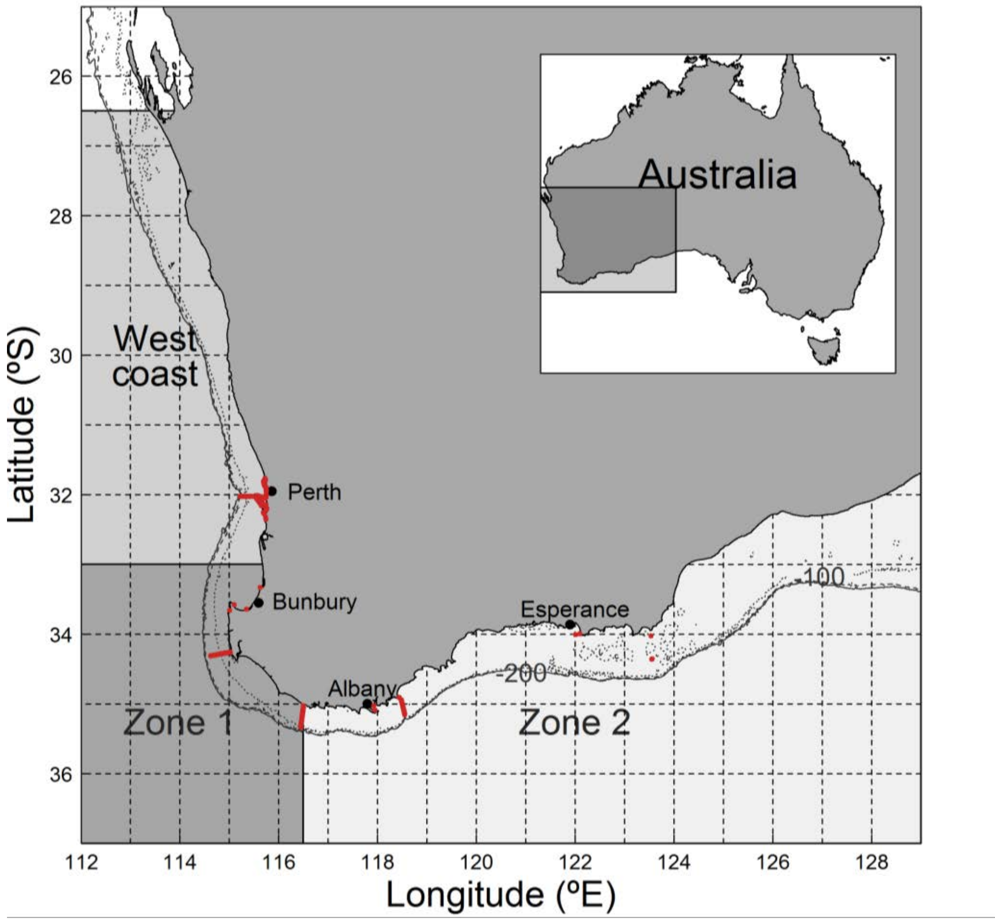

Figure 3. Map showing the location of receivers (red dots), management zones and fishing blocks (1° by 1°)

3.2 Catch and effort standardisation

Catch and effort data from the TDGDLF were standardised in the following three steps. Firstly, catch and effort data from targeted shark demersal gillnet and demersal longline fishing in waters of the TDGDLF were identified in statutory fishing return records. These data were then validated and corrected to account for known historical reporting problems following agreed business rules for improving data quality (see Simpfendorfer et al. 2000b; McAuley et al. 2005). Second, using the improved statistics, catch and effort data were standardised using the best model and error structures. Finally, procedures to impute "missing" observations (e.g. from normal variability or shifts in the distribution of fishing effort, the metropolitan closure in 2007 and the whiskery shark pupping closure west of Albany between 2006 and 2014, McAuley et al., 2015) were used to construct standardised CPUE time series for calibrating models representing gummy and whiskery shark stock dynamics.

3.2.1 Data collection

Information on catch (species weight in kg) and effort (gear type and quantity, number of days fished, number of shots per day and hours fished) was obtained from statutory fishing return records, which were reported monthly by 1 degree spatial blocks between 1975 and 2006 and reported at a daily frequency by a combination of 10 minute spatial blocks and GPS coordinates, since 2006. As licensing information is only available for the TDGDLF from 1988 onwards, catch and effort data relating to previous targeted shark fishing with demersal gillnets and demersal longlines within the waters of the TDGDLF, were instead defined according to fishing method (gillnet and longline only) and area of operation (between 26°S latitude and the Western-South Australian border). To avoid inclusion of records from small mesh gillnets that are/were used in nearshore and estuarine waters off the South and West coasts to target teleost species (e.g. Australian herring, *Arripis georgianus*), data from estuarine blocks and for records derived from net lengths of less than 100m were excluded from the dataset. This filtering also effectively removed other misreported non-'shark fishery' netting methods (e.g. haul nets, beach seines and throw nets).

3.2.1.1 Correction of catch data

3.2.1.1.1 Monthly catch returns

When FRDC-funded research into the status of WA's shark stocks began in 1993, the accuracy of catch records was examined and data from before 1989/90 were determined to be incomplete. Problems were also found with species identification in some vessels' returns, in particular where the reported catch of sharks was not identified to species level (e.g. records where all catches were reported as a single species or as unidentified species, 'shark, other', Figure 4).

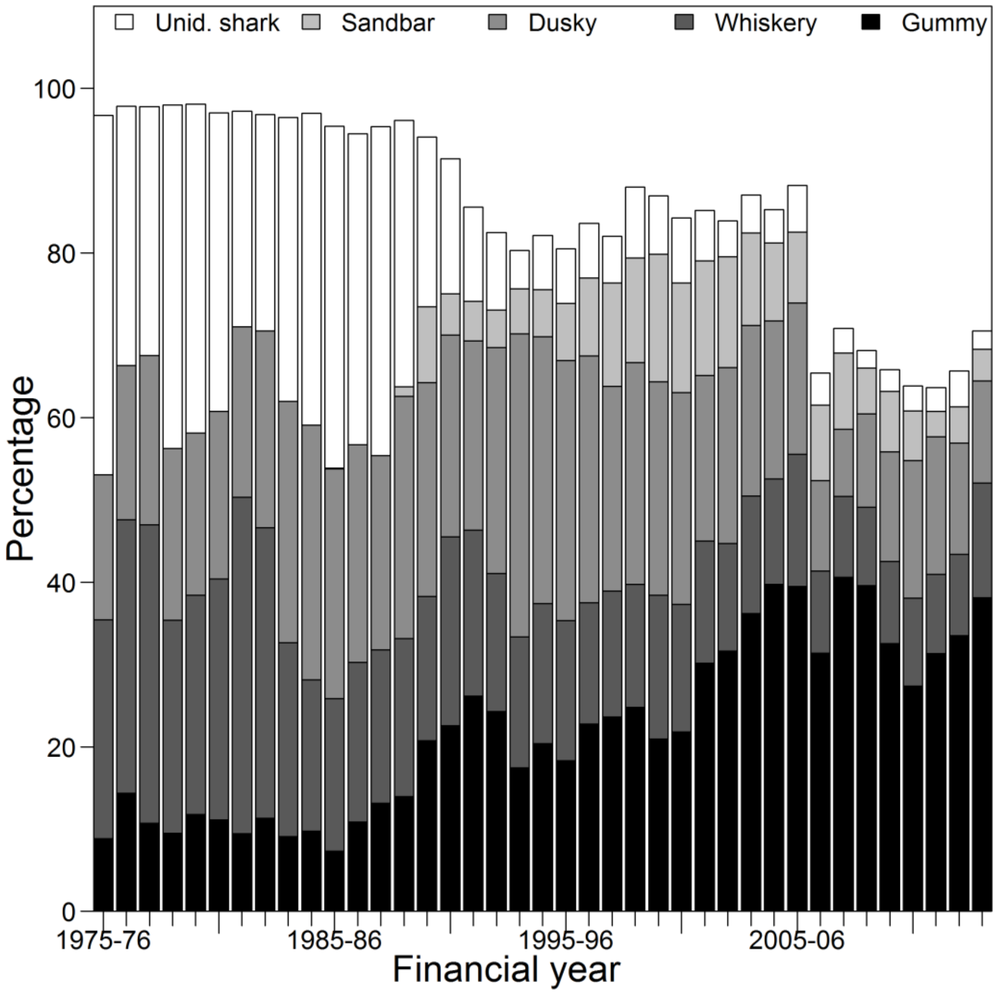

Figure 4. Illustration of shark catch and effort records by financial year. Bars show the percentage of total annual catch by major species

To overcome these problems, business rules (Figure 5) were developed to adjust catch (and effort) data from years where records were missing and to reapportion the shark catch from returns that were judged to be inadequately reported (Simpfendorfer and Donohue, 1998; Simpfendorfer et al., 2000b). These procedures were refined in 2003 to account for improved species identification and reporting in recent years and to allow for historical but regionally-specific catch characteristics, e.g. increased targeting of sandbar sharks in the WCDGDLF and high school shark and dogfish catches in Zone 2 of the JASDGDLF in earlier years (McAuley et al., 2005).

To amend misreported catch return data, vessels were classified as either ‘good reporters’ (i.e. providers of accurate catch information) or ‘bad reporters’ (i.e. providers of inaccurate catch information) following Simpfendorfer et al. (2000b). Catches from bad-reporting vessels were re-apportioned by multiplying the reported total shark catch by the mean proportion of individual species in records from good reporting vessels operating within the same Year-Month-Spatial Block (YMB). If good-reporter records were not available for a particular YMB, the mean proportion of species, for the same Year-Month-Management Zone (YMZ) was used. In the small number of cases where comparative YMZ fishing records were not available, the mean proportion of that species in records for the same year-month throughout the entire area of the fisheries was used. Catch records from vessels engaged in specific historical-targeting behaviours [e.g. dogfish/gulper sharks on the continental slope off Esperance in the early 1990s (Daley et al., 2002) and school sharks in the far-eastern part of Zone 2 during the 1980s and 1990s (Simpfendorfer and Donohue, 1998; Walker et al., 2001)], did not conform to these rules and these were therefore, excluded from this process.

Apart from those exclusions, these business rules were designed to systematically reflect the seasonal and regional variability and differences in the composition of TDGDLF catches of the fisheries' four principal target species. For dusky, whiskery and gummy sharks, 'bad reporters' were vessels which, within a year-month-block, reported: (i) ALL shark catch as 'sharks, other'; (ii) NO dusky or whiskery shark catches when fishing between 26° and 32° S and West of 125° E; (iii) NO or exactly equal proportions of dusky, whiskery and gummy shark catches South of 32° S and West of 125° E; (iv) NO gummy or school sharks when fishing East of 125° E. For sandbar sharks, 'bad reporters' were vessels that did not report any sandbar sharks when fishing South of 26° S and West of 118° E within a year after 1984, when sandbar sharks were allocated a logbook code. In all, 20% of monthly catch returns records were amended according to these rules.

Catch (and effort) records were also adjusted to account for missing and incomplete returns prior to 1990. Previously, catch and effort had been increased by 25% in 1986, 35% in 1987, and by 5% in all other years up to and including 1989/90, after which records are thought to be complete. However, it was subsequently determined (and confirmed by numerous industry-members from the time), that catches may also have been over-reported during the mid-1980s by fishers trying to demonstrate use of the stocks in order to secure their continued access under the JASDGDLF management plan, introduced in 1988. Thus, it was determined that the 25% and 35% corrections previously applied to those years' data were not applicable and to account for missing data, all catch (and effort) data prior to 1990 have instead been increased by a standard 5% per year.

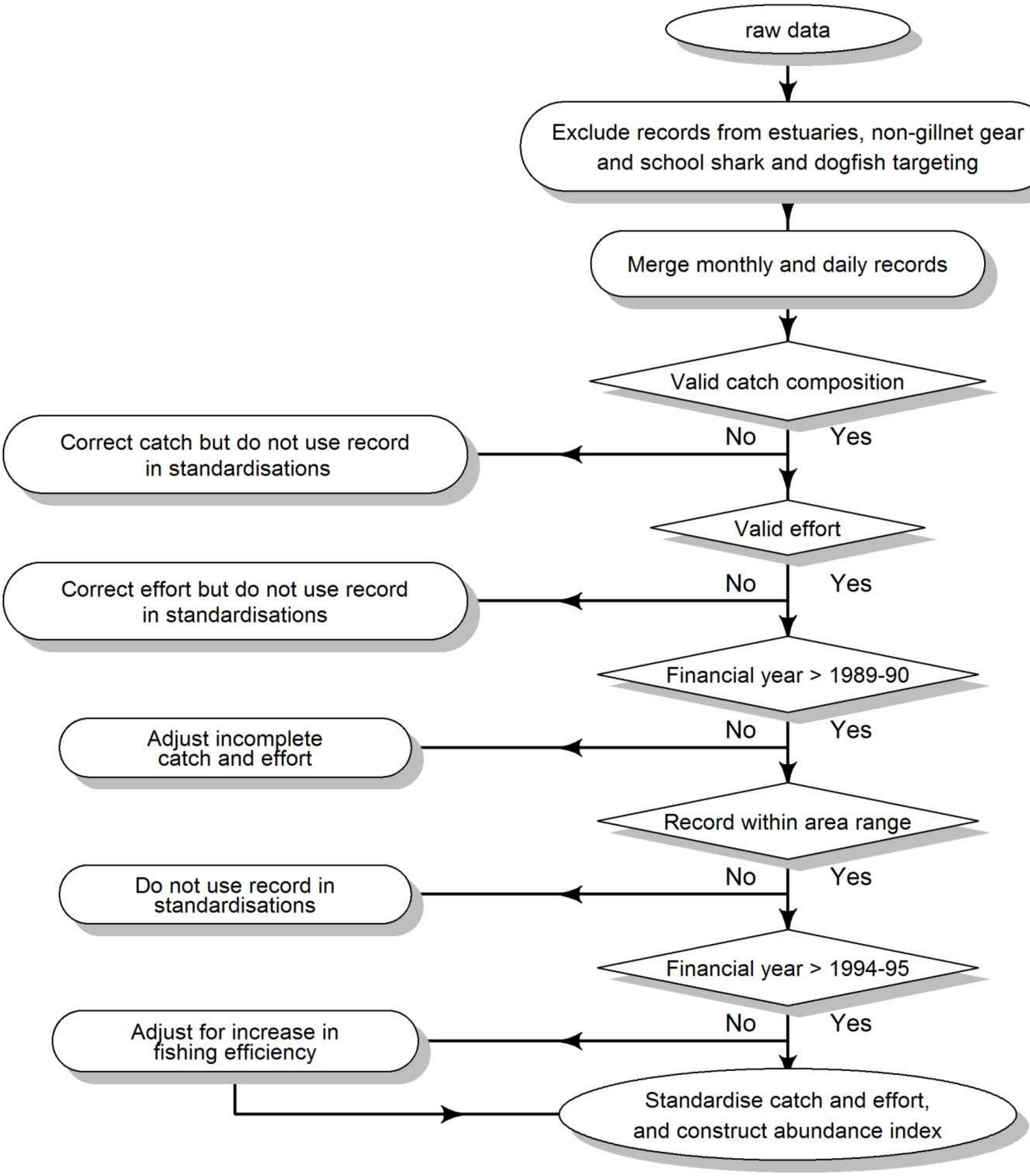

Figure 5. Flowchart of processes and business rules applied for verifying and correcting the catch and effort statistics used in the catch rate standardisations

3.2.1.1.2 Daily logbooks

The transition from monthly to daily reporting mechanisms proved problematic and a number of errors were identified in the first 3 years' of daily logbook data. Missing, misreported and confounded catches from this period were first recovered or corrected using fishers' personal records, fish processor returns, face to face and phone interviews with fishers. Since that initial catch reconstruction exercise, daily catch records appear to have been more completely and accurately recorded. Occasional errors and data omissions are still encountered but these are generally rectified at the time of submission or data-entry. For a very small number of records (mainly small quantities of minor catch components), missing catches could not be reconstructed from fishers' own records or recollections. In those cases, catch weights were estimated from the recorded number of fish (required information in daily logbook returns), and (in hierarchical order): the average weight of that species in good reporting vessels' records from the same YMB, YMZ or year-month was used. If none of these average weights were available, the mean weight of that species was estimated from the mean size of observed catches from the fisheries (McAuley and Simpfendorfer 2003) and an appropriate length-weight relationship.

3.2.1.2 Correction of effort data

Several problems have also been identified with reported gillnet fishing effort variables; including misreporting and non-reporting of the number of shots per day, net length, hours fished per day, and days fished per month (Figure 6). To address inaccurate or incomplete effort data, the data reported in (monthly and daily) fishing returns were corrected according to the following rules.

3.2.1.2.1 Monthly effort returns

A record was defined as invalid if hours fished was 0, incomplete or >24 h; or if net length was 0, incomplete or >12000 m; or if number of shots per day was 0, incomplete or >3; or if number of days fished per month was 0, incomplete or >31 days. For these records, the invalid effort variable was replaced by (i) the vessel's annual mean (excluding invalid records) was used; and (ii) if this was not available, the year-month-zone mean value (excluding invalid records) of the remainder of the fleet was used.

3.2.1.2.2 Daily logbooks

Missing records from the period 2006-2009 were re-constructed from fishers' personal records, processor returns, and interviews. The same rules used for defining invalid effort variables and for amending the monthly catch return data set were applied to the effort variables reported in daily logbooks.

For both data sets, <1% of the net length, days fished per month and hours fished per day, and 9% of the number of shots per day were amended. Fixing inaccurate catch and effort records is required for quantifying total annual catch and effort. However, catch and effort standardisations were done using only the 'good' records (Figure 5).

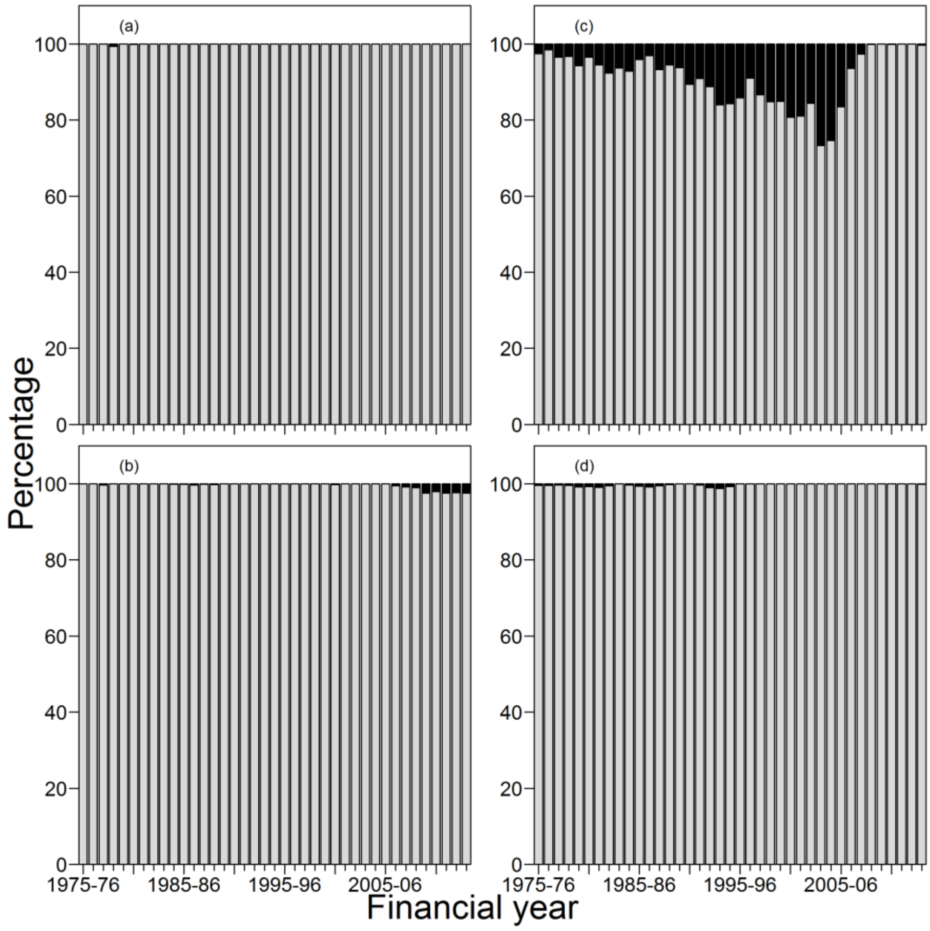

Figure 6. Illustration of the shark catch and effort records by financial year. The barplots show the percentage of records with erroneous (in black) (a) days fished per month, (b) hours fished per day, (c) shots per fishing day, and (d) net length

3.2.2 Quantification of corrected effort data

As TDGDLF vessels have predominantly used demersally-set gillnets of between 16.5cm and 17.8cm (6.5–7", stretched) mesh-size (>86% of records), the historically small and diminishing number of demersal longline records were not included in following analyses. Fishing effort was defined as the product of the net length used per day and the number of days fished per month. All effort values reported herein are expressed in units of kilometre gillnet days (km.gn.d), unless specified otherwise.

Due to the overlapping but differing distributions of the four study species within the fisheries, 'effective area' catches and fishing effort were defined according to where each species commonly occurs in the catch (Braccini et al. 2014). These effective areas were:

- South of latitude 28°S and East to longitude 129°E for whiskery sharks;
- Between longitudes 116°E and 129°E off the South coast for gummy sharks;
- South of latitude 28°S and East to longitude 120°E for dusky sharks; and
- Between latitudes 26°S and 30°S for sandbar sharks.

Effective area effort was adjusted by 2% y^{-1} for all years prior to 1994/1995 to account for increases in fishing efficiency due to technological advancements, e.g. increased vessel size/range, GPS plotter/sounders, monofilament nets and improved fishing knowledge (Simpfendorfer et al. 1999, McAuley, 2005). As most significant developments in vessels, gear and fishing behaviour had ceased by the mid-1990s, a constant efficiency factor has been applied to records since.

3.2.3 Distribution of TDGDLF gillnet effort

To investigate potential biases in Catch Per Unit Effort (CPUE) trends derived from fishery-dependent catch and effort data, the spatial distribution of TDGDLF demersal gillnet fishing effort was estimated by 1 degree reporting blocks (Figure 3). The number of blocks from which monthly-reported fishing effort (1975–2006) was reported, increased from 28 in 1975–76 to 58 in 1992–93, before stabilising at <50 during the latter years of the time-series (Figure 7). The number of active fishing vessels concurrently increased from 74 in 1975–76 to 172 in 1985–86, before declining to 31 in 2006 (McAuley, 2008, Figure 7). Nominal demersal gillnet fishing effort peaked at 38,695 km.gn.d during the early 1990s and has trended downwards since (Braccini et al. 2014). Since the introduction of daily logbook reporting and a new hourly effort management system in 2006, the level of nominal demersal gillnet effort declined to between 9,037 and 11,373 km.gn.d per year. During this time, the number of blocks from which fishing effort has been reported has remained at between 40 and 50 and the number of vessels reporting activity in the TDGDLF has declined from 25 in 2006–07 to 20 in 2013–14.

As the distribution of reported fishing effort has been dynamic across a large geographic range for the last 40+ years, although is generally characterised by an early expansion and slight subsequent contraction (Figure 7), time-series of data from many spatial blocks are truncated. Furthermore, the contraction in TDGDLF fleet-size and imposition of spatial and seasonal restrictions on fishing have led to ‘gaps’ in the available time-series data reported from many spatial blocks. Because these characteristics are recognised as being among those that can lead to biases in abundance indices derived from fishery-dependent data, some authors have argued that missing time-area observations should be imputed (Walters 2003; Carruthers et al. 2010, 2011).

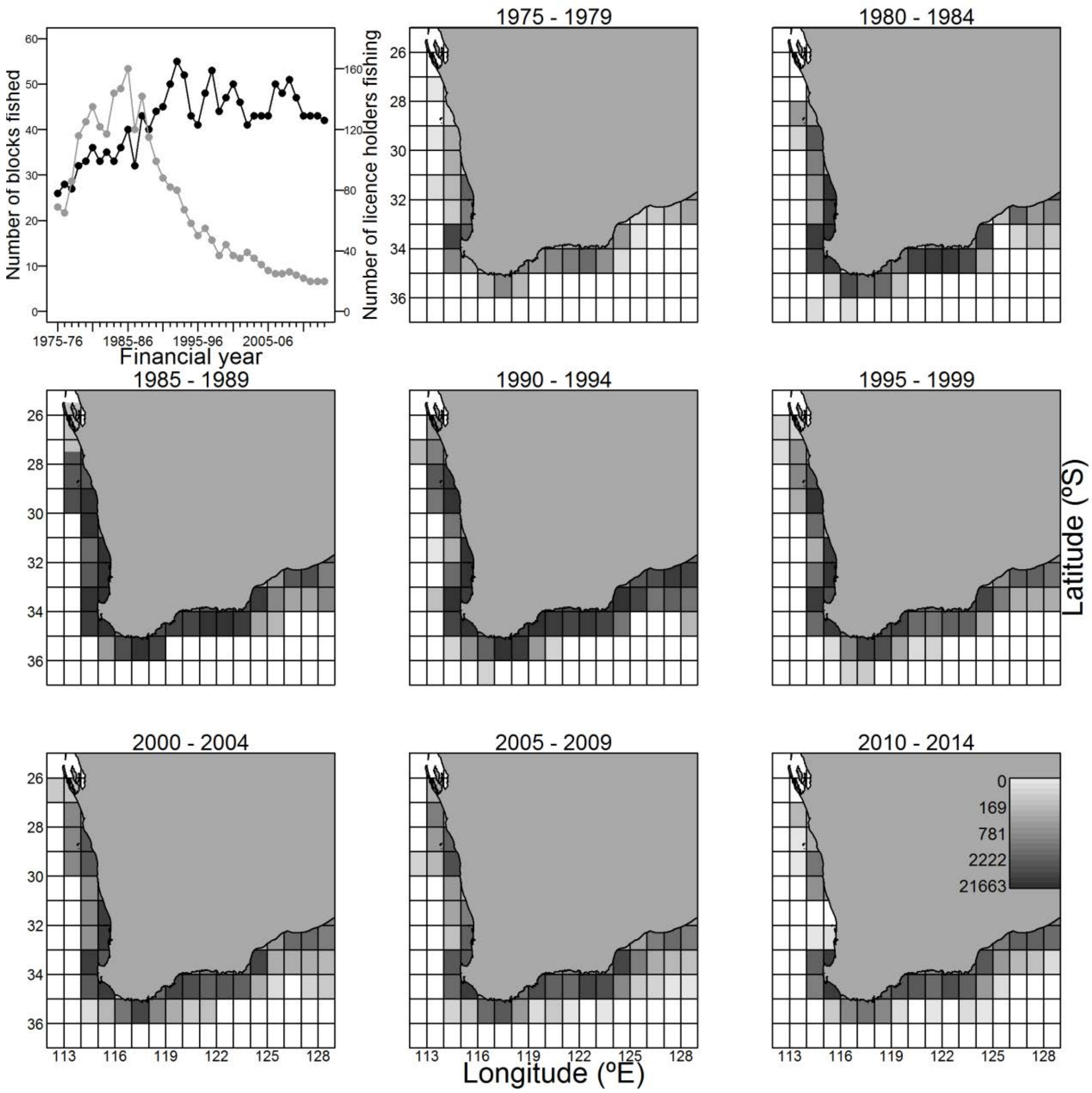

Figure 7. Spatial distribution and density of the Temperate Demersal Gillnet and Demersal Longline Fisheries gillnet effort by five financial year intervals. Top left panel shows the number of blocks fished (black dots) and active fishing vessels (grey dots) by financial year; maps show the distribution of the fisheries' total corrected nominal effort (km.gn.d) for each period

In total (i.e. 1975–2014), catch has been reported in 67, 42, 40, and 38 spatial blocks by 512, 184, 488, and 272 fishing vessels, within the effective fishing areas for whiskery, gummy, dusky and sandbar sharks, respectively. However, the rapid cumulative increase in catch and number of records per block and fishing vessels (Figure 8) indicates that shark catches were negligible and infrequent for some blocks and for many fishing vessels.

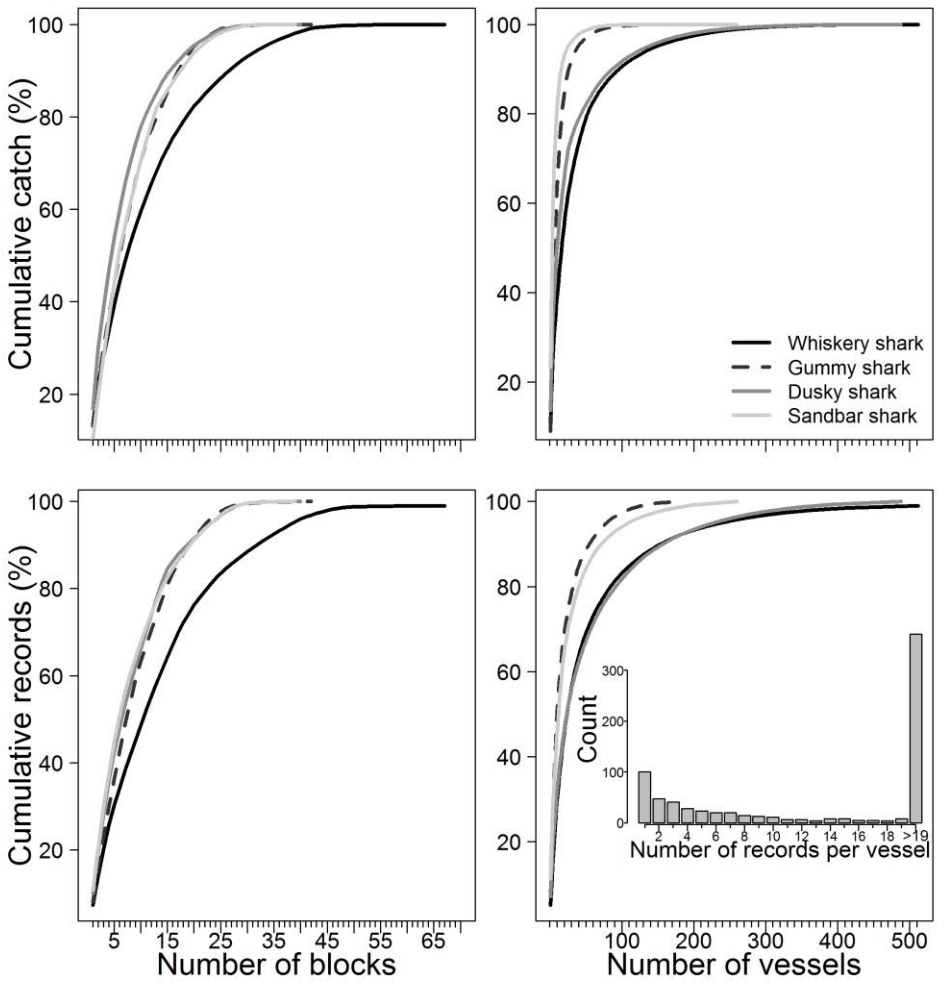

Figure 8. Cumulative total catch (upper panels) and cumulative number of records (lower panels) against number of fished block and number of vessels fishing, and the number of records per vessel (inset)

3.2.4 Construction of standardised CPUE time series

Current abundance indicators used for stock assessment of gummy and whiskery sharks are based on nominal catch rates calculated as the ratio of total annual catch and total effort. Hence, new CPUE indices were constructed based on statistical standardisation of commercial catch and effort data.

To account for a two month closure of the fishery west of 118° E between 2006 and 2014 (mid-August to mid-October) and the closure of metropolitan fishing grounds (between 31° and 33°S) in November 2007, catch and effort data from the TDGDLF were previously excluded from estimation of the CPUE trends that are used to infer stock status (Braccini et al. 2014). However, because exclusion of these data can lead to the loss of important information about trends in stock abundance, an alternative imputational approach to standardising catch and effort data, was developed.

Because the boundary between Zone 1 and Zone 2 (116^0 30’E) lies in the middle of blocks bounded by longitudes 116^{0}E and 117^{0}E (Figure 3) and some of the fishing vessels operating in those blocks were licenced to fish in both Zone 1 and Zone 2 areas of those blocks, it was not possible to accurately allocate catch and effort data from these blocks to each of the overlapping zones. However, as most of the effort in the three blocks overlapping this boundary was known to have been applied by Zone 1 vessels, all data were arbitrarily assigned to Zone 1 for the purposes of subsequent analyses and standardisation. For each species, blocks that accounted for 90% of the catch reported in 'good' records were selected. This reduced the number of blocks available for modelling of catch and effort (Table 1).

In an attempt to reduce the effects of vessels targeting other species, CPUE standardisation was based on catch and effort data from 'indicative' vessels, which were selected from the 'good' records for each of the four study species, based upon having: 1) at least 10 records of that species and 2) reported catch of that species within at least five years. From these vessels, we selected those that accounted for the top 90% of the annual TDGDLF catch of the species. For sandbar sharks, financial years prior to 1988/89 were removed from the analysis as none of the vessels reporting catch during these years met the selection criteria (prior to the early 1990s, the species was rarely targeted, of low value and was only given a unique reporting code in 1985/86). Indicative vessels' catch and effort data were standardised using Generalized Linear Models (GLMs). The response variable was the logged catch and the logged effort was modelled as an offset. Candidate explanatory variables included available seasonal (year and month), spatial (block) and available environmental (Southern Oscillation Index and Mean Fremantle Sea Level) terms. The catch of other shark species was also considered as a covariate proxy for fishers' targeting behaviour (Table 1).

Table 1. Model terms considered in the Generalized Linear Models

Component	Type	Acronym	Levels
Financial year (July-June)	Factor	Yr	1975–2013
Spatial block	Factor	Block	26 (whiskery shark)
			18 (gummy shark)
			14 (dusky shark)
			6 (sandbar shark)
Month	Factor	Mn	1–12
Vessel	Factor	Ves	84 (whiskery shark)
			40 (gummy shark)
			76 (dusky shark)
			8 (sandbar shark)
Catch of whiskery sharks	Variate	Whiskery_c	Continuous
Catch of gummy sharks	Variate	Gummy_c	Continuous
Catch of dusky sharks	Variate	Dusky_c	Continuous
Catch of sandbar sharks	Variate	Sandbar_c	Continuous
Southern Oscillation index	Variate	SOI	Continuous
Mean Freemantle sea level	Variate	MFS	Continuous
Effort	Variate (offset)	km.gn.d	Continuous

Exploratory analyses showed that the continuous covariates considered had low levels of correlation. For the monthly returns and the monthly-aggregated daily logbook data, most of the single species catches from indicative vessels were reported to be less than one tonne (Figure 9). Also, as the proportion of records with 0 catches ranged from relatively small (0.03 for dusky sharks) to moderately high (0.22 for sandbar sharks) (Figure 9), a two-component model was used for batch analysis. The probability of a positive record was modelled using a binomial GLM and the catch of the positive records was modelled using lognormal and gamma distributions.

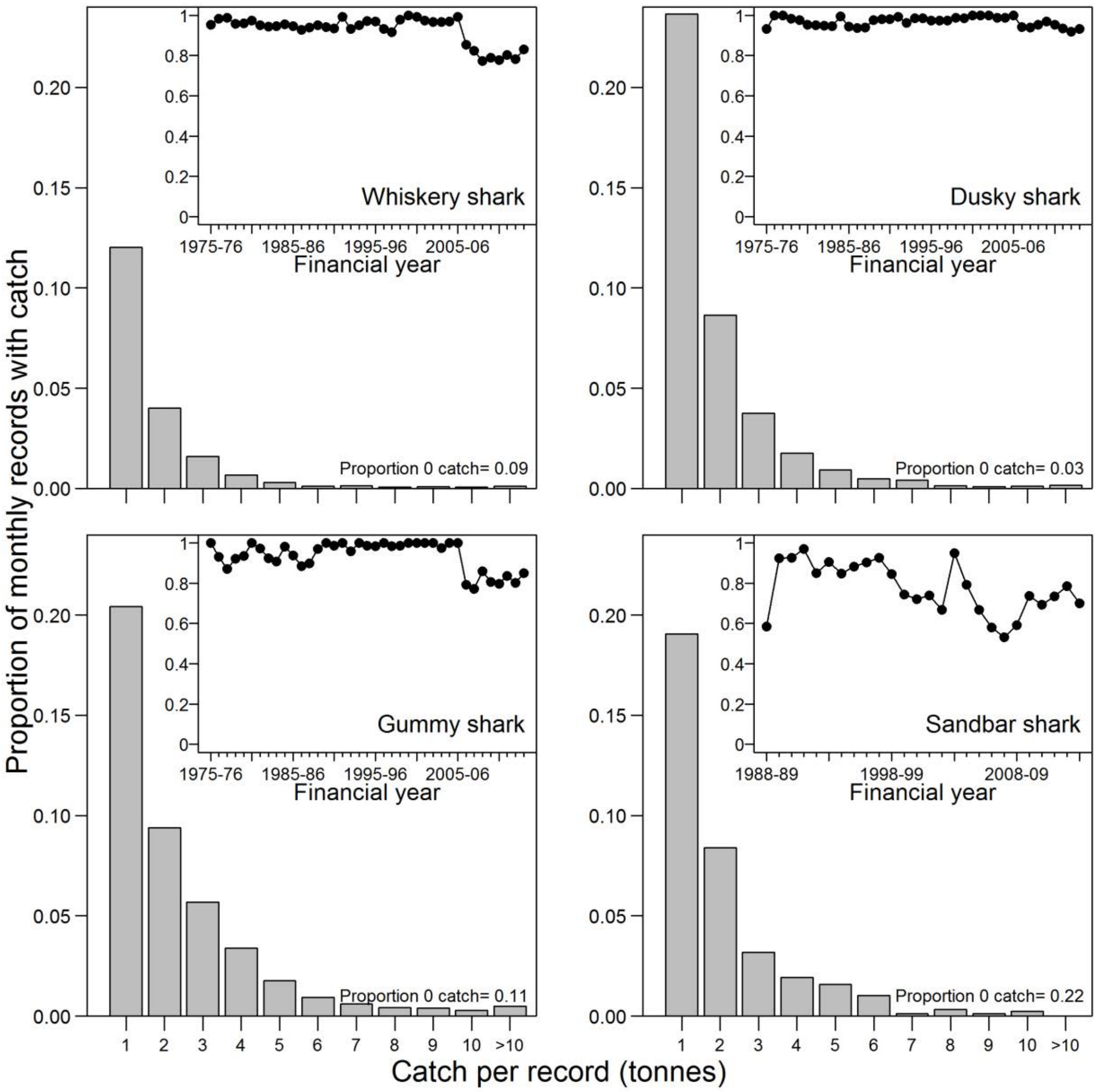

Figure 9. Distributions of catch records used in catch and effort standardisations. Bars show the ranges of positive monthly catches. The inset figures show the annual proportions of records with and without catch.

The explanatory variables included in the models were defined using a stepwise forward selection of candidate variables based on improving the Akaike Information Criterion (AIC) until the percentage of deviance explained was <2%. The interaction between 'financial year' and ‘spatial block’ is needed to capture the effect of catch rates in different parts of the fishery changing at different rates over the history of the fishery (Punt et al. 2000). In addition, this interaction is required for filling in missing time–area observations. For the probability of a positive record, no interactions were considered due to a lack of contrast between the presences/absence of catch for the ‘financial year’ and ‘spatial block’ combinations (i.e. financial year–spatial blocks with no 0 catch records). For each species, model diagnostics were used to evaluate the performance of the distributions fitted to the positive records and hence select the best error structure. All statistical analysis were coded in the statistical package R (R Development CoreTeam 2014).

Given that multiple year–block combinations were missing (23%, 26%, 17% and 30% for whiskery, gummy, dusky and sandbar sharks, respectively, Figure 10), imputation was required for constructing standardised CPUE series. Hence, the GLM predictions, imputation of missing financial year–spatial blocks, and quantification of uncertainty through bootstrapping were integrated into the catch and effort standardisation (as per Carruthers et al. 2011 and Marriot et al. 2014).

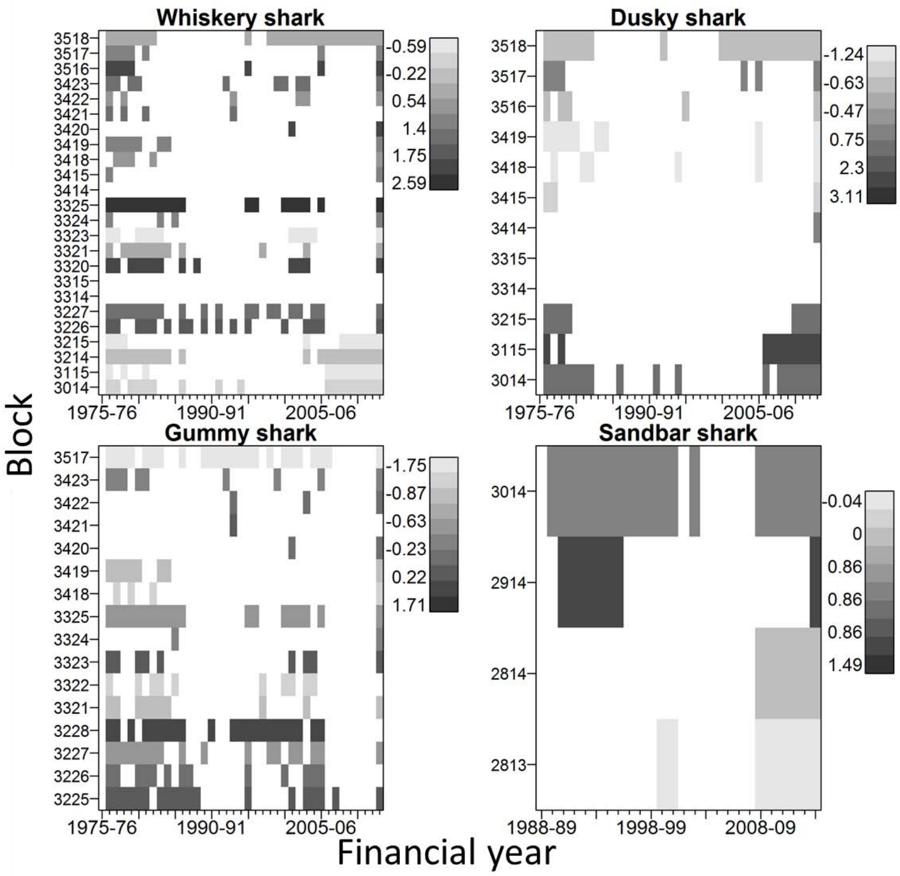

Figure 10. Temporal distribution of imputed spatial blocks for each species. White shading indicates no imputation. Imputed blocks are shaded according to the values used for replacing the missing value. Darker shades correspond to higher coefficient values

The imputation of missing year–block coefficients extends the algorithms of Carruthers et al. (2011) and Punt et al. (2000), which combined nearest-neighbour and mean imputation approaches. For blocks with missing coefficients prior to fishing, the block average of the first three years was used. For blocks with missing coefficients between years with coefficients, a linear interpolation between the years with coefficients before and after was used. For blocks with missing coefficients after fishing, rather than setting the missing values at the last coefficient (Walters, 2003; Carruthers et al. 2011), a linear model was fitted to the last 10 years for which coefficients could be estimated. If the model slope was negative, we imputed the missing coefficient values from a linear model with constant set at the coefficient value for the last year with observations and slope set at the population intrinsic growth rate, derived from demography. If the model slope was positive, we imputed missing coefficient values using the linear model. The linear-model imputation was adopted because without fishing (hence the reason for the missing records) the population is expected to increase.

Following Punt et al. (2000) and recommendations by Campbell (2015), the standardised CPUE series was constructed using the formula:

$$I_y = \sum_b A_b I_{y,b}$$

where I_y is the index for year y; A_b is the size of the available area of spatial block b (set at 200 m for whiskery, dusky and sandbar sharks, and at 100 for gummy sharks); and $I_{y,b}$ is the standardised index for year y and spatial block b. The value for $I_{y,b}$ was calculated as:

$$I_{y,b} = \upsilon_{y,b} \alpha_{y,b}$$

where $\upsilon_{y,b}$ is the probability of a non-zero catch in spatial block b during year y; and $\alpha_{y,b}$ is the catch in spatial block b during year y for positive records.

Standardised catch predictions were obtained using the 'predict' function included in the R base packages. To extract the $\upsilon_{y,b}$ and $\alpha_{y,b}$ coefficients, we set continuous explanatory variables to their means, and categorical variables to an average over all values, weighted by the relative frequency of each value (Maunder and Punt 2004). (NB setting categorical variables to their most common value in the data—another common approach—yielded the same trends).

Precision of standardised CPUE series, which is required for stock assessments when CPUE is used to indicate relative abundance, was quantified using bootstrapping. First, the residuals from the optimum fit were resampled and combined with the model predictions to generate new bootstrap samples of the observed time-series (Haddon 2001). Next, the GLM models were fitted to these bootstrapped data to obtain new estimates of model coefficients. Finally, missing year–block coefficients were imputed and the time series was constructed. This process was repeated 1,000 times to calculate 95% confidence intervals (2.5th and 97.5th percentiles).

3.3 Population dynamics of whiskery and gummy sharks

The model used as the base case is a size-based sex-structured spatial model. Simpler biomass dynamics, size-based and age-structured models of different degrees of complexity were used as sensitivity tests (Table 8 and Table 9). All models were conditioned on total annual catch because there is no evidence that the reported effort data are more accurate than the reported catch data. The compilation of data used in the stock assessments, the description of the assessment models and the sensitivity tests conducted are explained below.

3.3.1 Available data

3.3.1.1 Commercial catch

Sharks have been commercially harvested in Western Australian waters for nearly 70 years, thus the harvest process has a relatively long history of development. Whiskery, gummy, dusky and sandbar sharks are the most important species in terms of landings. Up until recently, the Northern Shark Fisheries (NSF) also caught substantial quantities of sandbar sharks and lesser but poorly-documented quantities of dusky sharks.

The TDGDLF comprises the JASDGDLF and the WCDGDLF, which operate in continental shelf waters along the south and lower west coasts, respectively. The majority of operators employ demersal gillnets and power-hauled reels to target sharks, with scalefish (teleosts) also being a legitimate component of retained catch. Demersal longlines are also a permitted method of fishing but are not widely used. On the south coast, operators primarily target gummy and dusky sharks, while dusky and sandbar sharks are targeted on the west coast. Whiskery sharks are an important component of the catch for both fisheries. Catch and effort records for what became known as the TDGDLF, have been collected since 1975. Although sharks are known to have been commercially-targeted prior to the introduction of mandatory fishing returns, those catches and associated fishing effort were considered to be relatively low. Therefore, for the purpose of stock assessments, the TDGDLF shark catch comprises gillnet and longline catches reported from vessels operating south of 26°S and outside estuarine blocks since 1975.

Reported catches of gummy shark in the West coast and part of Zone 1 have been confounded by catches of grey and whitespot gummy sharks. To remove the catches of these two minor species, catches of gummy shark in the West coast and Zone 1 were validated and corrected according to the monthly catch data correction methods described above (see ***Correction of catch data***) and multiplied by the proportion of gummy sharks (0.95) observed during onboard research programs between 1993 and 2004 (McAuley and Simpfendorfer, 2003; McAuley et al., 2005). The reported catches of whiskery and gummy shark in the TDGDLF are shown in Figure 11 and Figure 12, respectively.

The NSF comprises the State-managed WA North Coast Shark Fishery (WANCSF) in the Pilbara and western Kimberley and the Joint Authority Northern Shark Fishery (JANSF) in the eastern Kimberley. Given confidentiality requirements resulting from the small number of operators in the fisheries and their presumed operation on the same functional stocks, the two fisheries have been considered as a single fishery for reporting purposes. The primary fishing method employed in these fisheries was demersal longlining with a relatively small and sporadic amount of pelagic gillnetting in the JANSF. Since fishing commenced in 1994, NSF operators targeted various species, including sandbar, blacktip (*Carcharhinus* spp.), spot-tail (*Carcharhinus sorrah*), tiger (*Galeocerdo cuvier*), hammerhead (Family Sphyrnidae) and lemon (*Negaprion acutidens*) sharks. However, there has been no reported fishing activity in the NSF since April 2009 (Molony et al. 2013).

Before the State-wide commercial protection of sharks and rays in November 2007[2], other Western Australian commercial fisheries either reported catches of whiskery, gummy, dusky and sandbar sharks or simply reported shark catches as 'sharks, other'. A proportion of these undifferentiated catches were likely to have included whiskery, gummy, dusky and/or sandbar sharks. Hence, records reported as 'sharks, other' south of 26° S using methods other than gillnets or longlines were reapportioned based on the TDGDLF proportion of whiskery, gummy, dusky and sandbar sharks by fishing year and bioregion. Further, retention of whaler sharks with Inter Dorsal fin Lengths over 70 cm (approximating to 2.0 m Total Length; TL, *C. obscurus*) by all commercial (and recreational) fishers in South Coast and West Coast Bioregions was prohibited in 2007 in WA. As commercial fishers are not legally required to report discarded catches in WA, catches of commercially protected and 'over-sized' sharks, post-2007 shark bycatch could not be quantified. However, prior to 2007, reported catches of over-sized dusky sharks in the TDGDLF and bycatch of whiskery or gummy sharks in non-target commercial fisheries were minimal (Figure 11 and Figure 12, respectively). Therefore, these minor catches were merged with TDGDLF catches for assessment purposes.

Gummy and whiskery sharks are also caught in commercial fisheries beyond WA boundaries. Although gummy sharks form a single stock in southern Australia (MacDonald 1988; Gardner and Ward 2000), conventional tagging experiments suggest very low mixing between regions with only 3% of tagged females moving from WA to SA and 9% moving from SA to WA annually. For these reason, the population is divided in a number of sub-stocks for assessment purposes (Walker et al. 2000; Walker 2010) and catches of gummy sharks outside WA boundaries were not considered in the current assessment. Similarly, whiskery sharks also show limited movement with a very small proportion of individuals tagged in WA being recovered outside state boundaries (Simpfendorfer et al. 1999). Hence, catches of whiskery sharks outside WA were not considered in the current assessment.

3.3.1.2 Recreational catch

Sharks are not generally targeted by recreational fishers in WA. An integrated survey of boat-based recreational fishing in WA during 2011-12 provides an estimate of the total annual catch of sharks by recreational fishing vessels and also indicates that state-wide retention rates of sharks are only 17% (Ryan et al. 2013). It should be noted that these estimates do not include shore-based recreational fishing catches, which anecdotally may be significant in comparison to boat-based catches in some areas. To reconstruct a recreational catch series the following steps were undertaken. First, for species in the west and south coast bioregions the 2011-12 catch, in weight, was obtained by multiplying an average live weight of 5 kg by the number of individuals retained plus the number discarded multiplied by an arbitrary Post

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[2] The TDGDLF, NSF and small number of other non-target fisheries are excepted from this regulation.

Capture Mortality (PCM) rate of 0.25. As recreational whaler shark catch data are generally not identified to individual species, it was assumed that all whaler sharks caught in the west and south coasts were dusky sharks. Then, the 2011-12 catch values were multiplied by a time-series of the WA annual population size between 1975 and 2014 (www.abs.gov.au) and the rate of participation in recreational fishing reported by Ryan et al. (2013). The reconstructed catch series of whiskery and gummy sharks are shown in Figure 11 and Figure 12, respectively.

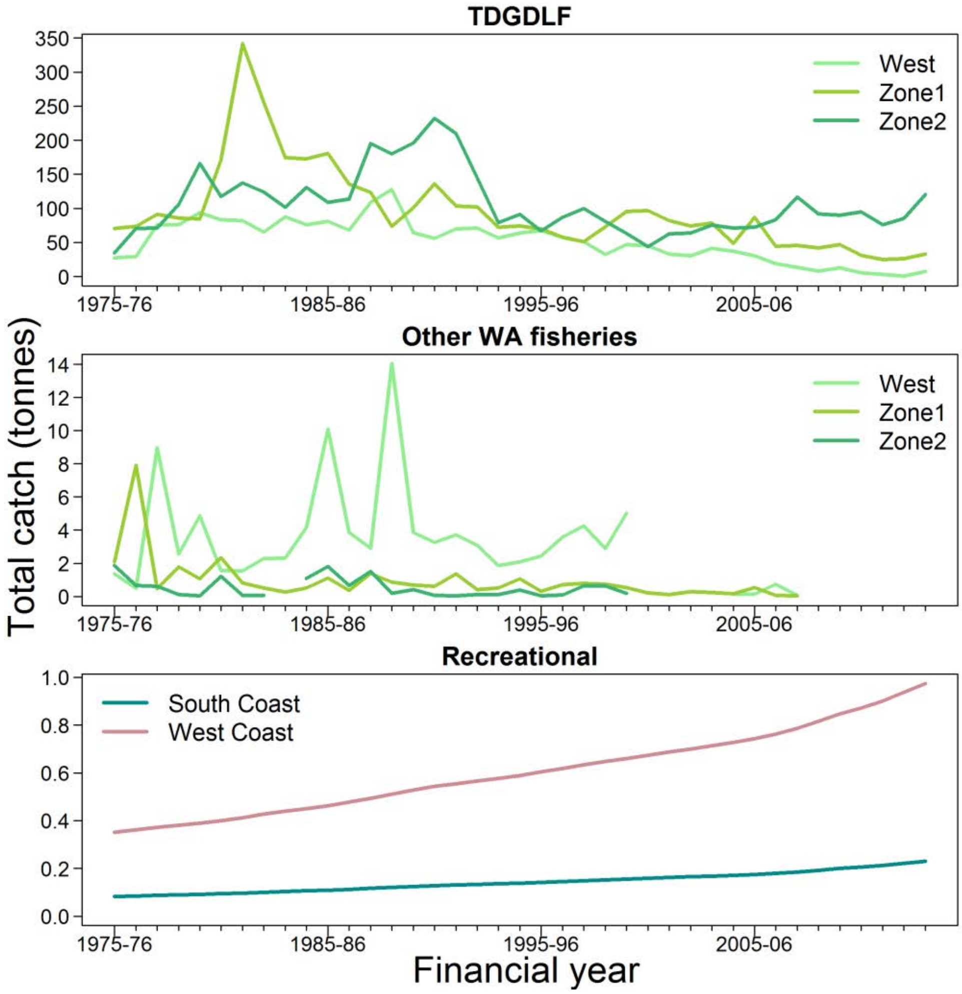


Figure 11. Whiskery shark catches used in the models

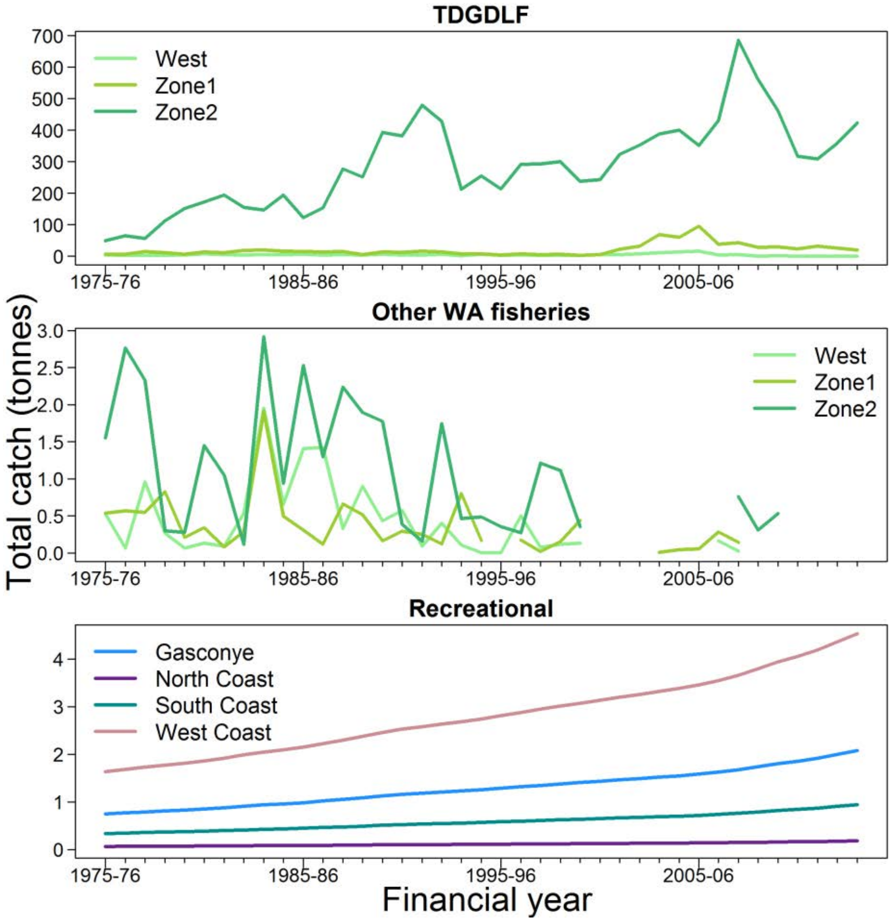


Figure 12. Gummy shark catches used in the models

3.3.1.3 Standardised catch rates

The standardised catch rate series constructed in ***3.2 Catch and effort standardisation*** were used to calibrate the assessment models. However due to unresolved differences in how fishing effort data were reported in monthly (1975-2006) and daily (>2006) returns, these two time-series of data are currently considered incompatible and are therefore unsuitable as indices of stock abundance. Thus the model outputs reported below should not be considered as a stock assessment.

3.3.1.4 Acoustic tagging

For the base case, the exchange rates among management zones estimated in ***3.1.2.7 Exchange rates***, were used to parametrise the movement transition matrix required for incorporating movement into the spatial model.

3.3.1.6 Catch size composition

Size compositions of TDGDLF catches were originally reported by McAuley and Simpfendorfer (2003). In this study, we used those data in addition to information collected in more recent years. Sharks were sampled between 1993 and 2013 on-board fishing vessels operating in the TDGDLF. For each gear deployment, the date, time, GPS location and bottom depth (in m) were recorded. Upon retrieval, all individuals were identified to species level and their fork lengths (FL) were measured (in cm) by scientific observers [for a detailed description of the sampling design refer to McAuley and Simpfendorfer (2003)]. Years with less than 10 observations and shots per zone were excluded (

Table 2 and Table 3 for whiskery sharks; Table 4 and Table 5 for gummy sharks). The catch size composition (5 cm length bins) of whiskery and gummy sharks are shown in (Figure 13) and (Figure 14), respectively.

The size-based models used 5-cm bin size classes, ranging between 0 cm and 150% of the maximum reported total length, L_{max}, to account for larger individuals than the maximum reported and to avoid accumulation of individuals in the last size class.

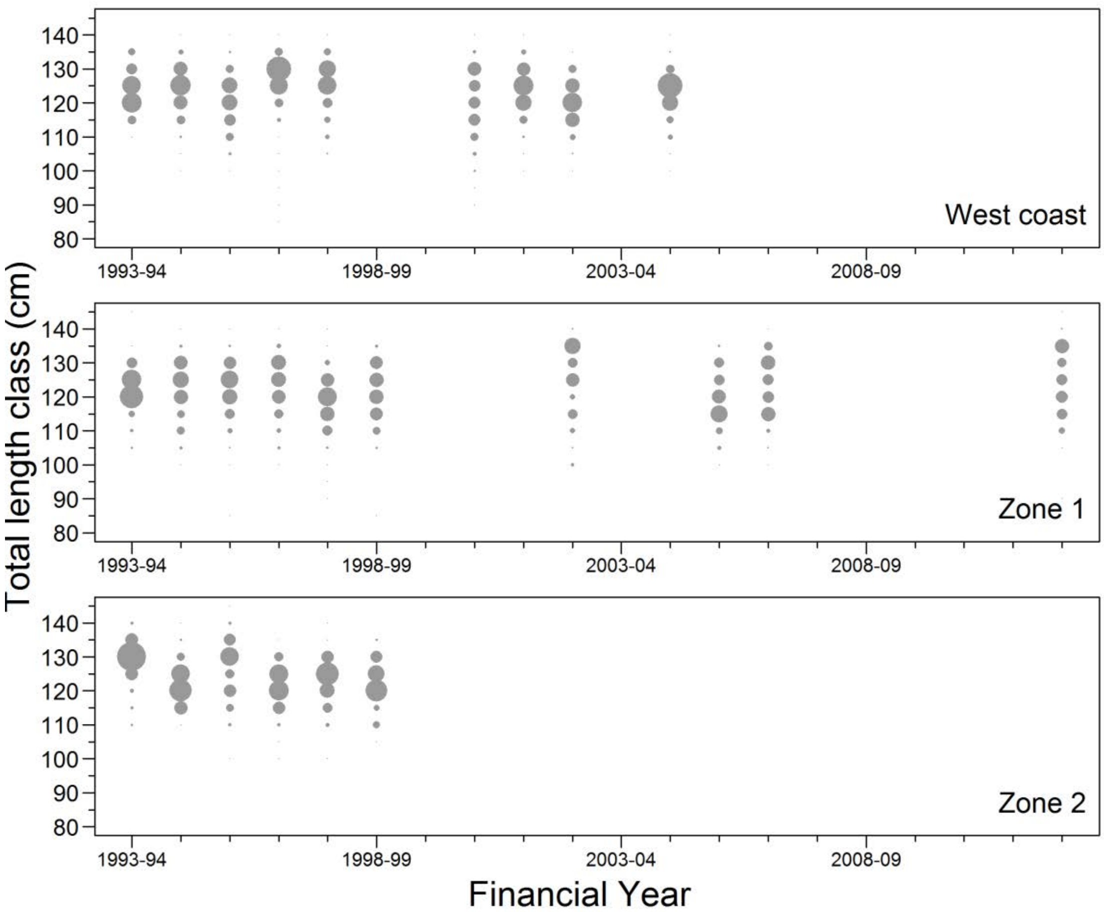


Figure 13. Observed whiskery shark (sexes combined) size composition (as an annual proportion) from the Temperate Demersal Gillnet and Demersal Longline Fisheries (16.5cm and 17.8cm mesh)

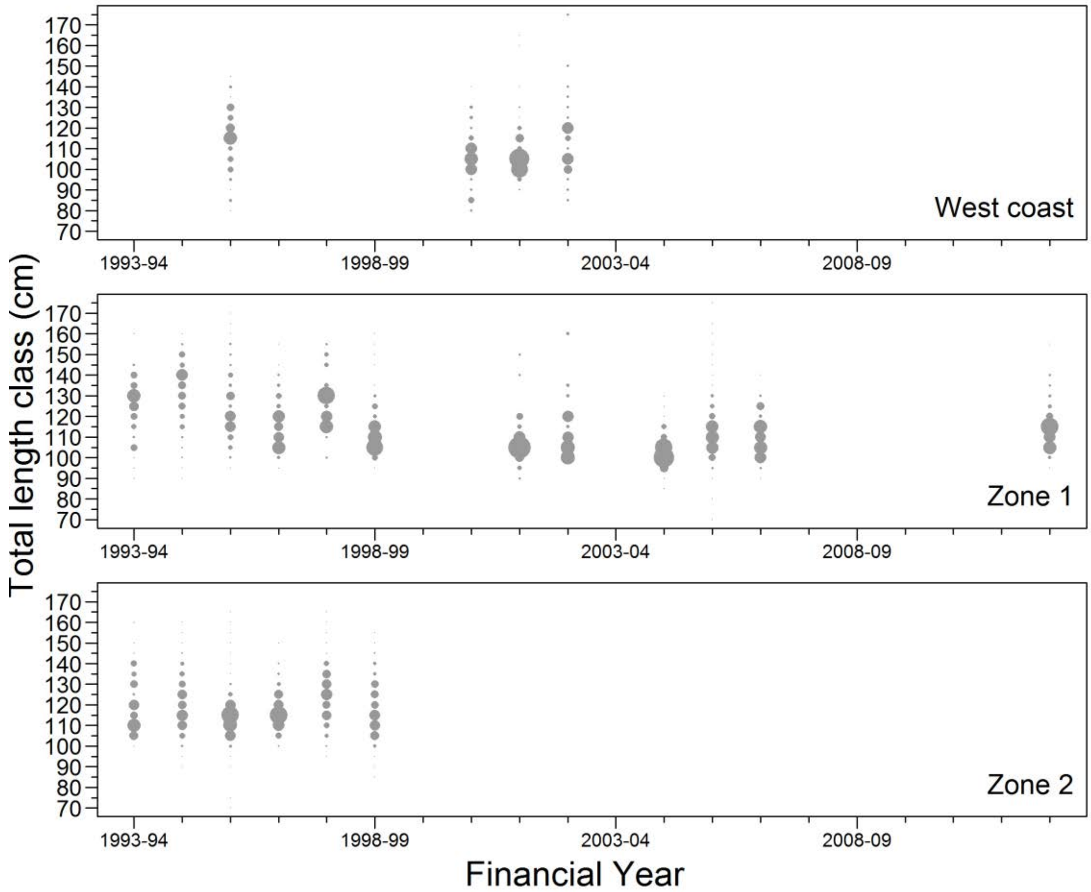


Figure 14. Observed gummy shark (sexes combined) size composition (as an annual proportion) from the Temperate Demersal Gillnet and Demersal Longline Fisheries (16.5cm and 17.8cm mesh)

Table 2. Annual number of observations used to derive the size composition of whiskery sharks in the Temperate Demersal Gillnet and Demersal Longline Fisheries

Zone	93-94	94-95	95-96	96-97	97-98	98-99	00-01	01-02	02-03	04-05	05-06	06-07	12-13
WC	56	296	180	365	176		629	463	172	211			
Zone1	128	337	370	367	887	258			36		204	146	183
Zone2	64	228	209	76	104	118							
Total	248	861	759	808	1167	376	629	463	208	211	204	146	183

Table 3. Annual number of shots sampled to derive the size composition of whiskery sharks in the Temperate Demersal Gillnet and Demersal Longline Fisheries

Zone	93-94	94-95	95-96	96-97	97-98	98-99	00-01	01-02	02-03	04-05	05-06	06-07	12-13
WC	14	53	46	34	25		83	95	56	19			
Zone1	41	55	49	48	42	45			16		27	30	45
Zone 2	20	51	57	21	36	51							
Total	75	159	152	103	103	96	83	95	72	19	27	30	45

Table 4. Annual number of observations used to derive the size composition of gummy sharks in the Temperate Demersal Gillnet and Demersal Longline Fisheries

Zone	93-94	94-95	95-96	96-97	97-98	98-99	00-01	01-02	02-03	04-05	05-06	06-07	12-13
WC			45				76	77	24				
Zone1	49	110	93	117	30	143		30	18	86	444	98	198
Zone2	53	953	1652	170	819	949							
Total	102	1063	1790	287	849	1092	76	107	42	86	444	98	198

Table 5. Annual number of shots sampled to derive the size composition of gummy sharks in the Temperate Demersal Gillnet and Demersal Longline Fisheries

Zone	93-94	94-95	95-96	96-97	97-98	98-99	00-01	01-02	02-03	04-05	05-06	06-07	12-13
WC			11				19	26	20				
Zone1	27	29	25	31	21	22		11	11	12	37	26	44
Zone2	29	81	152	29	63	76							
Total	56	110	188	60	84	98	19	37	31	12	37	26	44

4.3.1.6 Length at age data

The length at age data used by Simpfendorfer et al. (2000a) and Moulton et al. (1992) (Bass Strait 1973-76) for estimating the growth parameters of whiskery and gummy sharks, respectively, were used for calibrating the assessment model. This information is valuable for calculating the size transition matrix.

3.3.2 Life history parameters and relationships

The life history parameters used for the assessment of whiskery and gummy sharks are shown in Table 6 and Table 7, respectively. Relationships at length were converted to at age using a growth curve. The relationships at age used in the assessments are shown in Figure 15 and Figure 16 for whiskery and gummy sharks, respectively.

Table 6. Input parameter values for whiskery sharks. Parameter definition is given in the text

Parameter	Value	Units	Source
a	1.0044		DoF unpublished
b	13.171		
$b_{wt,f}$	2.75e-06		
$a_{wt,f}$	3.081		(McAuley and Simpfendorfer 2003)
$b_{wt,m}$	$2.75e^{-06}$		
$a_{wt,m}$	3.081		(McAuley and Simpfendorfer 2003)

Parameter	Value	Units	Source
L_{max}	160	cm	(TL) (Last and Stevens 2009)
A_m	13	years	(Simpfendorfer et al. 2000b)
A_f	15	years	(Simpfendorfer et al. 2000b)
K_f	0.369	$years^{-1}$	(Simpfendorfer et al. 2000a)
$L_{\infty,f}$	120.7	cm	(FL) (Simpfendorfer et al. 2000a)
$t_{0,f}$	-0.544	years	(Simpfendorfer et al. 2000a)
K_m	0.423	$years^{-1}$	(Simpfendorfer et al. 2000a)
$L_{\infty,m}$	121.5	cm	(FL) (Simpfendorfer et al. 2000a)
$t_{0,m}$	-0.472	years	(Simpfendorfer et al. 2000a)
$Bree$	0.5	years	(Simpfendorfer and Unsworth 1998a)
L_0	25	cm	(TL) (Simpfendorfer and Unsworth 1998a)
L_{0_SD}	5	cm	Assumed
L_{50}	125	cm	(TL) estimated using the data presented in (Simpfendorfer and Unsworth 1998a)
L_{95}	136	cm	(TL) estimated using the data presented in (Simpfendorfer and Unsworth 1998a)
Mat_{50}	6	years	(Simpfendorfer et al. 2000a)
$Ls_{\min}$	4		(Simpfendorfer and Unsworth 1998a)
$Ls_{\max}$	28		(Simpfendorfer and Unsworth 1998a)
a_{emb}	0.314		(Simpfendorfer and Unsworth 1998a)
b_{emb}	-17.8		(Simpfendorfer and Unsworth 1998a)
P_g'''	0.5		(Simpfendorfer and Unsworth 1998a)
α	49.239		(Simpfendorfer and Unsworth 1998b) for a 16.5cm mesh
β	22.93		(Simpfendorfer and Unsworth 1998b) for a 16.5cm mesh
Pmc_{WC}	0.288		DoF unpublished
Pmc_{Zn1}	0.267		DoF unpublished
Pmc_{Zn2}	0.383		DoF unpublished
$Pmc_{all.zn}$	0.291		DoF unpublished
M	0.270	$years^{-1}$	(Simpfendorfer et al. 2000b)

Table 7. Input parameter values for gummy sharks. Parameter definition is given in the text

Parameter	Value	Units	Source
a	1.080		DoF unpublished
b	4.642		DoF unpublished
$b_{wt,f}$	4.62e^{-07}		DoF unpublished
$a_{wt,f}$	3.477		DoF unpublished
$b_{wt,m}$	4.21e^{-06}		DoF unpublished
$a_{wt,m}$	2.976		(Walker 2007)
L_{max}	185	cm	(TL) (Last and Stevens 2009)
A_m	13	years	(Walker 2010)
A_f	16	years	(Walker 2010)
K_f	0.123	years^{-1}	(Moulton et al. 1992) for Bass Strait 1973–76
$L_{\infty,f}$	201.9	cm	(TL) (Moulton et al. 1992) for Bass Strait 1973–76
$t_{0,f}$	-1.550	years	(Moulton et al. 1992) for Bass Strait 1973–76
K_m	0.253	years^{-1}	(Moulton et al. 1992) for Bass Strait 1973–76
$L_{\infty,m}$	138.7	cm	(TL) (Moulton et al. 1992) for Bass Strait 1973–76
$t_{0,m}$	-0.9	years	(Moulton et al. 1992) for Bass Strait 1973–76
$Bree$	1	year	(Lenanton et al. 1990)
L_0	33	cm	(TL) (Walker 2007)
L_{0_SD}	5	cm	Assumed
L_{50}	112.9	cm	(TL) (Walker 2007) for West of Kangaroo Island
L_{95}	139.2	cm	(TL) (Walker 2007) for West of Kangaroo Island
Mat_{50}	4	years	(Braccini et al. 2015)
$Ls_{\min}$	1		(Lenanton et al. 1990)
$Ls_{\max}$	31		(Lenanton et al. 1990)
a_{emb}	0.049		(Lenanton et al. 1990)
b_{emb}	-4.133		(Lenanton et al. 1990)
P_g'''	0.500		(Lenanton et al. 1990)
α	49.181		(Kirkwood and Walker 1986) for a 16.5cm mesh
β	24.358		(Kirkwood and Walker 1986) for a 16.5cm mesh
Pmc_{WC}	0.221		DoF unpublished
Pmc_{Zn1}	0.062		DoF unpublished
Pmc_{Zn2}	0.292		DoF unpublished
$Pmc_{all.zn}$	0.238		DoF unpublished
M	0.283	years^{-1}	(Walker et al. 2000)

3.3.2.1 Allometric relationships

Some biological relationships have been reported as a function of fork length (e.g. the age-length relationship for whiskery sharks) and others as a function of total length (e.g. the age-length relationship for gummy sharks). Hence, for standardisation purposes all relationships were converted to total length (L_j, in cm) using the following allometric relationship

$$L_j = aFL_j + b.$$

where FL_j is the fork length (set to the mid-point of size class j for the size-based models) and a and b are parameters of the allometric relationship. The values of these parameters are shown in Table 6 and Table 7 for whiskery and gummy sharks, respectively.

The total weight (in kg) of an individual in size class j of sex g, $w_{j,g}$, was calculated as:

$$w_{j,g} = b_{wt,g} L_j^{a_{wt,g}}$$

where $b_{wt,g}$ and $a_{wt,g}$ are the sex-specific weight-length parameters. The values of these parameters are reported in Table 6 and Table 7 for whiskery and gummy sharks, respectively. These parameters and a growth curve (see below) were used to calculate $w_{a,g}$, the total weight (in kg) of an individual in age class a of sex g. For female gummy sharks, total weight was capped at 30 kg.

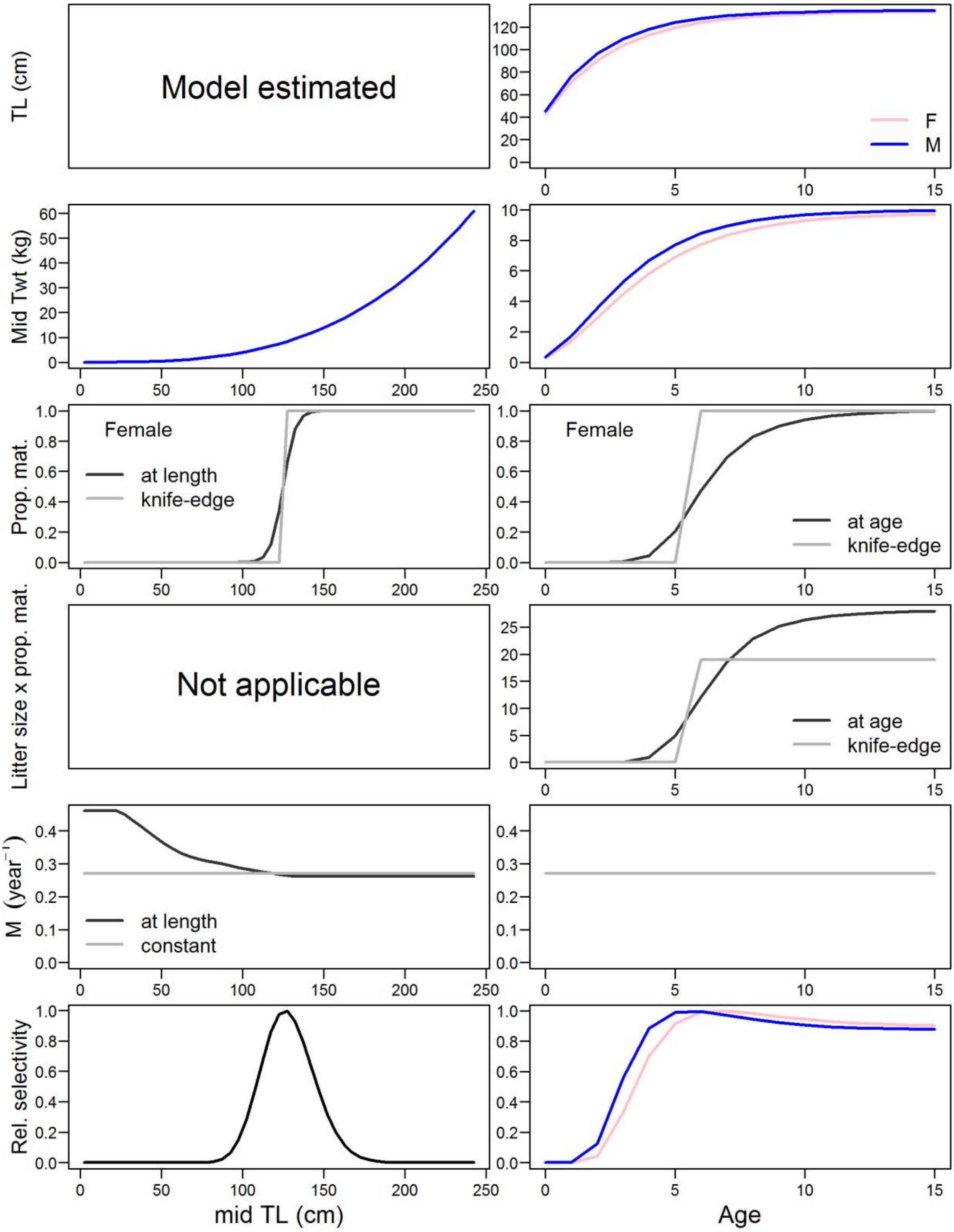


Figure 15. Whiskery shark biological and gear selectivity relationships at size (first column) and at age (second column)

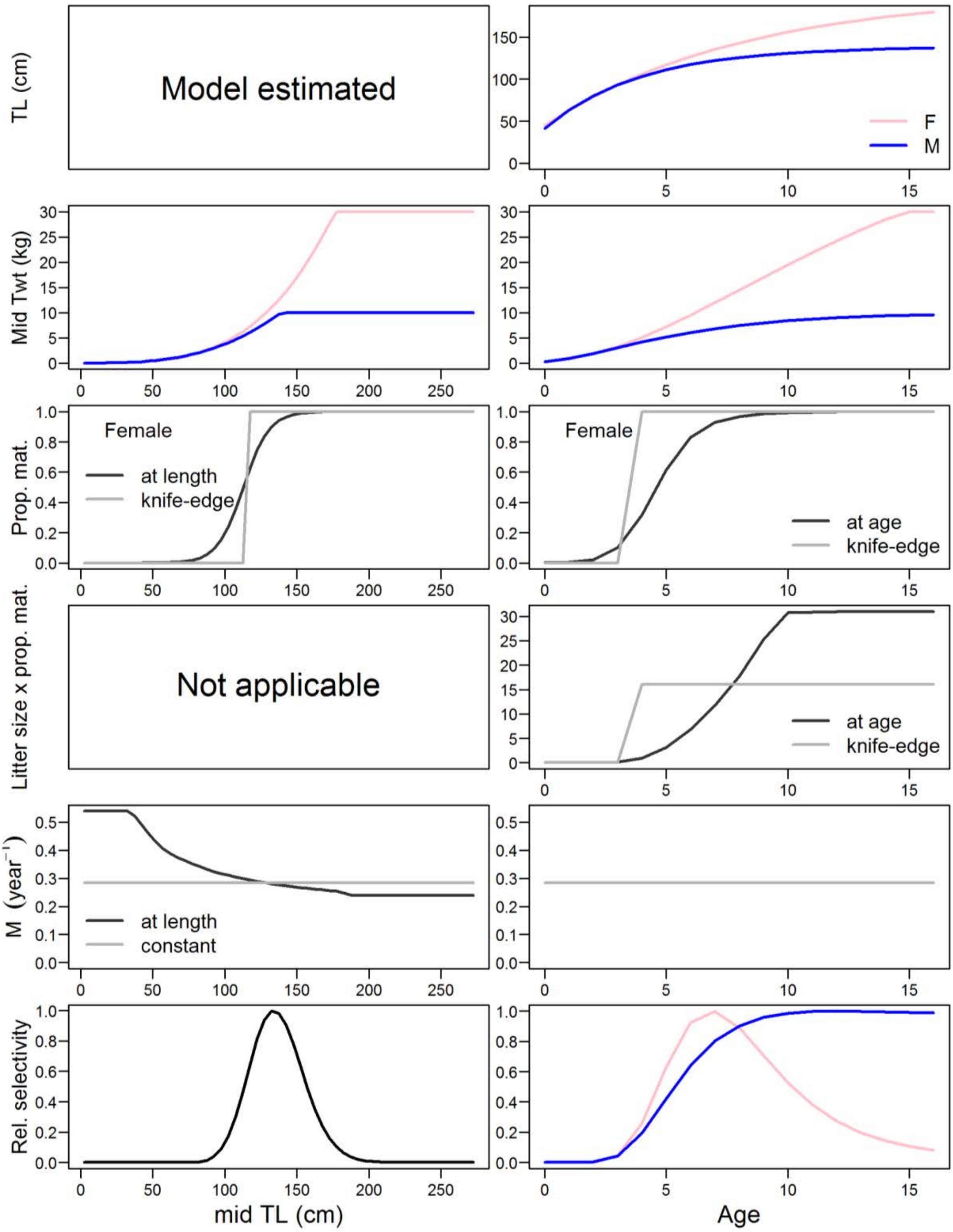


Figure 16. Gummy shark biological and gear selectivity relationships at size (first column) and at age (second column)

3.3.2.2 Age and growth

The age-structured models used age classes ranging between 1 and the maximum age, A_g.

Whiskery sharks are fast growing and short to moderately long-lived. Males and females reach at least 10.5 and 11.5 years, respectively (Simpfendorfer et al. 2000a) so Simpfendorfer et al. (2000b) set A_g at 13 and 15 years for males and females, respectively (Table 6). For the S1 scenario, growth was modelled using a Von Bertalanffy curve (Figure 15) with the length of age class *a* and sex *g* was calculated as

$$L_{a,g} = L_{\infty,g}(1 - e^{-K_g(a - t_{0,g})})$$

where $L_{\infty,g}$ is the asymptotic total length for individuals of sex g; K_g is the growth coefficient for individuals of sex *g*; and $t_{0,g}$ is the age at zero length for individuals of sex *g*. The values of these parameters are shown in Table 6.

Gummy sharks are relatively fast growing and moderately long lived with a maximum age of 13+ and 16+ for males and females, respectively (Walker 2010). Growth was modelled using a Von Bertalanffy curve (Figure 16). The value of the growth parameters for males and females are shown in Table 7.

3.3.2.3 Reproduction

Whiskery sharks are viviparous with mating and parturition occurring between August and October, ovulation occurring between late January and early April, and a gestation period of 7–9 months (Simpfendorfer and Unsworth 1998c). Reproduction is synchronous across the population but females produce litters every second year (Simpfendorfer and Unsworth 1998c), hence, the breeding cycle, *Bree*, was assumed to be 2 years (Table 6). L_0 is 22–27 cm (mean of 25 cm). A maturity ogive (Figure 15) was used in scenarios where the proportion of mature females was assumed to vary with age. The proportion of mature females in size class j, $P_j^{''}$, was calculated as:

$$P_j^{''} = \frac{1}{1 + e^{-\log(19)\frac{L_j - L_{50}}{L_{95} - L_{50}}}}$$

where L_{50} and L_{95} are the total lengths at 50 and 95% maturity (Table 6). These parameters were determined by refitting the data provided in (Simpfendorfer and Unsworth 1998a). The growth curve was used to convert $P_j^{''}$ to $P_a^{''}$, the proportion of mature females at age *a*. For scenarios assuming knife-edge maturity, females ≥ 6 years old (Mat_{50}) were considered to be mature (Table 6).

Litter size, *Ls*, ranges between 4 and 28 embryos and it shows a weak linear relation with maternal size. Hence, $P_j^{'}$, the number of pups produced by a female in size class j, was calculated as:

$$P_j^{'} = L_j a_{emb} + b_{emb}$$

The values of the a_{emb} are b_{emb} parameters are shown in (Table 6). $P_j^{'}$ was capped at 28 pups for length classes larger than the maximum size of the females studied by Simpfendorfer and Unsworth (1998c). The growth curve was used to convert $P_j^{'}$ to $P_a^{'}$, the number of pups produced by a female in age class a. For scenarios where litter size was assumed to be constant, $P_j^{'}$ and $P_a^{'}$ were set at 16 pups (the mid-point of the reported range).

Gummy sharks are viviparous with parturition, mating and ovulation occurring between November and early February and a one year gestation period (Lenanton et al. 1990; Walker 2007). Reproduction is synchronous across the population with WA gummy sharks reproducing annually (Lenanton et al. 1990), hence, *Bree* was assumed to be 1 year (Table 7). L_0 is ~33 cm TL. A maturity ogive (Figure 16) was used in scenarios where the proportion of mature females was assumed to vary with size/age. The values of the L_{50} and L_{95} parameters are shown in (Table 7). In scenarios where knife-edge maturity was assumed, females ≥ 4 years old (Mat_{50}) were assumed to be mature (Table 7). *Ls* ranges between 1 and 31 pups but it shows an exponential relation with maternal size (Lenanton et al. 1990). Hence, $P_j^{'}$ was calculated as:

$$P_j^{'} = e^{L_j a_{emb} + b_{emb}}$$

$P_j^{'}$ was capped at 31 pups for length classes larger than the maximum size of the females studied by (Lenanton et al. 1990). For scenarios where litter size was assumed to be constant, $P_j^{'}$ and $P_a^{'}$ were set at 16 pups (the mid-point of the reported range).

3.3.3 Fishing gear selectivity

For both, whiskery (Simpfendorfer and Unsworth 1998b) and gummy (Kirkwood and Walker 1986) sharks, empirical estimates of gear selectivity at length (Figure 15 and Figure 16) are available for the gillnet mesh sizes used in the TDGDLF. Hence, Sel_j, the gillnet selectivity of individuals in size class j was calculated as:

$$Sel_j = \left(\frac{L_j}{\alpha\beta}\right)^{\alpha} e^{\alpha - \left(\frac{L_j}{\beta}\right)}$$

The values of α and β corresponding to a 16.5cm mesh size are reported in Table 6 and Table 7 for whiskery and gummy sharks, respectively. The growth curve was used to convert Sel_j to Sel_a, the gillnet selectivity of individuals in age class a a .

3.3.4 Proportion of male sharks in the commercial catch

For some scenarios (Table 8 and Table 9), the commercial catch was split into males and females using information collected by the several scientific observer programs conducted by DoF. The proportion of males observed in the catch, *Pmc*, of management zone *z* is shown in Table 6 and Table 7 for whiskery and gummy sharks, respectively.

3.3.5 Natural mortality

For whiskery sharks, empirical natural mortality, *M*, estimates are not available. Hence, Simpfendorfer et al. (2000b) used the life history method of Hoenig (1983) and assumed a maximum age of 15 years for an unexploited population to derive an age independent rate of 0.27 yr^{-1} (Table 6). This value was used in all scenarios. For gummy sharks, empirical *M* estimates are based on conventional tagging. The estimated rate is 0.283 yr^{-1} (Walker et al. 2000) (Table 7).

3.3.6 Sensitivity analyses

Multiple sources of uncertainty exist in the indirect stock size and fishing mortality information used to assess the status of exploited fish stocks which can result in biases in model outputs. To account for this, a range of sensitivity analyses were done to investigate uncertainty in model inputs and in the model used to describe population dynamics (i.e. structural uncertainty). Process error, a source of uncertainty typically modelled in current stock assessments, was not considered in the present study because the recruitment dynamics of viviparous sharks, such as whiskery and gummy sharks, differ markedly from broadcast spawners, such as invertebrates and most teleosts. In viviparous sharks, recruitment is likely to be proportional to adult biomass and not affected by environmental conditions to the same extent as in broadcast spawners (Walker 1998). Hence, we assumed that population dynamics are deterministic and that (time-invariant) size-specific selectivity is known on the basis of the experimental work of Simpfendorfer and Unsworth (1998b) and Kirkwood and Walker (1986).

In the past, gummy and whiskery shark stocks in WA had been assessed using simple age- and sex-structured population dynamics models fitted only to 'effective' CPUE (Simpfendorfer et al. 1996, 2000b, respectively). Since the development of these models, additional information useful for calibrating population dynamics model has become available. Hence, to incorporate this information, an integrated stock assessment approach was applied for assessing these species. Also, to illustrate the effect of incorporating new data and test uncertainty in model structure a series of sensitivity tests were conducted (Table 8 and Table 9). Model sensitivity to M was tested by using the M values derived by Braccini et al. (2015), who used a combination of age-independent and age-dependent life history methods. The effect of M and h input values is tested jointly given their high correlation. The sensitivity analyses were done in steps, evaluating the effects of incremental changes that bring the assessment model from its original model form to the final model form which makes used of all available data.

All models were developed in Automatic Differentiation Model Builder (ADMB; Fournier et al. 2012). The estimation process consists of a maximum likelihood step (all scenarios) followed by Markov Chain Monte Carlo (MCMC) sampling (base case only) with posterior estimates based on 1,000,000 samples run, a burn in of 5% and a thinning of 100 for ensuring acceptance ratios of about 0.3. MCMC chains are analysed using the 'coda' package of the software R.

3.3.7 Modelling approach

The population dynamics models used an annual time step and, for the size-based and age-structured models, it tracked the numbers and biomass of sharks by their sex and age (age-structured models) or size (size-based models), and included the processes of mortality, movement and recruitment. The relationship between annual recruitment and mature female stock size is assumed to follow a Beverton-Holt stock recruitment relationship (e.g. Simpfendorfer et al. 2000b). Parameter estimation was undertaken using multiple phases; a penalty, $Catch_{pen}$, was included to prevent negative population biomasses in the early estimation phases.

3.3.7.1 Model S1

This scenario is based on a Bayesian Schaefer surplus production model fitted to CPUE. To reduce estimation uncertainty, we followed McAllister et al. (2001) and constructed a prior for *r*, the population intrinsic growth rate, based on demographic methods (Figure 17). The use of a simple model allows an understanding of the consistency and robustness of the assessment results and the influence of different data types and parameters (Haddon 2001).

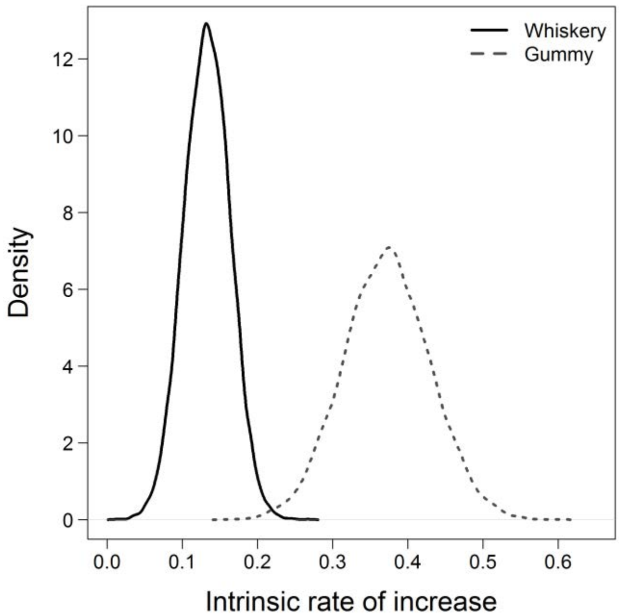


Figure 17. Whiskery and gummy sharks r prior derived from demographic methods

3.3.7.2 Models S2–S6

The Excel model constructed by Simpfendorfer et al. (1996, 2000b) was coded in ADMB and used in the S2–S6 scenarios which extend the model developed by Simpfendorfer et al. (1996, 2000b) by incorporating a maturity ogive, a fecundity relationship, spatial structure and movement among spatial zones. Below is a description of the population dynamics implemented and the objective function used.

Table 8. Whiskery shark population dynamics models used. Base case and sensitivity tests considering alternative model inputs and structures. Size: size composition; A&G: age and growth; *Pmc*: proportion of males in catch; *M*: natural mortality; *h*: steepness.

Model	Data		Input parameters					Q	Movement	Spatial	Model
	Size	A&G	Pmc	Fecundity	Maturity	M	h			structure	type
Base case	Yes	Yes	Observed	N/A	At length	constant	0.419	2	Yes	3 zones	Length-based
S1	No	No	N/A	N/A	N/A	Constant	N/A	2	N/A	1 zone	Biomass dynamics
S2	No	No	Same	Constant	Knife edge	Constant	N/A	2	N/A	1 zone	Age-structured
S3	No	No	Same	At age	At age	Constant	N/A	2	N/A	1 zone	Age-structured
S4	No	No	Observed	At age	At age	Constant	N/A	2	No	3 zones	Age-structured
S5	No	No	Observed	At age	At age	Constant	N/A	1	Yes	3 zones	Age-structured
S6	No	No	Observed	At age	At age	Constant	N/A	2	Yes	3 zones	Age-structured
S7	Yes	Yes	Observed	N/A	At length	Constant	0.419	2	N/A	1 zone	Length-based
S8	Yes	Yes	Same	N/A	At length	Constant	0.419	2	N/A	1 zone	Length-based
S9	Yes	Yes	Observed	N/A	Knife edge	Constant	0.419	2	N/A	1 zone	Length-based
S10	Yes	Yes	Observed	N/A	At length	At length	0.351	2	N/A	1 zone	Length-based
S11	Yes	Yes	Observed	N/A	At length	Constant	0.419	1	N/A	1 zone	Length-based

Table 9. Gummy shark population dynamics models used. Base case and sensitivity tests considering alternative model inputs and structures. Size: size composition; A&G: age and growth; *Pmc*: proportion of males in catch; *M*: natural mortality; *h*: steepness.

Model	**Data**		**Input parameters**					**Movement**	**Spatial**	**Model**
	Size	**A&G**	**Pmc**	**Fecundity**	**Maturity**	**M**	**h**		**structure**	**type**
Base case	Yes	Yes	Observed	N/A	At length	constant	0.616	Yes	3 zones	Length-based
S1	No	No	N/A	N/A	N/A	Constant	N/A	N/A	1 zone	Biomass dynamics
S2	No	No	Same	Constant	Knife edge	Constant	N/A	N/A	1 zone	Age-structured
S3	No	No	Same	At age	At age	Constant	N/A	N/A	1 zone	Age-structured
S4	No	No	Observed	At age	At age	Constant	N/A	No	3 zones	Age-structured
S5	No	No	Observed	At age	At age	Constant	N/A	Yes	3 zones	Age-structured
S6	No	No	Observed	At age	At age	Constant	N/A	Yes	3 zones	Age-structured
S7	Yes	Yes	Observed	N/A	At length	Constant	0.616	N/A	1 zone	Length-based
S8	Yes	Yes	Same	N/A	At length	Constant	0.616	N/A	1 zone	Length-based
S9	Yes	Yes	Observed	N/A	Knife edge	Constant	0.616	N/A	1 zone	Length-based
S10	Yes	Yes	Observed	N/A	At length	At length	0.481	N/A	1 zone	Length-based
S11	Yes	Yes	Observed	N/A	At length	Constant	0.616	N/A	1 zone	Length-based

3.3.7.2.1 Population dynamics

The population dynamics are modelled using an age- , sex- and spatially-structured model. Stock dynamics are described by

$$N_{a+1,g,t+1,z} = \begin{cases} N_{0,g,t+1,z} & a = 0, \\ (N_{a,g,t,z} - C_{a,g,t,z})e^{-M} & 1 \le a < A_g, \\ (N_{a,g,t,z} - C_{a,g,t,z} + N_{a-1,g,t,z} - C_{a-1,g,t,z})e^{-M} & a = A_g, \end{cases}$$

where $N_{a,g,t,z}$ is the numbers of individuals of age *a* and sex *g* at time *t* in zone *z*; $C_{a,g,t,z}$ is the predicted catch in numbers of individuals of age *a* and sex *g* at time *t* in zone *z*; *M* is the instantaneous rate of natural mortality; and A_g is the maximum age of sex *g*.

The movement transition matrix, Θ, estimated in in ***3.1.2.7 Exchange rates*** was used to incorporate movement as follows

$$N_{a,g,t,z} = \begin{cases} N_{a,g,t,z} & a < Mat_{50} \\ N_{a,g,t,z}\Theta & a \ge Mat_{50} \end{cases}$$

Recruitment, $N_{0,g,t,z}$, is given by

$$N_{0,g,t,z} = \frac{S_{t,z}}{(b_z + c_z S_{t,z})} P'''_{g=f}$$

where $P'''_{g=f}$ is the proportion of female embryos and $S_{t,z}$, b_z and c_z are given by

$$S_{t,z} = \sum_a^{A_g} N_{a,g=f,t,z} P'_a P''_a Bree$$

where P'_a is the number of pups per pregnant female at age *a*; P''_a is the proportion of mature females at age *a ;* and $Bree$ is the breeding cycle.

$$b_z = \frac{S^*_z(1-((\delta-0.2)/0.8\delta))}{R^*_z}$$

where S^*_z is the unexploited egg production in zone *z;* R^*_z is the model-estimated recruitment at virgin biomass in zone *z*; and δ is the model-estimated proportion of R^*_z obtained at 20% of the virgin biomass

$$c_z = \frac{(\delta-0.2)}{0.8\delta R^*_z}$$

where δ must satisfy

$$\delta \le \frac{S^*_z}{4R^*_z + S^*_z}$$

For the derivation of the upper bound of δ see Simpfendorfer et al. (2000b).

The $C_{a,g,t,z}$ is calculated as

$$C_{a,g,t,z} = N_{a,g,t,z} Sel_a F_{g,t,z}$$

where $F_{g,t,z}$ is the fishing mortality on individuals of sex *g* at time *t* in zone *z*, which is calculated as

$$F_{g,t,z} = \frac{Y_{g,t,z}}{Be_{g,t,z}}$$

where $Y_{g,t,z}$ is the reported catch (in weight) of individuals of sex *g* at time *t* in zone *z*; and $Be_{g,t,z}$ is the exploitable biomass of individuals of sex *g* at time *t* in zone *z.*

Total biomass at time *t* is calculated as

$$B_t = \sum_g \sum_a \sum_z N_{a,g,t,z} w_{a,g}$$

For scenarios assuming knife-edge maturity, mature female biomass at time *t* is calculated as

$$Bm_t = \sum_{a=m} \sum_z N_{a,g=f,t,z} w_{a,g}$$

For scenarios using a maturity ogive, mature female biomass at time *t* is calculated as

$$Bm_t = \sum_a \sum_z N_{a,g=f,t,z} w_{a,g} P_a^{''}$$

The exploitable biomass at time *t* in zone *r* is calculated as

$$Be_{t,z} = \sum_g \sum_a N_{a,g,t,z} w_{a,g} Sel_a$$

The predicted catch rate at time *t* in zone *r* is calculated as

$$U_{t,z} = q_{p,z} Be_{t,z}$$

where $q_{p,z}$ is the model-estimated catchability coefficient for period *p* in zone *z*. As done by Simpfendorfer et al. (2000b), two time periods were assumed for whiskery sharks to account for changes in targeting practices; a single *q* was assumed for gummy sharks.

3.3.7.2.2 Per recruit analyses and initial conditions

To account for fishing prior to 1975 (first year with catch and effort records) the state of the population in 1975 in zone z is determined by

$$N_{a+1,g,1975,z} = \begin{cases} R_{0,z} P_g^{'''} & a = 0, \\ N_{a,g,1974,z} e^{-(M+F_{init})} & 1 \le a < A_g, \\ \dfrac{N_{a,g,1974,z} e^{-(M+F_{init})}}{(1-e^{-(M+F_{init})})} & a = A_g, \end{cases}$$

where F_{init} is the model-estimated fishing mortality prior to 1975; and $R_{0,z}$ is the pre-1975 recruitment in zone z, which is calculated as

$$R_{0,z} = \frac{X_0 - b_z}{X_0 c_z}$$

where X_0 is the pre-1975 embryos per recruit, which is calculated as

$$X_0 = \sum_{a}^{A_g} N^*_{a,g,0} P'_a P''_a P'''_{g=f}$$

where

$$N^*_{a+1,g,0} = \begin{cases} 1 & a = 0, \\ N^*_{a,g,0} e^{-(M+F_{init})} & 1 \le a < A_g, \\ \dfrac{N^*_{a,g,0} e^{-(M+F_{init})}}{(1-e^{-(M+F_{init})})} & a = A_g, \end{cases}$$

Virgin biomass is calculated as

$$B_0 = \sum_g \sum_a \sum_z N_{a,g,0,z} w_{a,g}$$

where

$$N_{a+1,g,0,z} = \begin{cases} R^*_z P'''_g & a = 0, \\ N_{a,g,0,z} e^{-M} & 1 \le a < A_g, \\ \dfrac{N_{a,g,0,z} e^{-M}}{(1-e^{-M})} & a = A_g, \end{cases}$$

For scenarios assuming knife-edge maturity, virgin mature biomass is calculated as

$$Bm_0 = \sum_{a=m} \sum_z N_{a,g=f,0,z} w_{a,g}$$

For scenarios using a maturity ogive, virgin mature biomass is calculated as

$$Bm_0 = \sum_a \sum_z N_{a,g=f,0,z} w_{a,g} P''_a$$

For models that assume movement among zones, model initialisation required the cycling of the model to allow for movement among the zones and attain equilibrium conditions before entering the dynamic phase.

3.3.7.2.3 Objective function

To estimate F_{init}, R^*_r, δ, $q_{p,z}$, and σ, the model is fitted to the catch rate data by minimizing the following objective function, λ,

$$\lambda = -(\frac{ssq}{2\sigma^2}) - (n \ln(\sqrt{\sigma^2 2\pi}))$$

where ssq is the sum of squares; and σ is the standard deviation of the catch rate data.

For the spatial models of gummy shark, the CPUE from Zone 2 only was used (see 3.2 Catch and effort standardisation for a justification). For the spatial models of gummy sharks, R^*_{WC} and R^*_{ZN1} could not be estimated because CPUE information is only available for Zone 2 of the JASDGDLF (ZN2). Hence, these two parameters were set at the observed mean proportion of the annual catch in those zones relative to the annual catch in ZN2 (3.5% and 9% for West Coast; WC, and Zone 1 of the JASDGDLF; ZN1, respectively).

3.3.7.3 Base case model and models S7–S11

Below is a description of the integrated spatial size-base, sex-structured model proposed as the base case. A size-based model is appropriate because all biological (e.g. fecundity, maturity) and fishery (e.g. gillnet selectivity) relationships are available as a function of size, not age. Also the data used for fitting the model are a function of size (e.g. catch size composition). Using a size-based model therefore removes the uncertainty introduced in age-structured models where a growth curve is required for converting at-size to at-age relationships.

3.3.7.3.1 Growth

Following Simpfendorfer et al. (2000a), growth is modelled using a modified version of the von Bertalanffy equation to ensure that the curve passed through the known size at birth:

$$L_{a,g} = L_0 + (L_{\infty,g} - L_0)(1 - e^{-K_g a})$$

3.3.7.3.2 Size-distribution of recruits

Sharks are considered to recruit into the population at age 1. The size distribution of these individuals is considered to follow a normal distribution. Hence, θ_j, the probability that a 1 year old individual belongs to size class j is calculated as

$$\theta_j = \int_{L_j^-}^{L_j^+} f_{a=1}(L)dL$$

where L_j^+ and L_j^- are the upper and lower limits of size class j, respectively, and $f_{a=1}(L)$ is the value of the normal probability density function for individuals of age 1 with length L, calculated using a constant standard deviation over all ages, i.e. $L \sim N(L_0, {L_{0\_SD}}^2)$. That is

$$f_{a=1}(L) = \frac{1}{L_{0\_SD}\sqrt{2\pi}} e^{\left[-\frac{1}{2}\left(\frac{1-L_0}{L_{0\_SD}}\right)\right]^2}$$

where L_0 is the mean total length at birth; and L_{0_SD} is the standard deviation of L_0.

3.3.7.3.3 Per recruit analyses and initial conditions

The unfished level of female mature biomass per recruit, BmR_0, is calculated as

$$BmR_0 = \sum_j N_{0,j,g=f} w_{j,g=f} P_j^{"}$$

where $w_{j,g=f}$ is the weight of a female individual in size class *j*; and $P_j^{''}$ is the proportion of mature females in size class *j*.

The initial numbers of females per recruit in size class *j*, $N_{0,j,g=f}$, considering the process of survival and growth is given by

$$N_{0,j,g=f} = Surv_{j,g=f}\Psi_{j',j,g=f}$$

where $Surv_{j,g=f}$ is the survival probability of female individuals in size class *j*; and $\Psi_{j',j,g=f}$ is the size-transition matrix of females, which represents the fraction of individuals in size-class j' that grows into size-class j during the modelled time step.

$Surv_{j,g}$ is calculated as

$$Surv_{j,g} = \begin{cases} \theta_j P_{g=f}^{'''} & a = 1, \\ \sum_a N_{a,j,g} e^{-(M_{j,g}+(Sel_j F))} & 1 < a < A_{f\_size}, \\ \dfrac{N_{a,j,g} e^{-(M_{j,g}+(Sel_j F))}}{1 - e^{-(M_{j,g}+(Sel_j F))}} & a = A_{f\_size}, \end{cases}$$

where $P_{g=f}^{'''}$ is the proportion of female embryos; $N_{a,j,g}$ is the numbers per recruit of age class *a,* size class *j* and sex *g*; $M_{j,g}$ is the natural mortality rate of individuals in size class *j* of sex *g*; Sel_j is the gillnet selectivity of individuals in size class *j*; and F is the fishing mortality rate. For the unfished conditions, F was set at 0 whereas for the initial conditions, F was set at the model-estimated F_{init}, which is the fishing mortality rate prior to 1975. Finally, to loop over enough years A_{f_size} is set at double A_f .

Following Sadovy et al. (2007), $\Psi_{j',j,g}$ is computed as

$$\Psi_{j',j,g} = \frac{X_{j',j,g}}{\sum_{j'} X_{j',j,g}}$$

$$X_{j',j,g} = e\left[-\frac{\left\{L_j - \left[L_{\infty,g}(1-e^{-K_g}) + L_{j'}e^{-K_g}\right]\right\}^2}{2\sigma_G^{\,2}}\right]$$

where σ_G is the standard deviation of the growth increment, assumed to be independent of age and current size. Growth in the model was considered as a discrete event that occurs at the end of the biological year.

The unexploited female mature biomass, S_0, is calculated as

$$S_0 = R^* BmR_0$$

where R^* is the model-estimated unfished recruitment.

Then, $R_{init,z}$, the recruitment at the initial level of fishing mortality (F_{init}) in zone z is calculated as

$$R_{init,z} = pR_z \frac{(BmR_{F_{init}} - a_{SRR})}{(b_{SRR} BmR_{F_{init}})}$$

where pR_z is the model-estimated proportion of the initial recruitment in zone z; a_{SRR} and b_{SRR} are parameters of the Beverton and Holt stock-recruitment relationship; and $BmR_{F_{init}}$ is the female mature biomass per recruit at the F_{init} level.

a_{SRR} is calculated as

$$a_{SRR} = \left(\frac{S_0}{R^*}\right)\left[\frac{(1-h)}{4h}\right]$$

where h is the steepness parameter, which was calculated analytically by Braccini et al. (2015) using the method of Brooks et al. (2010).

b_{SRR} is calculated as

$$b_{SRR} = \frac{(h-0.2)}{0.8hR^*}$$

3.3.7.3.4 Population dynamics

The number of individuals in length class j and sex g growing and surviving to the end of time t in zone z, $N_{j,g,t,z}$, is calculated as

$$N_{j,g,t,z} = \begin{cases} N_{F_{init},j,g} R_{init,z} & t = 1, \\ N_{j,g,t,z} e^{-Z_{j,g,t,z}} \Psi_{j',j,g} & t > 1, \end{cases}$$

where $Z_{j,g,t,z}$ is the total mortality rate of individuals in length class j, sex g at time t in zone z, which is calculated as

$$Z_{j,g,t,z} = F_{j,g,t,z} + M_{j,g}$$

where $F_{j,g,t,z}$ is the fishing mortality rate of individuals in length class j, sex g at time t in zone z, calculated as

$$F_{j,g,t,z} = Sel_j FSF_{g,t,z}$$

where $FSF_{g,t,z}$ is the fully selected fishing mortality rate of individuals of sex g at time t in zone z, calculated using Newton's methods to solve the Baranov catch equation:

$$C_{j,g,t,z} = \frac{F_{j,g,t,z}(1-e^{-Z_{j,g,t,z}}) N_{j,g,t,z} w_{j,g}}{Z_{j,g,t,z}}$$

where $C_{j,g,t,z}$ is the predicted catch biomass of individuals of length class *j,* sex *g* at time *t* in zone *z*.

Movement among zones (West Coast, Zone 1 and Zone 2) was incorporated as follows

$$N_{j,g,t,z} = \begin{cases} N_{j,g,t,z} & j < \omega, \\ N_{j,g,t,z}\Theta & \mathrm{j} \geq \omega, \end{cases}$$

where ω is the size of the smallest individual recaptured in a different zone; and Θ is the movement transition matrix estimated in in ***3.1.2.7 Exchange rates***.

The expected number of recruits in year *t*+1 and zone *z*, $R_{t+1,z}$, is calculated as

$$R_{t+1,z} = \frac{Bm_{t,z}}{(a_{SRR} + b_{SRR}Bm_{t,z})}$$

where $Bm_{t,z}$ is the female mature biomass at time *t* in zone *z*, calculated as

$$Bm_{t,z} = \sum_j N_{j,g=f,t,z} w_{j,g=f} P_j^{"}$$

Total biomass at time *t* in zone *z* is calculated as

$$B_{t,z} = \sum_g \sum_j N_{j,g,t,z} w_{j,g}$$

The exploitable biomass at time *t* in zone *z* is calculated as

$$Be_{t,z} = \sum_g \sum_j N_{j,g,t,z} w_{j,g} Sel_j$$

The predicted catch rate at time *t* in zone *z*, $U_{t,z}$, is calculated as

$$U_{t,z} = q_{p,z} Be_{t,z}$$

where $q_{p,z}$ is the model-estimated catchability coefficient for period *p* in zone *z*.

The size compositions are assumed to have a multinomial distribution so $P_{j,g,t,z}$, the predicted proportion of the catch in size class *j*, sex *g* at time *t* in zone *z*, is calculated as

$$P_{j,g,t,z} = \frac{C_{j,g,t,z}}{\sum_j C_{j,g,t,z}}$$

3.3.7.3.5 Objective function

To estimate K_g , $L_{\infty,g}$, υ (the standard deviation of the growth data), σ_G (the standard deviation of the size transition matrix), F_{init}, R^*, pR_z , $q_{p,z}$, τ (the standard deviation of the catch rate data), and the p_{ij} parameters, the model is fitted to the catch rate, catch size composition, age and growth, conventional tagging, and acoustic tagging data by minimizing an overall objective function, λ, which contains seven terms

$$\lambda = \lambda_1 + \varphi\lambda_2 + \varphi_2\lambda_3 + \lambda_4 + \lambda_5 + Tag_{pen} + F_{init\,prior}$$

where λ_1, λ_2, λ_3, λ_4, and λ_5 are the negative log-likelihoods for the catch rate, catch size composition, growth data, conventional tagging, and acoustic tagging data, respectively; φ is a scaler for the size composition likelihood, set at 0.005; φ_2 is a scaler for the growth likelihood, set at 0.05; Tag_{pen} is a penalty used to maintain all p_{ij} parameters between 0 and 1; and $F_{init\,prior}$ is the prior distribution of the initial fishing mortality. This was required to avoid numerical solutions that set F_{init} to unrealistically low values (<0.0001). We used a lognormal distribution with mean 0.01 [derived from the value estimated by Simpfendorfer et al. (2000b)] and Standard Deviation (SD) (in log space) of 0.5 (Figure 18).

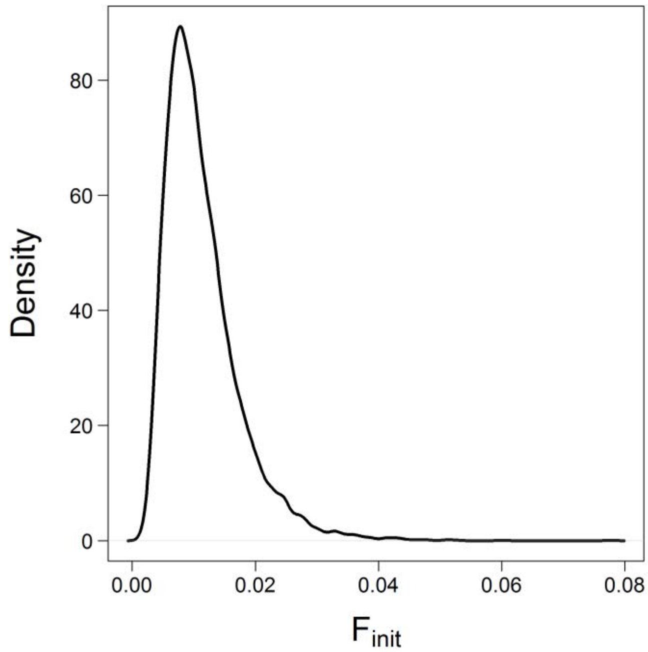


Figure 18. F_{init} prior

Sharks, unlike teleosts, are not expected to exhibit very variable recruitment and, when combined with selective fishing, the size-composition data are not expected to show substantial variability among time periods. Hence, as suggested by Francis (2011), primary importance was given to the standardised catch rate data.

Following Francis (2011), λ_1 includes a weighting factor, which incorporates the estimating uncertainty of the CPUE index, and it is calculated as

$$\lambda_1 = \sum_t \sum_z \log(\gamma_t) + 0.5\left[\frac{\log(U_{t,z} / \hat{U}_{t,z})}{\gamma_{t,z}}\right]^2$$

where $U_{t,z}$ is the observed catch rate at time t in zone z; and $\gamma_{t,z}$ is the total standard deviation at time t in zone z, which was calculated as

$$\gamma_t = \sqrt[2]{\tau^2 + SD_{t,z}^2}$$

where $SD_{t,z}$ is the standard deviation of the observed catch rate at time t in zone z (derived from the catch rate standardisation process).

λ_2 is calculated as

$$\lambda_2 = \sum_j \sum_g \sum_t \sum_z -Neff_{g,t,z} P_{j,g,t,z} \log(P_{j,g,t,z})$$

where $Neff_{g,t,z}$ is the effective sample size for sex g at time t in zone z; and $P_{j,g,t,z}$ is the observed proportion of the catch in size class j, sex g and time t in zone z.

For both species, $Neff_{g,t,z}$ was set at the minimum of 300 and $n_{g,t}$, where $n_{g,t}$ is the sample size for sex g at time t, because the sample mean size and standard deviation stabilize at about 300 samples (Figure 19 and Figure 20).

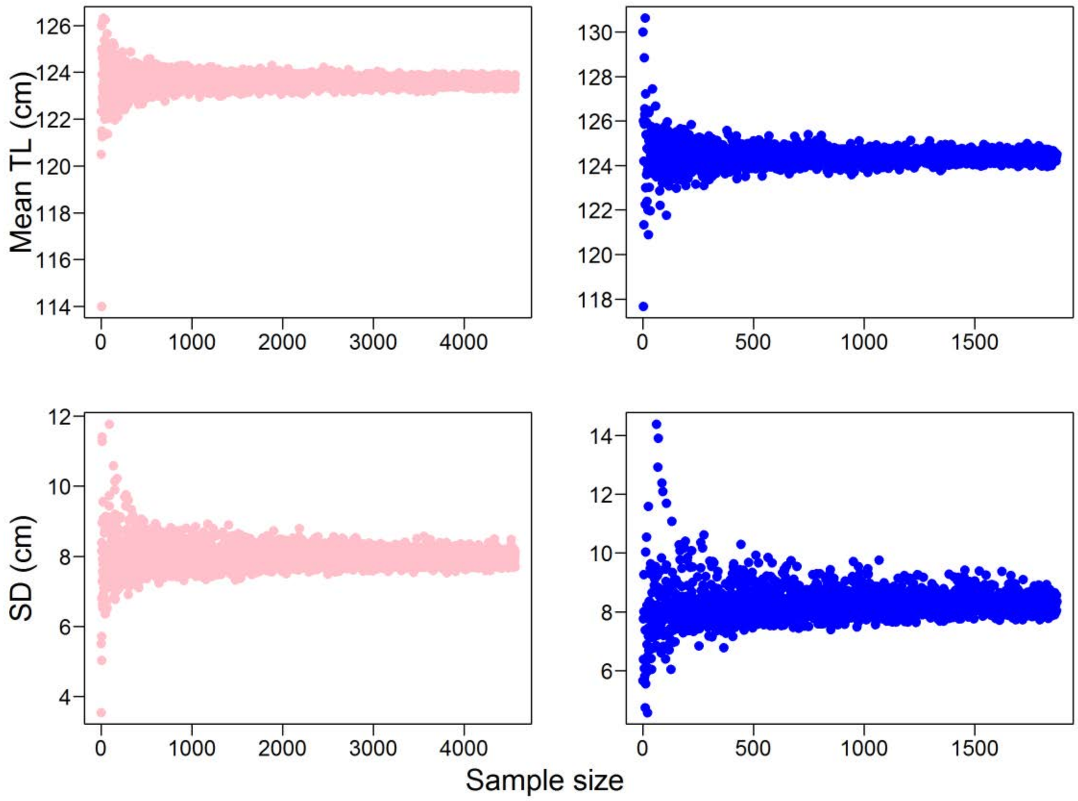


Figure 19. Effect of sample size on the sample mean and Standard Deviation (SD) for female (pink) and male (blue) whiskery sharks

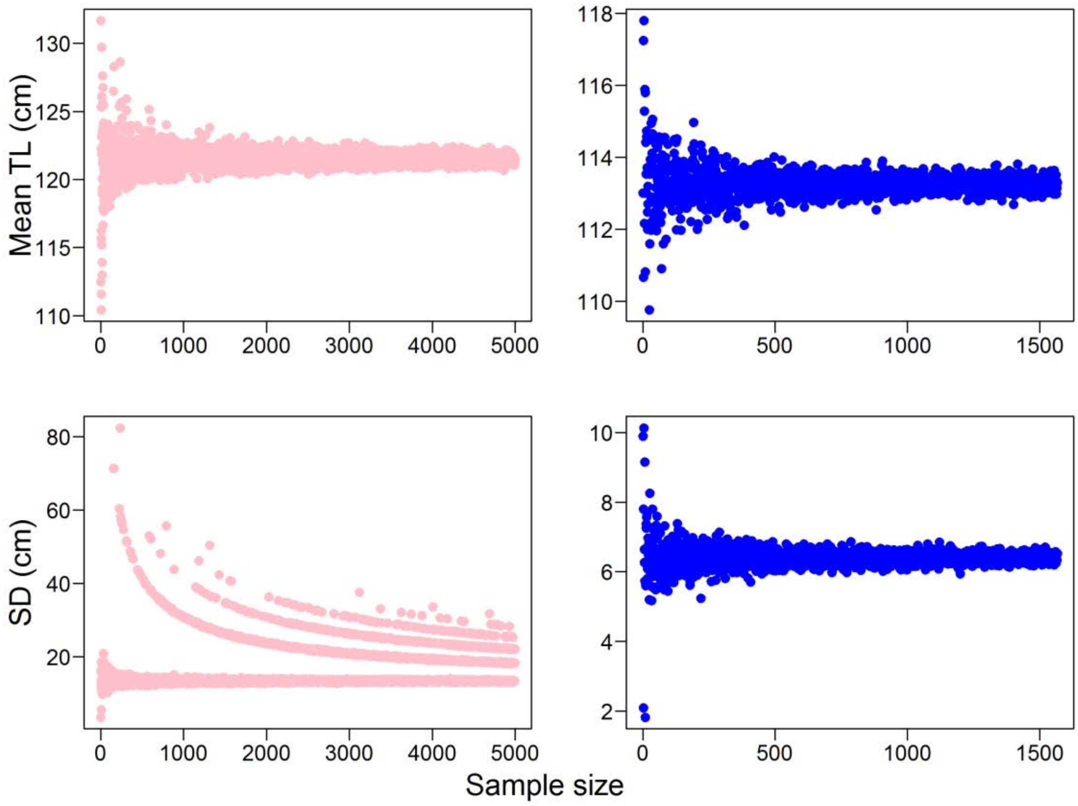


Figure 20. Effect of sample size on the sample mean and Standard Deviation (SD) for female (pink) and male (blue) gummy sharks

λ_3 is calculated using the robust regression function implemented in ADMB (Fournier 2011) with standard deviation υ.

Finally, λ_4 and λ_5 are calculated as

$$\lambda_5 = -\sum_n \hat{p}_{conv,ij}$$

$$\lambda_5 = -\sum_n \hat{p}_{acous,ij}$$

where $\hat{p}_{conv,ij}$ and $\hat{p}_{acous,ij}$ are the predicted recapture probabilities for individuals tagged with conventional or acoustic tags, respectively.

3.4 Risk assessment of dusky and sandbar sharks

3.4.1 Framework

A risk assessment for dusky and sandbar sharks was undertaken using a qualitative, consequence-likelihood (C × L) method developed for prioritising issues as per the National ESD framework (Fletcher et al. 2002; Fletcher 2005; Fletcher 2014). This process is used to implement Ecosystem Based Fisheries Management (EBFM) in Western Australia and enables efficient screening of the large number of potential ecological, social, economic and governance issues that routinely arise in fisheries management and that must be considered to achieve ESD (Fletcher 2002). The EBFM framework used in WA provides the operating policy-basis for implementing sustainable fisheries and ecosystem management in WA and is based on the global standard for risk assessment and risk management (AS/NZS ISO 31000), adapted for use in a fisheries context. The risk analysis process involves examination of the sources of risk (issue identification), the potential consequences (impacts) associated with each issue and the likelihood (probability) of a particular level of consequence actually occurring. This combination produces an estimated level of comparative risk, which can then be used to assist in determining the level of management response required.

3.4.2 Scope

This assessment was generated by considering issues relevant to the ecological sustainability of WA's dusky shark and sandbar shark resources. Assessment was made against meeting the following management objective:

To maintain the mature biomass of dusky and sandbar sharks above B_{MSY} to maintain high productivity and ensure the main factor affecting production of pups is the environment.

This risk assessment relates specifically to the status of dusky and sandbar shark as fisheries resources and does not consider other contributions to ESD such as other ecological components, social or economic components. The risk of not achieving this objective was evaluated over a five year time frame. However, given the inherently low biological productivity of these species, which have generation times of 20 to 30 years (McAuley et al. 2007a), it was also important to consider that the implications of not meeting this objective over even a relatively short-time frame could have much longer lasting consequences.

3.4.3 Issue identification

Two broad categories of issues were identified as posing a threat to the ecological sustainability of dusky and sandbar sharks; extractive fishing in WA and external influences on stocks that are outside Western Australian State jurisdiction or direct control. To more precisely determine the source and nature of risks, extractive fishing was further separated into five issues and external influences into three issues (Table 10). Extractive fishing included a category for each of the three main sources of fishing in WA, an 'other' category for all minor fisheries, and a category for the cumulative effects of extractive fishing in WA. Because one of these major sources, the Northern Shark Fisheries, is currently in hiatus but under consideration for resumption, where relevant the risks associated were split into those under current conditions and those arising from a resumption of fishing. External influences included risks posed by extractive fishing from non-WA fisheries, coastal and offshore development, and environmental influences.

Table 10. Issues identified for risk analysis of dusky and sandbar sharks resources in Western Australia (WA)

Issue group	Risk/issue
Extractive Fishing in WA	Temperate Demersal Gillnet & Demersal Longline Fishery
	Recreational fishing
	Northern Shark Fisheries (current conditions and resumption)
	Other WA fisheries
	Cumulative WA fisheries
External Influences	Non-WA extractive fisheries
	Coastal and offshore development
	Environmental influences

The component tree for the risk assessment contained two components; dusky and sandbar sharks as retained species. Both species are distributed throughout large extents of WA coastal waters and have a complex life cycle that includes large-scale spatial separation of different life stages. To reflect the vulnerability of different life stages to different threats, and incorporate new and pre-existing information on the spatial ecology of these species, the component tree was further subdivided into three categories for each species (Figure 21). The adult subcomponent was based on age classes above the age at 50% maturity for each species (McAuley et al. 2007a), and the division of the two juvenile subcomponents was based on the size selectivity of the main target fishing methods [i.e. 16.5cm (6.5”) and 17.8cm (7.0”) demersal gillnet mesh sizes). Dusky sharks less than seven years of age and sandbar sharks between 6 and 15 years old were considered most vulnerable to these mesh sizes (Simpfendorfer and Unsworth, 1998b; McAuley et al. 2007c).

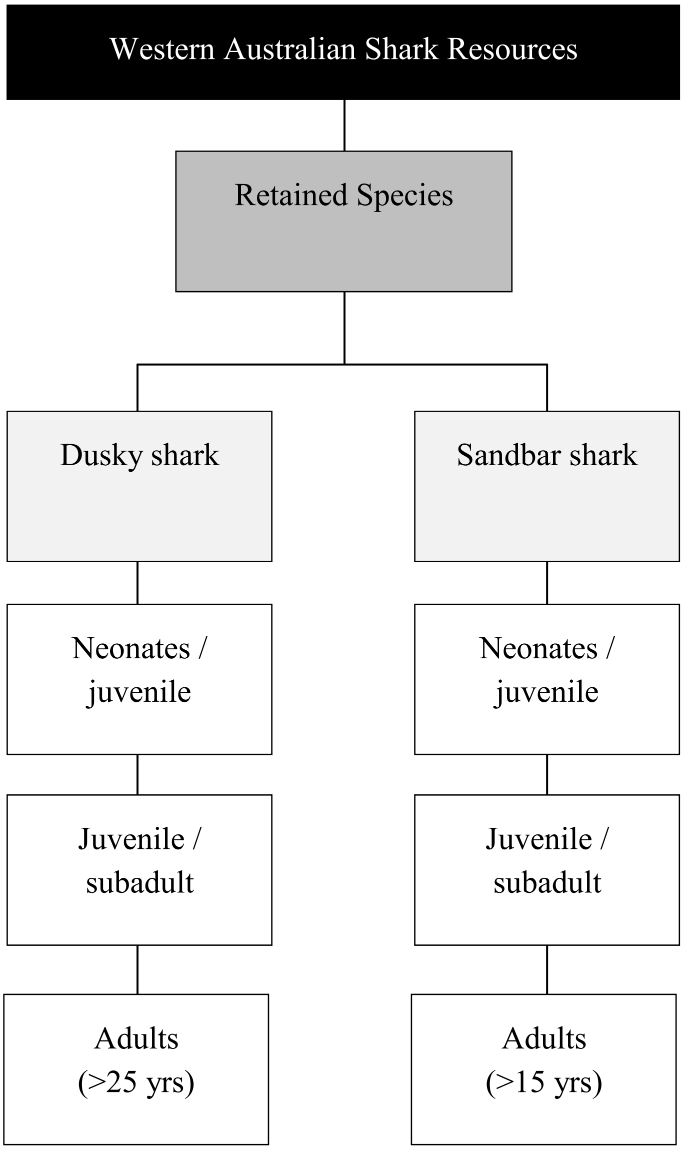


Figure 21. Component tree for ecological sustainability of dusky and sandbar shark resources in Western Australia

Taking into account the eight issues (Table 10) for both of the retained species, separation of Northern Shark Fisheries issues into 'current conditions' and 'resumption of fishing' scenarios and each of the three life stages (Figure 21), a total of 54 issues were considered as part of this risk assessment.

3.4.4 Risk assessment process and reporting

After the components and issues were identified, a process of risk analysis was completed using the formal ISO 31000-based qualitative risk assessment method. The risk analysis was conducted on the 5th and 6th November 2015 by DoF research scientists (R. McAuley, M. Braccini, and A. Harry). The group made what it considered to be its most objective estimate of the risk level for each issue, based on the combined judgement of the participants at the workshop, who collectively had considerable expertise in the issues examined.

Although the risk assessment included specific subcomponents of each stock, the level of consequence for each issue was determined at the component level, i.e. the whole of stock level for each species. For example, the consequence of fishing on neonate / juvenile dusky sharks by the TDGDLF was evaluated in the context of its impact on the overall dusky shark stock. Consequence levels ranged from 0 to 5, with 0 being negligible and 5 being catastrophic (Box 1).

CONSEQUENCE LEVELS

FISH STOCKS (target and non-target) – measured at stock level

1. No measurable depletion of stock
2. Measurable but minor levels of depletion of stock
3. Maximum acceptable level of depletion of stock
4. Level of depletion of stock unacceptable but still not affecting recruitment level of the stock
5. Level of depletion of stock are already (or will definitely) affect future recruitment potential / level of the stock
6. Permanent or widespread and long-term depletion of key fish stock, close to extinction levels

Box 1. Description of consequence levels for target and non-target fish stocks; from DoF 2015

For each consequence, participants assigned the level of likelihood to one of five levels, 1 being remote and 5 being certain (Box 2). Likelihood was described as the conditional likelihood that a specific level of impact (consequence) may occur within the defined time frame, given the current or proposed set of management arrangements either from an accumulation of small ‘events’ and/or from a single large ‘event’ (Fletcher 2014). In line with this description, the selections of likelihood and consequence levels formed a pair, and were not chosen independently.

LIKELIHOOD LEVELS

1. Remote – Never heard of but not impossible here (< 5 % probability)
2. Unlikely – May occur here but only in exceptional circumstances (> 5 %)
3. Possible – Clear evidence to suggest this is possible in this situation (> 30 %)
4. Likely – It is likely, but not certain, to occur here (> 50 %)
5. Certain – It is almost certain to occur here (> 90 %)

Box 2. Description of likelihood levels; from DoF 2015

The overall risk for a specific issue was the product of consequence and likelihood pairs that produced the highest risk (Figure 22). Finally, each issue was assigned a corresponding Risk

Rating within one of five categories: negligible, low, medium, high or severe (Table 11), and the rationale for classifying issues at each risk level was documented.

		Likelihood				
		Remote (1)	Unlikely (2)	Possible (3)	Likely (4)	Certain (5)
Consequence	Minimal (1)	1	2	3	4	5
	Moderate (2)	2	4	6	8	10
	High (3)	3	6	9	12	15
	Major (4)	4	8	12	16	20
	Catastrophic (5)	5	10	15	20	25

Figure 22. Standard Consequence — Likelihood Risk Matrix (based on AS 4360 / ISO 31000; from DoF 2015)

Table 11. Risk levels applied to all assets by the Department of Fisheries Western Australia (modified from Fletcher 2005)

Risk Category / Level	Description	Likely Reporting & Monitoring Requirements	Likely Management Action
1 Negligible	Acceptable; Not an issue	Brief justification – no monitoring	Nil
2 Low	Acceptable; No specific control measures needed	Full justification needed – periodic monitoring	None specific
3 Medium	Acceptable; With current risk control measures in place (no new management required)	Full Performance Report – regular monitoring	Specific management and/or monitoring required
4 High	Not desirable; Continue strong management actions OR new / further risk control measures to be introduced in the near future	Full Performance Report – regular monitoring	Increased management activities needed
5 Severe	Unacceptable; Major changes required to management in immediate future	Recovery strategy and detailed monitoring	Increased management activities needed urgently

3.4.5 Available data

3.4.5.1 Commercial catch

The reported commercial catches of dusky and sandbar sharks in WA are shown in Figure 23 and Figure 24 respectively.

In the Southern and West Coast bioregions of WA, whaler sharks with an inter-dorsal fin length greater than 70 cm (herein referred to as 'oversized') have been totally protected since 2006. Hence, commercial (and recreational) fishers catching these individuals are required to release them. The only records of over-sized dusky shark captures are protected species ('TEPS') records from TDGDLF vessels' daily logbook returns, although it is unclear how complete these data are. Nevertheless, to quantify the catches of oversized dusky sharks, all records from TDGDLF daily logbooks (2006–07 onwards) were compiled. The average estimated weight of a 3m dusky shark (166 kg) was multiplied by the number reported dead plus the number reported to be released alive times a PCM of 0.3. The calculated annual catches are shown in Figure 23 (TEPS panel). It must be noted that the calculations were made on the unrealistic assumption of 100% reporting rate, hence, these are considered to be under- estimates of the true levels of catch.

3.4.5.2 Recreational catch

The reconstructed catch series of dusky and sandbar sharks are shown in Figure 23 and Figure 24, respectively.

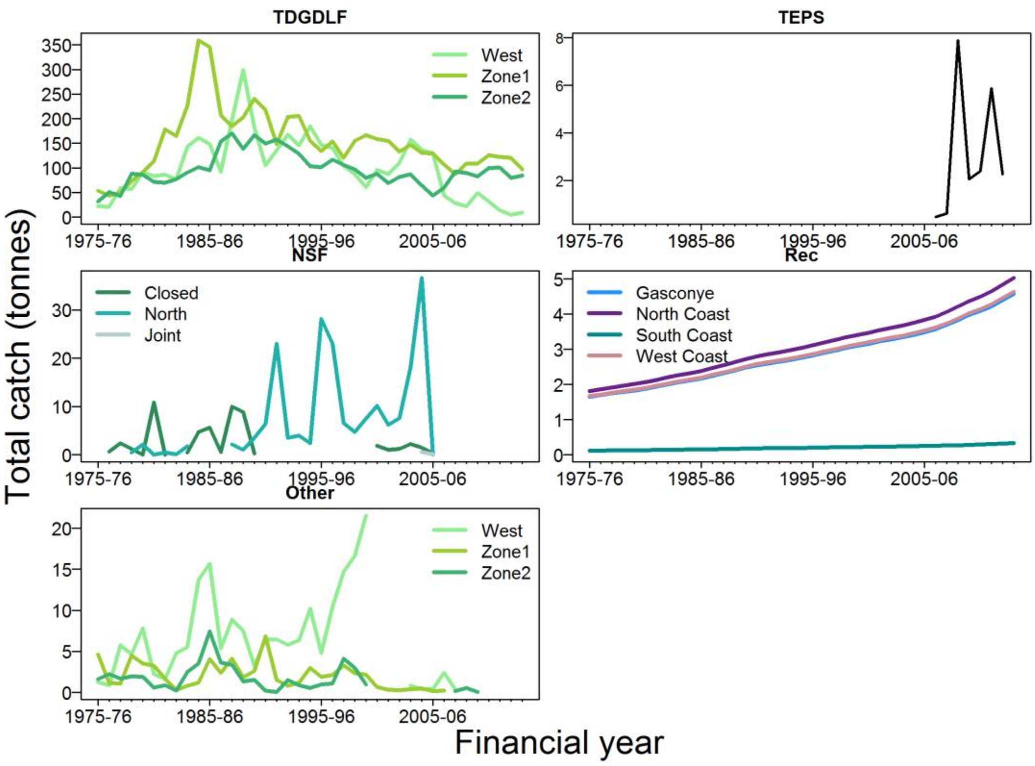


Figure 23. Dusky shark catches used in the risk assessment

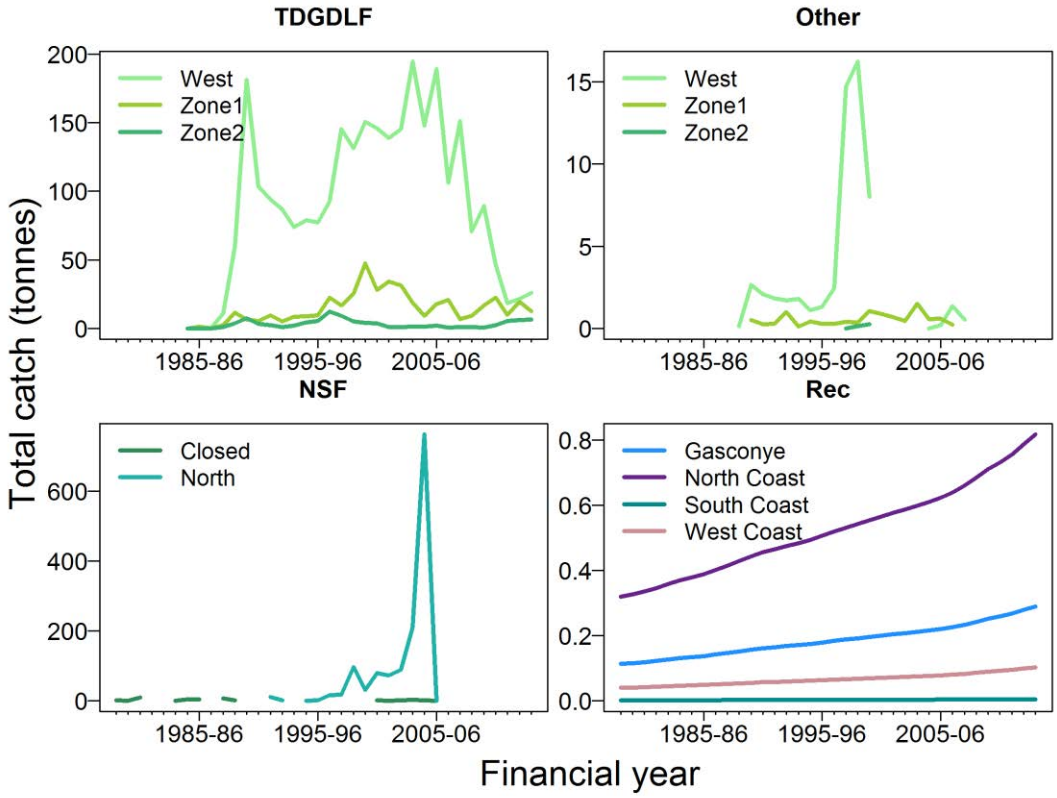


Figure 24. Sandbar shark catches used in the risk assessment

3.4.5.3 Catch size composition

Size composition for the TDGDLF catch between 1994 and 1999 was originally reported by McAuley and Simpfendorfer (2003) and sampling continued subsequently until 2004 (McAuley et al., 2005) and on a more limited level through the current project (Figure 25, Figure 27). For each gear deployment, the date, time, GPS location and bottom depth (in m) were recorded. Upon retrieval, all individuals were identified to species level and their fork lengths (FL) measured (in cm) by scientific observers [for a detailed description of the sampling design refer to McAuley and Simpfendorfer (2003) and McAuley et al. (2005)]. Catch size composition data are also available for dusky (Figure 26) and sandbar (Figure 28) sharks from the NSF and for sandbar sharks from the Pilbara trawl fishery (Figure 29) (McAuley et al. 2005). The number of observations and shots used to derive the size composition of dusky and sandbar sharks in the TDGDLF and the NSF are show in Table 12, Table 13, Table 14 and Table 15. Fork lengths have been transformed to TL using the allometric relationships (McAuley unpublished).

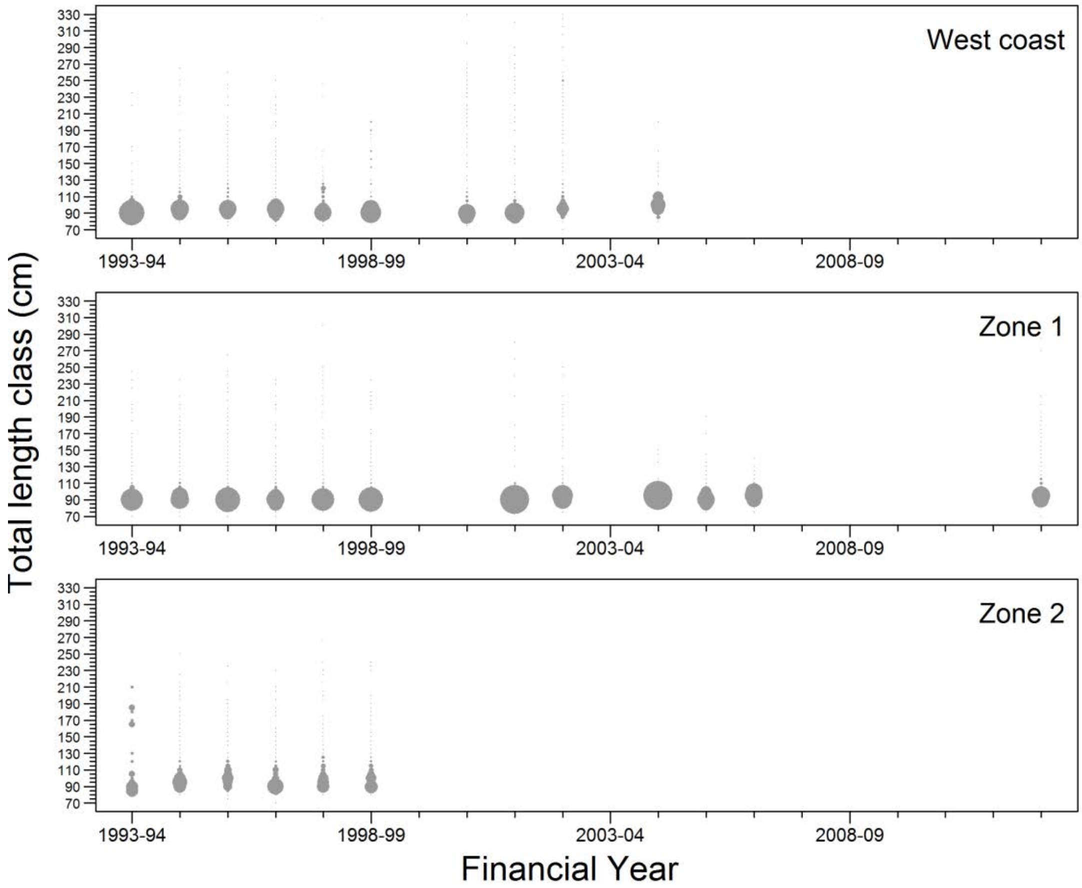


Figure 25. Observed dusky shark (sexes combined) size composition (as an annual proportion) from the Temperate Demersal Gillnet and Demersal Longline Fisheries (16.5cm and 17.8cm mesh)

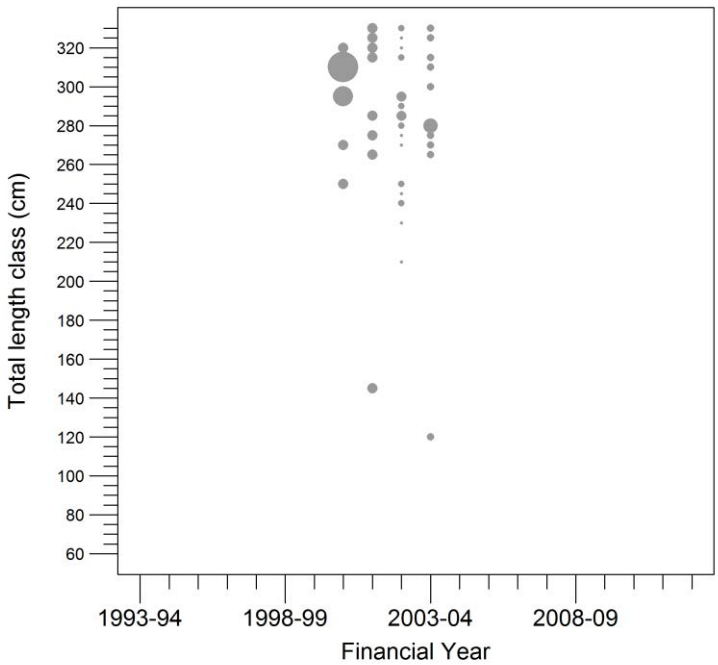


Figure 26. Observed dusky shark (sexes combined) size composition (as an annual proportion) from the Northern Shark Fisheries

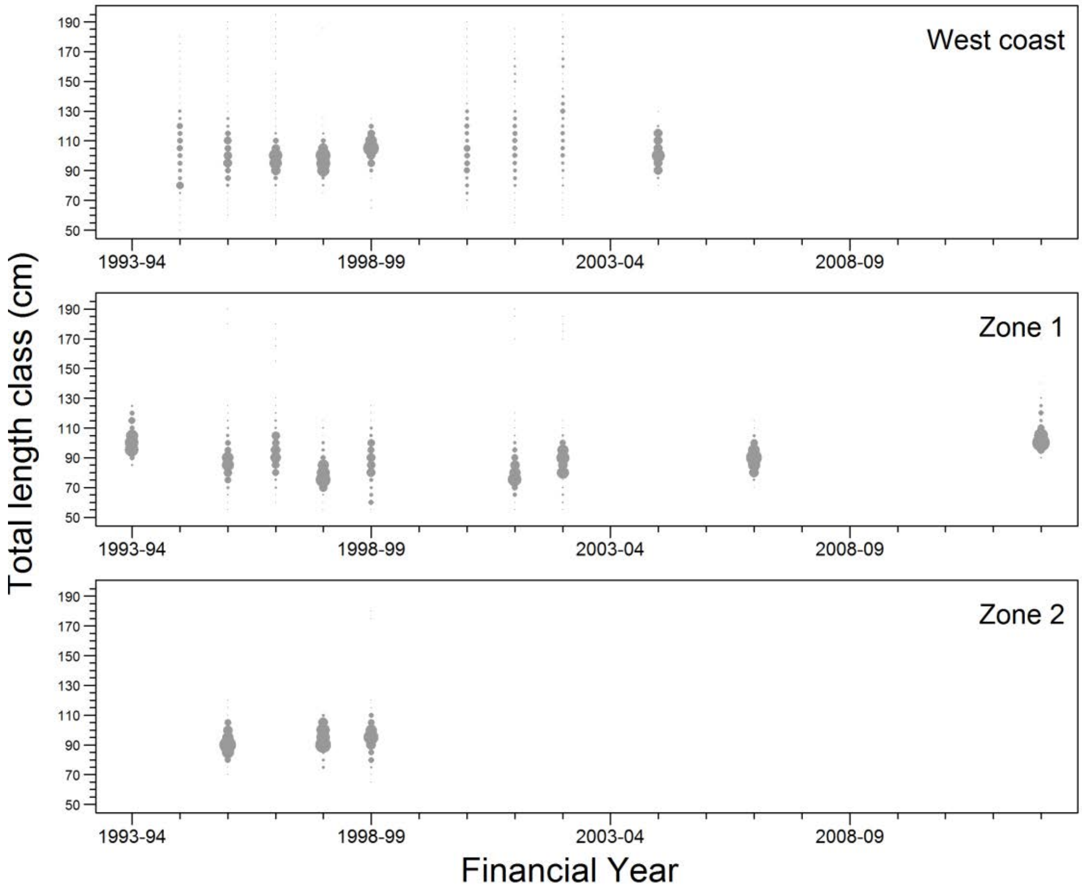


Figure 27. Observed sandbar shark (sexes combined) size composition (as an annual proportion) from the Temperate Demersal Gillnet and Demersal Longline Fisheries (16.5cm and 17.8cm mesh)

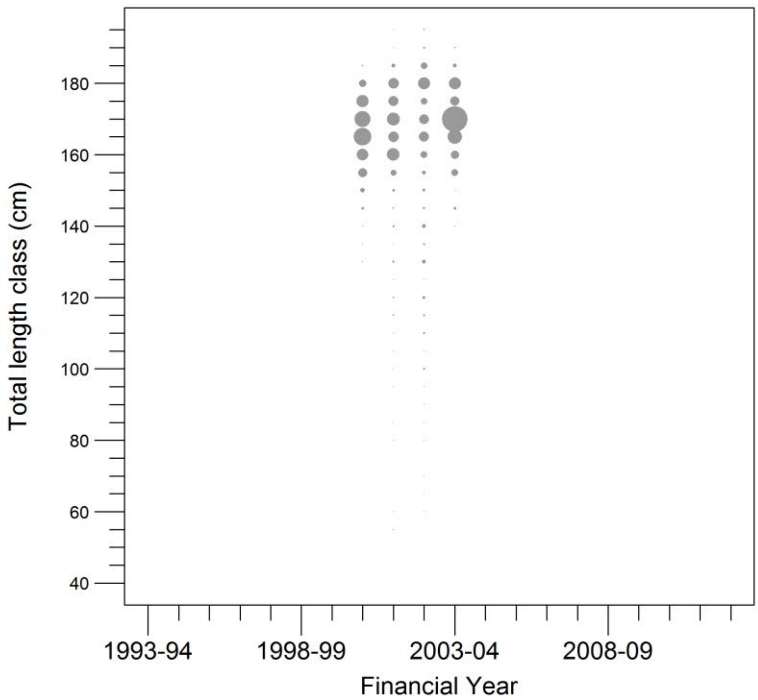


Figure 28. Observed sandbar shark (sexes combined) size composition (as an annual proportion) from the Northern Shark Fisheries

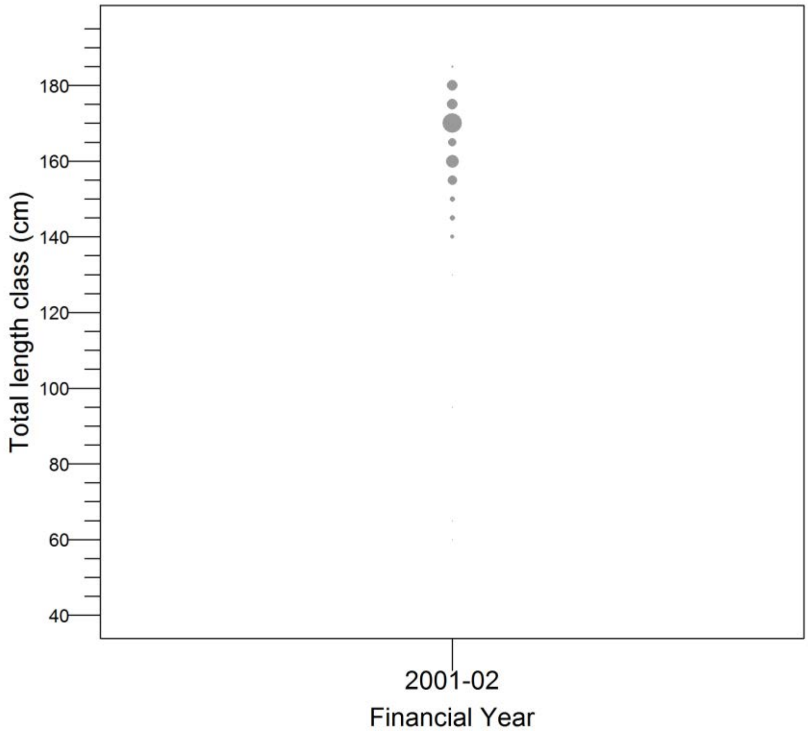


Figure 29. Observed sandbar shark (sexes combined) size composition (as an annual proportion) from the Pilbara trawl fishery

Table 12. Annual number of observations used to derive the size composition of dusky sharks in the Temperate Demersal Gillnet and Demersal Longline Fisheries (TDGDLF) and the Northern Shark Fisheries (NSF)

Fishery	93-94	94-95	95-96	96-97	97-98	98-99	00-01	01-02	02-03	03-04	04-05	05-06	06-07	12-13
TDGDLF														
WC	177	1522	799	959	563	78	324	253	228		86			
Zone1	2320	1580	2862	2023	1524	2468		150	240		229	1050	548	1005
Zone2	23	573	367	678	581	240								
NSF							8	8	25	11				
Total	2520	3675	4028	3660	2668	2786	332	411	493	11	315	1050	548	1005

Table 13. Annual number of shots sampled to derive the size composition of dusky sharks in the Temperate Demersal Gillnet and Demersal Longline Fisheries (TDGDLF) and the Northern Shark Fisheries (NSF)

Fishery	93-94	94-95	95-96	96-97	97-98	98-99	00-01	01-02	02-03	03-04	04-05	05-06	06-07	12-13
TDGDLF														
WC	13	81	157	82	58	17	108	104	89		19			
Zone1	126	92	99	77	78	59		11	17		15	40	45	64
Zone2	13	91	82	47	60	59								
NSF							7	6	6	4				
Total	152	264	338	206	196	135	115	121	112	4	34	40	45	64

Table 14. Annual number of observations used to derive the size composition of sandbar sharks in the Temperate Demersal Gillnet and Demersal Longline Fisheries (TDGDLF) and the Northern Shark Fisheries (NSF)

Fishery	93-94	94-95	95-96	96-97	97-98	98-99	00-01	01-02	02-03	03-04	04-05	06-07	12-13
TDGDLF													
WC		509	588	545	291	52	1326	1295	1353		52		
Zone1	28		331	420	249	113		312	208			282	73
Zone2			341		20	139							
NSF							348	498	381	162			
Total	28	509	1260	965	560	304	1674	2105	1942	162	52	282	73

Table 15. Annual number of shots sampled to derive the size composition of sandbar sharks in the Temperate Demersal Gillnet and Demersal Longline Fisheries (TDGDLF) and the Northern Shark Fisheries (NSF)

Fishery	93-94	94-95	95-96	96-97	97-98	98-99	00-01	01-02	02-03	03-04	04-05	06-07	12-13
TDGDLF													
WC		20	96	56	35	20	126	131	152		11		
Zone1	14		40	25	25	18		16	22			10	18
Zone2			15		10	31							
NSF							26	33	10	19			
Total	14	20	151	81	70	69	152	180	184	19	11	10	18

For dusky sharks, given that 16.5cm and 17.8cm mesh gillnets select predominately 0+ to 2 year old sharks, the annual proportion of sharks <= 82.5 cm FL (the mid-point between the minimum and maximum sizes of neonate sharks reported by Simpfendorfer (2000), was used as an indicator of the annual proportion of neonate sharks. For standardisation purposes, analyses were done using blocks with at least five observations per year with data. Also, only blocks with at least five years of data were selected. Results are presented by spatial block, rather than by grouping blocks within a year (Figure 30).

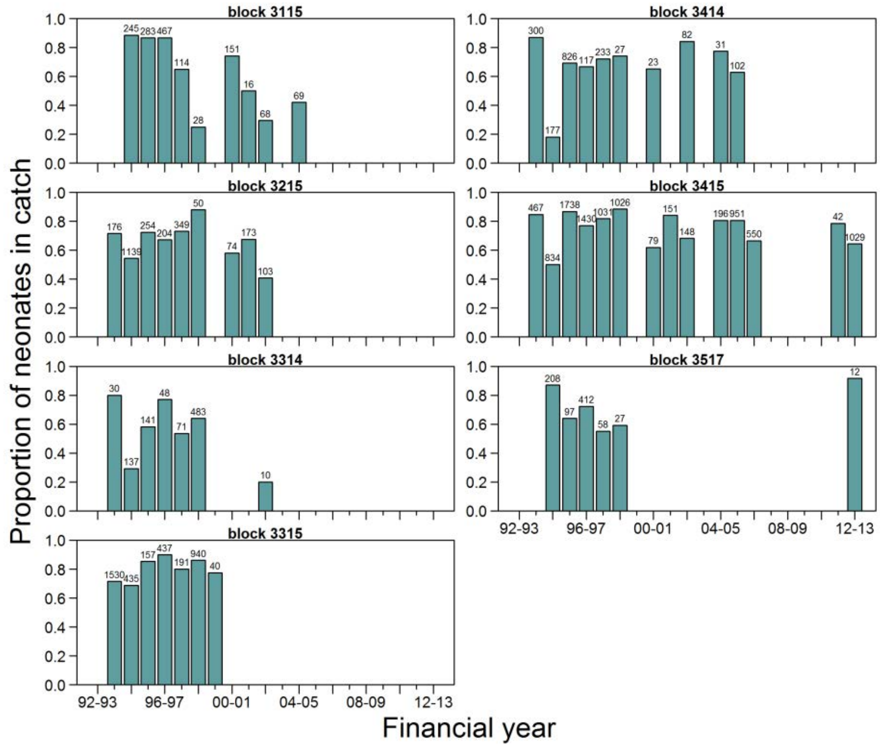


Figure 30. Annual proportion of dusky sharks <= 82.5 cm Fork Length in the observed catch of selected spatial blocks. The total number of sharks observed is shown on top of each bar

3.4.5.4 Average weights from logbook catch records

Time-series data on the average catch weight in the TDGDLF were also available for dusky (Figure 31) and sandbar (Figure 32) sharks.

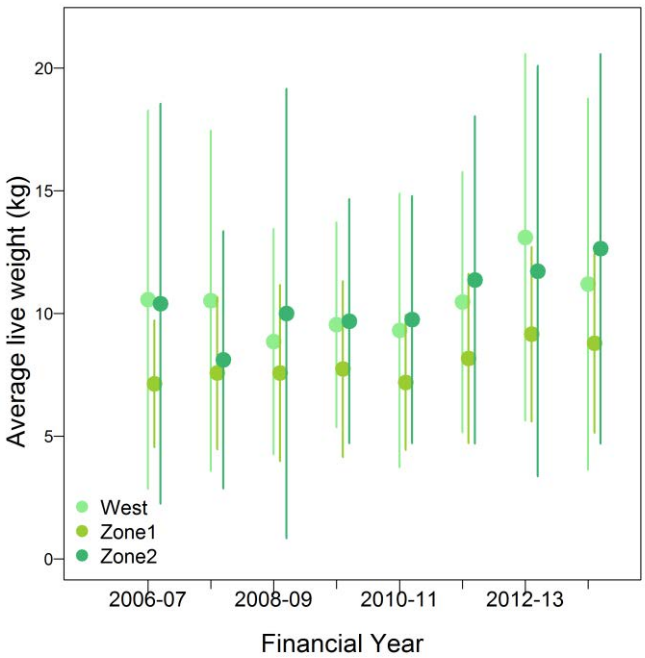


Figure 31. Dusky shark average weight (± Standard Deviation) calculated from the Temperate Demersal Gillnet and Demersal Longline Fisheries logbooks

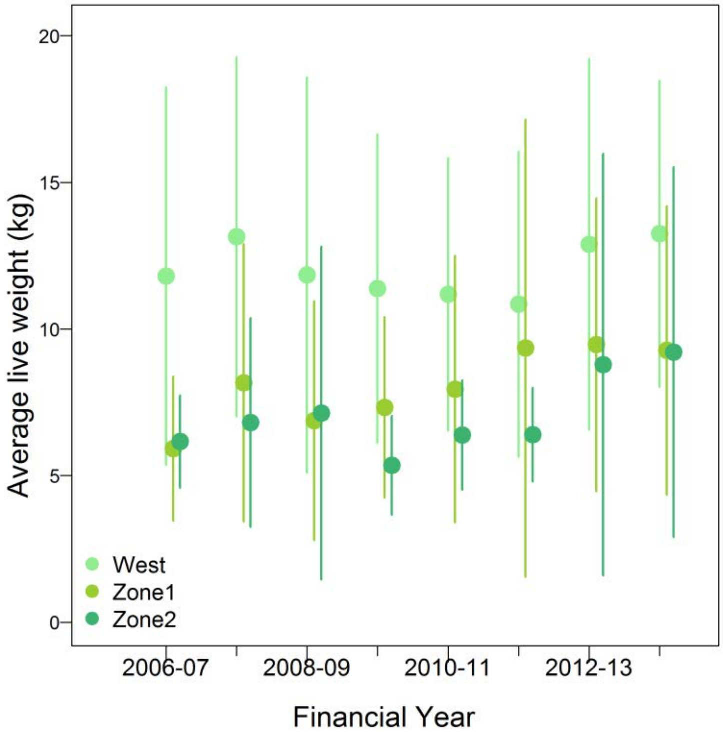


Figure 32. Sandbar shark average weight (±Standard Deviation) calculated from the Temperate Demersal Gillnet and Demersal Longline Fisheries logbooks

3.4.5.5 Acoustic tagging

The proportion of time spent by each tagged shark in each of WA's fishing management zones calculated in *3.1.2.5 Proportion of time per area* was used to assess the exposure of dusky and sandbar sharks to fishing pressure.

3.4.5.6 Conventional tagging

Extensive conventional tagging of dusky (Figure 33 and Figure 34) and sandbar (Figure 35 and Figure 36) sharks occurred as part of FRDC projects 93/067 (Simpfendorfer et al. 1996) and 2000/134 (McAuley et al. 2005) and through annual fishery-independent research surveys since 2000.

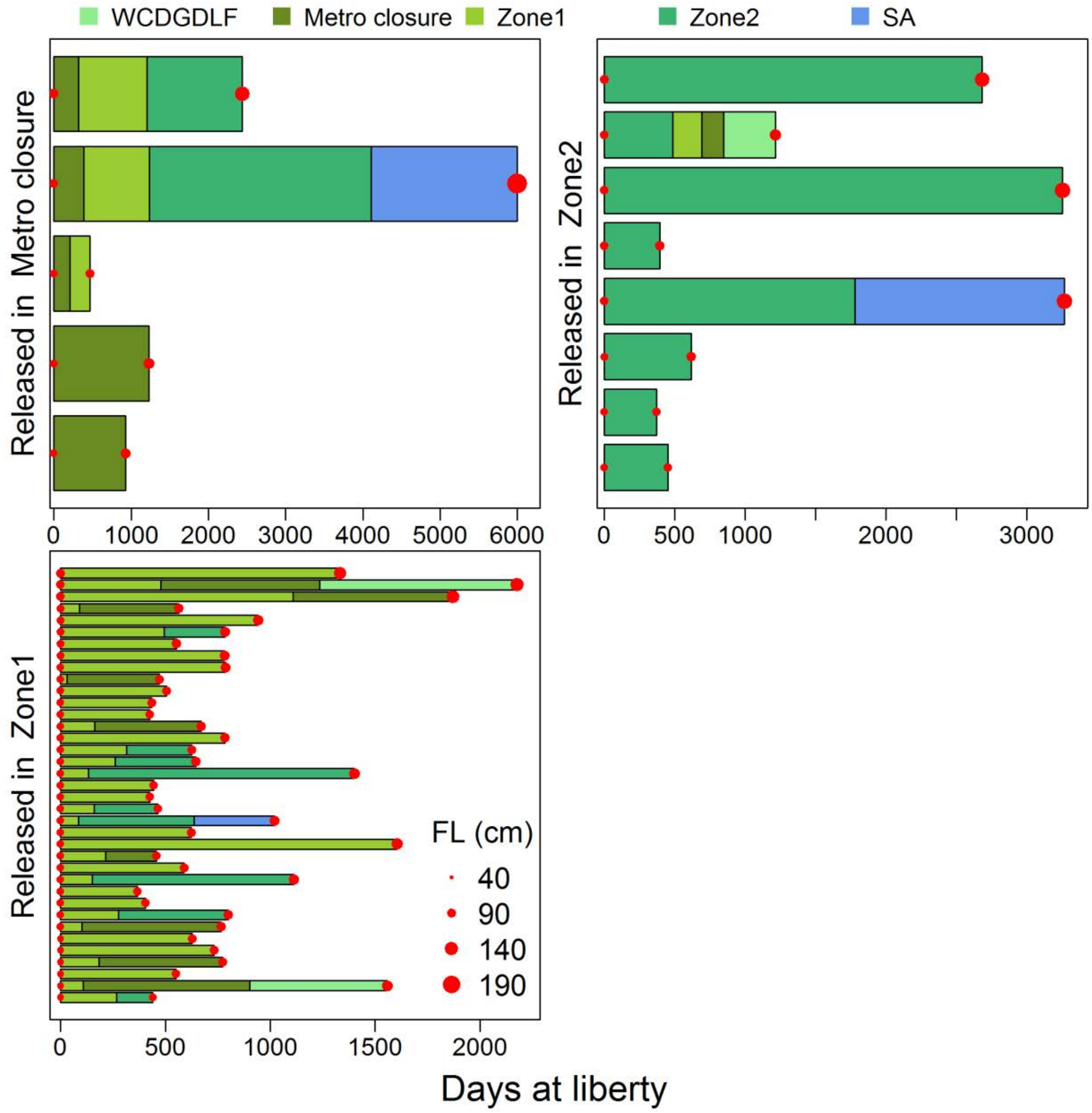


Figure 33. Proportion of time at liberty per management zone for recaptured female dusky sharks released in different management zones. Bars represent the proportional time (interpolated) each recaptured individual spent per management zone. Red dots denote size at release and recapture. Individuals are sorted in descending order by their size at release. A reference key with four arbitrary Fork Length (FL) sizes is provide in the bottom left panel for comparative purposes only. WCDGDLF: West Coast Demersal Gillnet and Demersal Longline (Interim) Managed Fishery; Zone 1: Zone 1 of the Joint Authority Southern Demersal Gillnet and Demersal Longline Managed Fishery; Zone 2: Zone 2 of the Joint Authority Southern Demersal Gillnet and Demersal Longline Managed Fishery; SA: South Australia

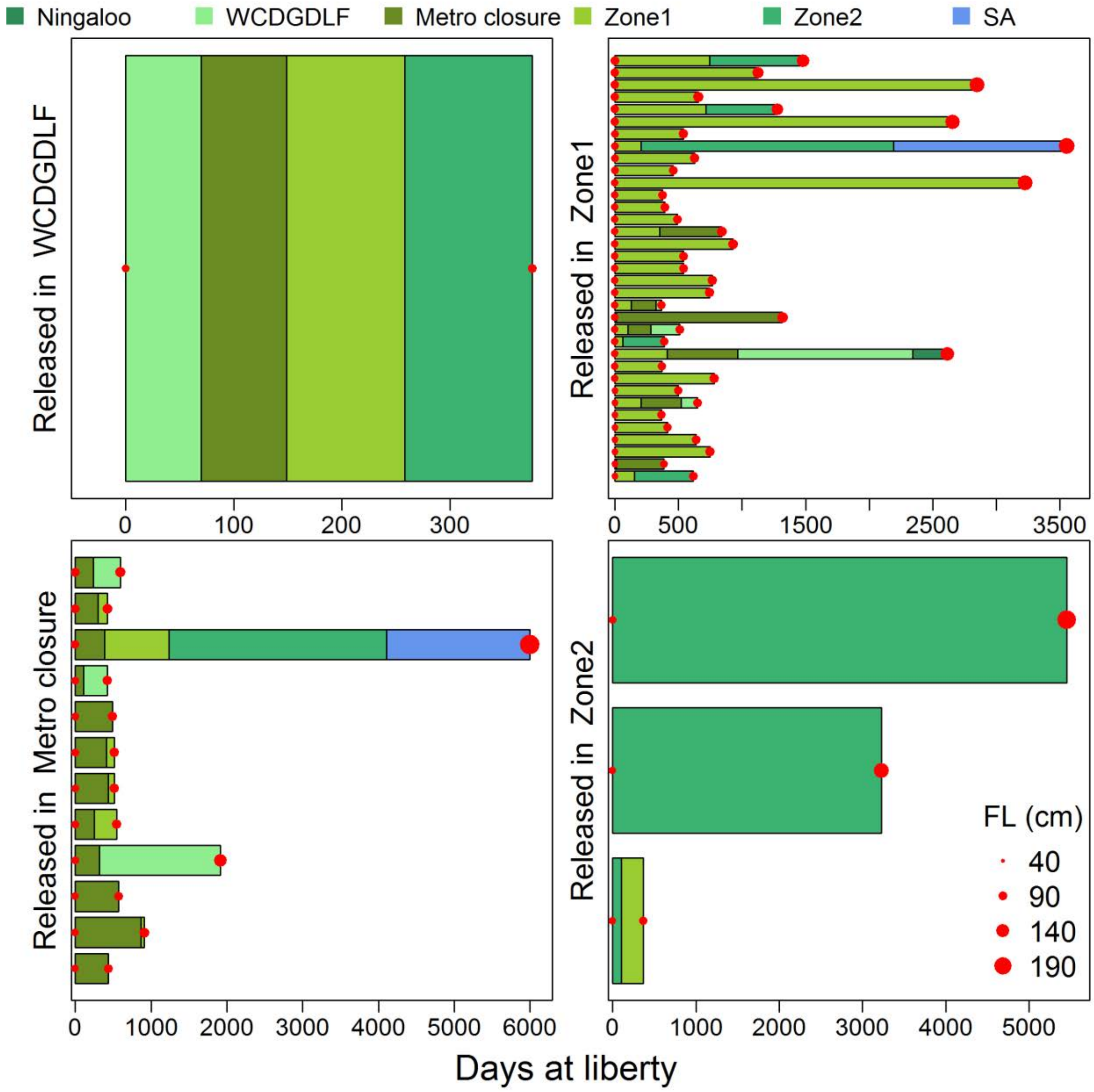


Figure 34. Proportion of time at liberty per management zone for recaptured male dusky sharks released in different management zones. Bars represent the proportional time (interpolated) each recaptured individual spent per management zone. Red dots denote size at release and recapture. Individuals are sorted in descending order by their size at release. A reference key with four arbitrary Fork Length (FL) sizes is provide in the bottom right panel for comparative purposes only. Ningaloo: Ningaloo closure; WCDGDLF: West Coast Demersal Gillnet and Demersal Longline (Interim) Managed Fishery; Zone 1: Zone 1 of the Joint Authority Southern Demersal Gillnet and Demersal Longline Managed Fishery; Zone 2: Zone 2 of the Joint Authority Southern Demersal Gillnet and Demersal Longline Managed Fishery; SA: South Australia

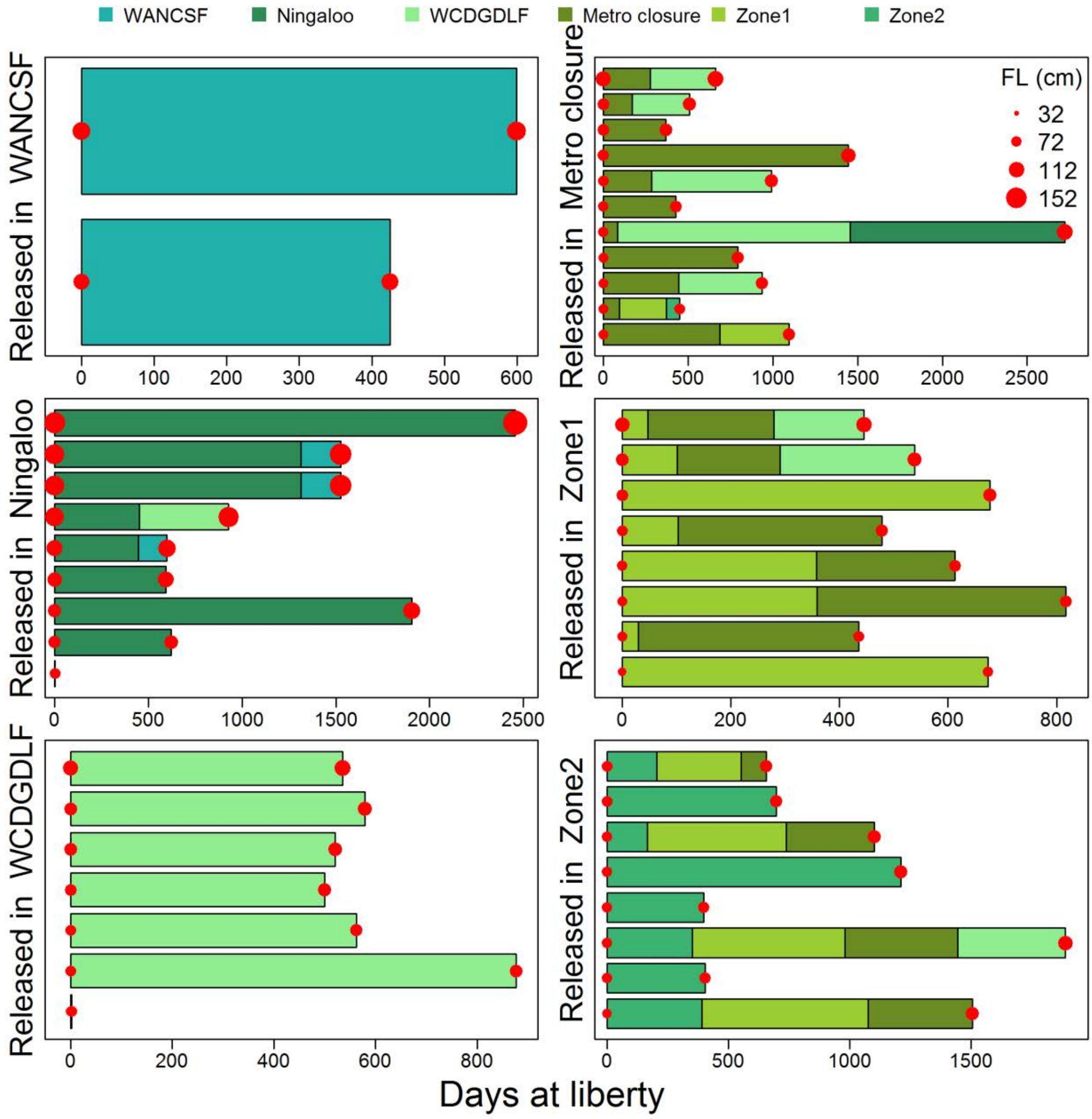


Figure 35. Proportion of time at liberty per management zone for recaptured female sandbar sharks released in different management zones. Bars represent the proportional time (interpolated) each recaptured individual spent per management zone. Red dots denote size at release and recapture. Individuals are sorted in descending order by their size at release. A reference key with four arbitrary Fork Length (FL) sizes is provide in the top right panel for comparative purposes only. WANCSF: Western Australia North Coast Shark Fishery; Ningaloo: Ningaloo closure; WCDGDLF: West Coast Demersal Gillnet and Demersal Longline (Interim) Managed Fishery; Zone 1: Zone 1 of the Joint Authority Southern Demersal Gillnet and Demersal Longline Managed Fishery; Zone 2: Zone 2 of the Joint Authority Southern Demersal Gillnet and Demersal Longline Managed Fishery

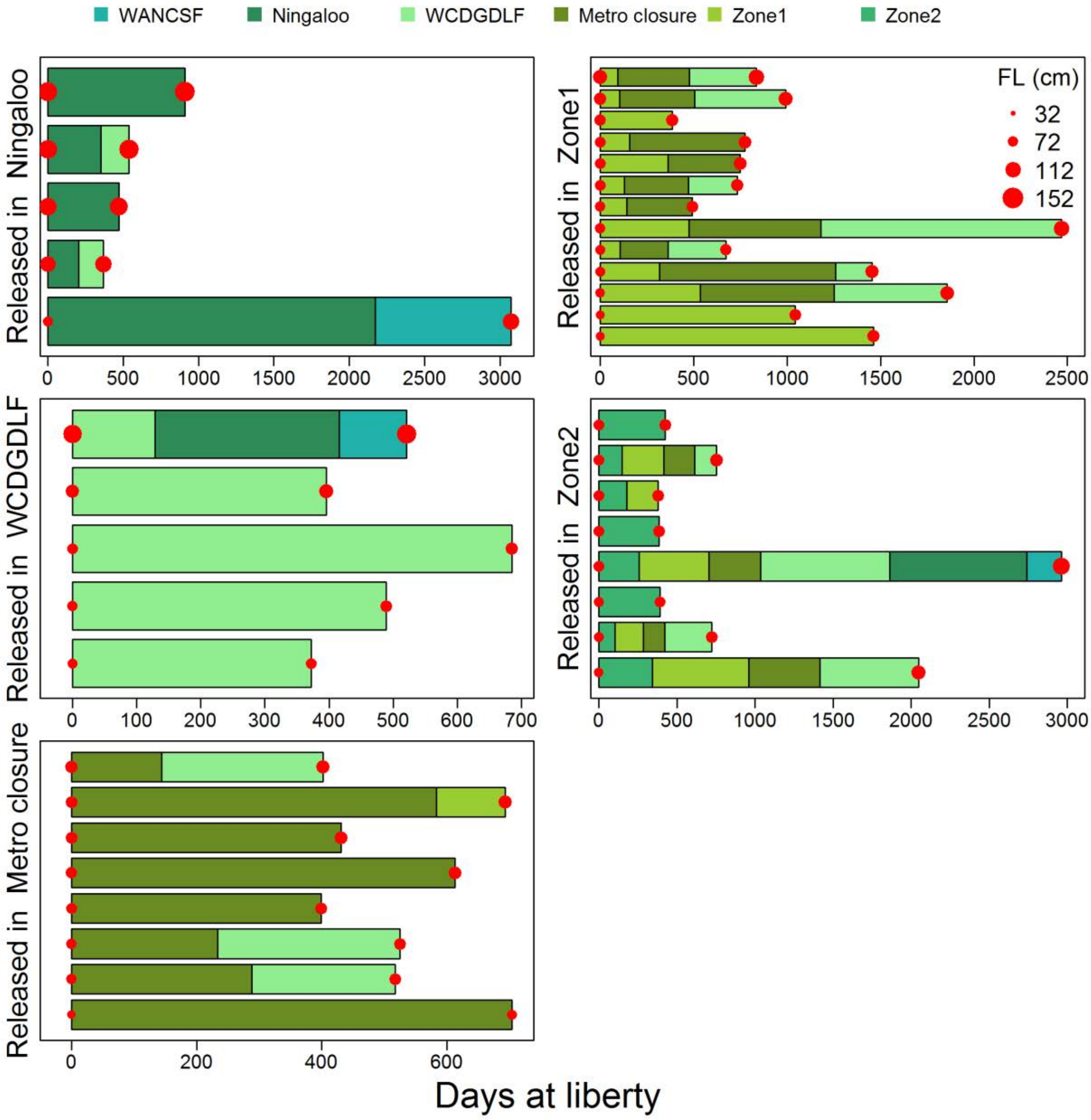


Figure 36. Proportion of time at liberty per management zone for recaptured male sandbar sharks released in different management zones. Bars represent the proportional time (interpolated) each recaptured individual spent per management zone. Red dots denote size at release and recapture. Individuals are sorted in descending order by their size at release. A reference key with four arbitrary Fork Length (FL) sizes is provide in the top right panel for comparative purposes only. WANCSF: Western Australia North Coast Shark Fishery; Ningaloo: Ningaloo closure; WCDGDLF: West Coast Demersal Gillnet and Demersal Longline (Interim) Managed Fishery; Zone 1: Zone 1 of the Joint Authority Southern Demersal Gillnet and Demersal Longline Managed Fishery; Zone 2: Zone 2 of the Joint Authority Southern Demersal Gillnet and Demersal Longline Managed Fishery

4. Results

4.1 Acoustic tagging

A summary of the characteristics of the tagged and detected individuals is shown in Table 16. A total of 103 dusky, 101 sandbar, 100 gummy, and 40 whiskery sharks were implanted with acoustic transmitters. The size frequency distributions of the tagged sharks are shown in Figure 37. For all four species, tagged individuals were close to or above the size at 50% maturity. For all species, the sex ratio was biased towards females. Of the tagged sharks, 60 dusky, 55 sandbar, 33 gummy and 13 whiskery sharks have been detected. In addition, 53 bronze whaler sharks were implanted with acoustic transmitters and 46 individuals have been detected (Table 16). For this species, the sex ratio was also biased towards females.

The mean number of days between release and first detection was lower for bronze whaler and dusky sharks than for the other species. On average, sandbar and dusky sharks were monitored for longer periods than bronze whaler, gummy and whiskery sharks (Table 16). Bronze whaler and sandbar sharks had the largest number of detections, mostly in the Perth and Ningaloo arrays, respectively, followed by dusky sharks, which showed a more even number of detections in the three arrays. Gummy and whiskery sharks had considerably less detections, and were, unsurprisingly, not detected in the Ningaloo array. Finally, bronze whaler and dusky sharks were detected by the largest number of receivers, followed by gummy, sandbar and whiskery sharks (Table 16).

Table 16. Data summary for all individuals tagged in Western Australia and for individuals tagged in South Australia and detected in Western Australia

Variable	Dusky	Sandbar	Gummy	Whiskery	Bronze whaler
Tagged					
N° of individuals	103	101	100	40	53
Mean FL (SD)	242(32)	141(8)	102(10)	112(9)	222(18)
Sex ratio (male:female)	1:1.8	1:1.8	1:3.2	1:2.3	1:2.8
Detected					
Total N° individuals	60	55	33	13	46
Mean FL (SD)	241(34)	142(9)	103(10)	110(8)	222(18)
N° ind. detected in the Ningaloo array	39	55	0	0	2
N° ind. detected in the Perth array	32	2	5	0	41
N° ind. detected in the Southern Lines array	37	1	32	13	40
Sex ratio (male:female)	1:1.8	1:2.6	1:7.2	1:2.2	1:4.1
N° days between release and first detection					
Mean (SD)	89(124)	148(216)	158(150)	228(302)	15(45)
Max	623	1020	611	952	193
Min	0	0	0	1	0

Variable	Dusky	Sandbar	Gummy	Whiskery	Bronze whaler
N° days monitored					
Mean (SD)	668(382)	730(439)	377(312)	293(356)	475(318)
Max	1453	1325	1087	1062	1016
Min	1	1	9	1	1
N° days between first and last detection					
Mean (SD)	580(364)	581(484)	220(264)	65(127)	460(329)
Max	1331	1259	952	453	1016
Min	1	1	1	1	1
Total N° detections	11821	121154	2509	492	150062
N° detections in the Ningaloo array	7318	121095	0	0	18
N° detections in the Perth array	1167	6	45	0	149280
N° detections in the Southern Lines array	3336	53	2464	492	764
Total N° receivers detecting individuals	205	60	107	35	215

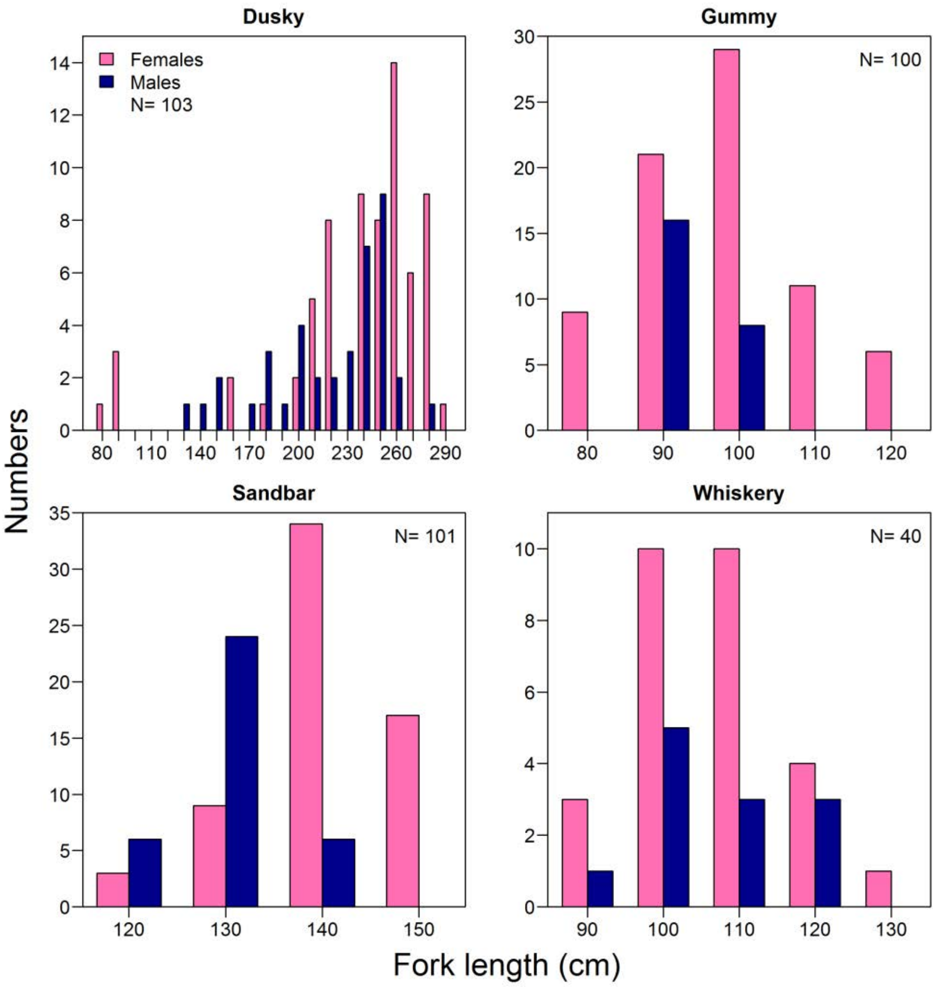


Figure 37. Size frequency distribution of tagged individuals

For the four intended study species, the proportion of detections per array is shown in Figure 38. Most detected dusky sharks were detected in all three arrays. Sandbar sharks were detected in all three arrays but predominately in Ningaloo. Most gummy sharks were detected in the Southern Lines array, although five individuals were also detected in the Perth array. Whiskery sharks were only detected in the Southern Lines array.

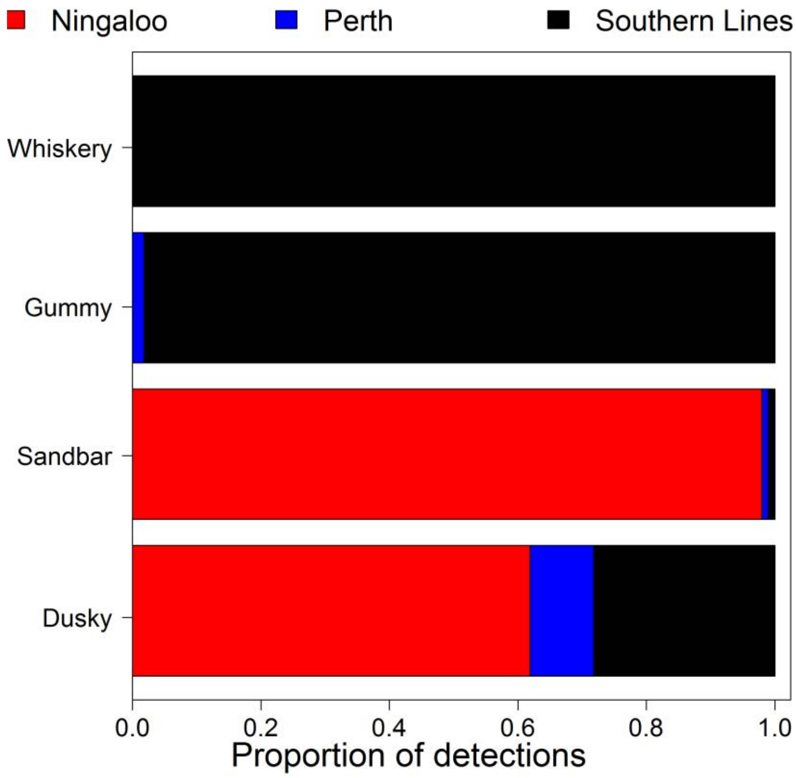


Figure 38. Proportion of detections per array. Barplot showing the proportion of detections (all individuals of the same species combined) by array for each species

The number of individuals detected in more than one array is shown in Table 17. For dusky sharks, 13 individuals were detected in the three arrays and a considerable number of individuals were detected in two arrays. For sandbar sharks, only one individual was detected in the three arrays and only one or two individuals were detected in two arrays. For gummy sharks, four individuals were detected in the Perth and Southern Lines arrays. No whiskery sharks were detected in more than one array.

Table 17. Number of individuals detected in more than one array

	Ningaloo & Perth & Southern Lines	Ningaloo & Perth	Ningaloo & Southern Lines	Perth & Southern Lines
Dusky shark	13	16	16	29
Sandbar shark	1	2	1	1
Gummy shark	0	0	0	4
Whiskery shark	0	0	0	0

There were no significant differences in the size distribution, sex ratio and release condition of tagged and detected individuals (Table 18). For sandbar sharks, all tagged individuals had a release condition of 1 so no test was performed.

Table 18. Statistical comparison between the size at release (Kolmogorov-Smirnov test), sex ratio and release condition (Pearson's Chi-squared Test) of tagged and detected individuals

	Size comparison *p* value	Sex ratio comparison *p* value	Release condition comparison *p* value
Dusky shark	0.99	0.88	0.12
Sandbar shark	0.99	0.38	—
Gummy shark	0.82	0.23	0.93
Whiskery shark	0.99	0.99	0.46

Of the acoustically tagged individuals, one dusky, one bronze whaler, one sandbar, 32 gummy and 9 whiskery sharks were recaptured by commercial and recreational fishers and reported (Table 19).

Table 19. Release and recapture information on recaptured sharks as of December 2015

Species	Sex	Date		Release		Recapture	
		Release	Recapture	Latitude	Longitude	Latitude	Longitude
Dusky shark	M	2011-06-28	2011-10-13	-22.40	113.70	-14.10	123.55
Bronze whaler shark	M	2013-06-15	2014-03-03	-35.05	118.03	-35.10	115.97
Gummy shark	F	2013-05-28	2013-12-16	-34.39	115.34	-34.44	121.13
Gummy shark	F	2012-12-07	2013-02-24	-34.33	115.22	-34.53	115.36
Gummy shark	F	2012-07-07	2013-06-20	-34.79	118.45	-34.92	118.42
Gummy shark	F	2013-04-14	2015-07-01	-34.50	115.43	NA	NA
Gummy shark	F	2013-04-14	2013-05-06	-34.49	115.40	-34.43	115.50
Gummy shark	F	2013-04-14	2013-04-29	-34.49	115.40	-34.64	115.65
Gummy shark	F	2013-04-15	2013-04-24	-34.34	115.36	-34.33	115.36
Gummy shark	M	2013-04-15	2014-01-17	-34.35	115.38	-34.42	115.27
Gummy shark	F	2012-07-06	2014-02-07	-34.78	118.82	-34.50	120.25
Gummy shark	M	2012-07-04	2013-10-07	-34.74	118.94	-32.54	125.87
Gummy shark	M	2012-07-04	2013-04-02	-34.74	118.94	-34.68	118.92
Gummy shark	F	2012-07-01	2013-06-01	-34.54	118.93	-34.98	118.77
Gummy shark	F	2012-07-01	2012-11-17	-34.57	118.97	-34.76	119.36
Gummy shark	M	2012-07-01	2014-11-15	-34.54	118.93	-34.80	119.03
Gummy shark	F	2012-07-01	2014-05-04	-34.57	118.97	-34.81	118.44
Gummy shark	F	2012-07-01	2013-03-10	-34.57	118.97	-34.72	119.06

Species	Sex	Date		Release		Recapture	
		Release	Recapture	Latitude	Longitude	Latitude	Longitude
Gummy shark	F	2012-07-01	2014-08-28	-34.57	118.97	-34.28	121.08
Gummy shark	F	2012-07-01	2014-07-14	-34.57	118.97	-34.04	123.38
Gummy shark	F	2012-07-01	2013-10-12	-34.57	119.05	-33.47	115.11
Gummy shark	F	2012-07-01	2013-04-03	-34.57	119.05	-34.59	119.12
Gummy shark	F	2013-05-28	2013-12-16	-34.39	115.34	-34.41	121.11
Gummy shark	F	2013-05-15	2014-01-22	-34.57	115.62	-33.18	125.97
Gummy shark	F	2013-05-15	2014-09-24	-34.56	115.62	-34.49	115.80
Gummy shark	F	2012-07-01	2013-06-01	-34.57	118.97	-35.00	119.00
Gummy shark	F	2012-07-01	2012-08-21	-34.57	119.01	-34.55	119.07
Gummy shark	F	2012-07-01	2013-03-22	-34.57	119.01	-34.69	118.78
Gummy shark	F	2012-07-01	2015-06-07	-34.57	119.01	-34.65	118.82
Gummy shark	F	2012-05-30	2013-11-21	-34.32	115.22	-34.58	115.40
Gummy shark	F	2012-07-01	2013-04-30	-34.57	119.01	-34.48	118.98
Gummy shark	F	2012-07-01	2012-12-01	-34.57	119.01	-35.00	119.00
Gummy shark	F	2012-07-01	2013-03-18	-34.57	119.01	-34.91	118.62
Sandbar shark	F	2012-05-26	2015-04-27	-23.04	113.70	-19.78	116.03
Whiskery shark	F	2013-05-16	2014-02-01	-34.70	115.65	-35.00	119.00
Whiskery shark	F	2012-11-23	2014-02-01	-34.61	115.28	-34.62	115.43
Whiskery shark	F	2012-11-17	2013-06-01	-34.30	115.01	-35.00	119.00
Whiskery shark	F	2012-07-05	2014-11-15	-34.79	118.51	-34.80	119.03
Whiskery shark	F	2013-05-16	2013-10-17	-34.68	115.67	-34.70	115.64
Whiskery shark	F	2013-05-15	2014-09-17	-34.64	115.69	-34.52	115.15
Whiskery shark	M	2012-07-01	2013-06-01	-34.57	118.97	-34.53	118.81
Whiskery shark	F	2012-07-01	2013-06-01	-34.57	119.01	-35.00	119.00
Whiskery shark	F	2012-07-02	2013-03-31	-34.61	118.99	-34.63	118.96

NA: No recapture location provided

4.1.1 Residency

Detected sharks were labelled by combining the common name initials (e.g. DS for dusky shark) and chronological order of tagging. For dusky sharks, individuals were only detected briefly within arrays during the monitored period, reflecting the high mobility of this species (Figure 39). For sandbar sharks, the proportion of time detected was also generally low but several individuals that were monitored for a substantial period of time were detected regularly (Figure 39). For gummy and whiskery sharks, most detected individuals were detected for a small proportion of the monitored time (Figure 40).

The Ningaloo array recorded by far the highest number of detections. Hence, a detailed summary of the number of detections by month is presented for each shark detected in this array (Table 20). Very few dusky sharks were detected in most months. In contrast, several sandbar sharks were detected in most months with nine individuals (most of them above L_{50}) being detected in all months.

Presence/absence timeline-plots show the residency patterns within the detection arrays and the movements between regions. Dusky sharks were detected within the three arrays with most individuals being detected within at least two arrays (Figure 41). In general, dusky sharks were not detected within the arrays for very long periods and showed very complex movement patterns. Also, most sharks showed a considerable period of time between detections in different arrays. In addition, 55 individuals (382 trajectories) undertook long-scale movements (>100 km), of up to 2,098 km at ROMs of up to 107 km per day (Table 21). (NB, trajectories were calculated over straight-line distances so the reported distances and ROMs are minimum averages.)

Male dusky sharks tagged in southern WA were mostly detected in the Perth and Southern Lines receivers although DS.26, which corresponds to a male above the size at 50% maturity (L_{50}) was detected in the Perth and Southern Lines arrays, then in the Ningaloo array and then again in the Perth and Southern Lines arrays. Three of the female dusky sharks tagged in southern WA were only detected in the Perth and Southern Lines receivers whereas DS.20 which corresponds to a female above L_{50} was first detected within the Ningaloo array and then within the Perth and Southern Lines arrays (Figure 41).

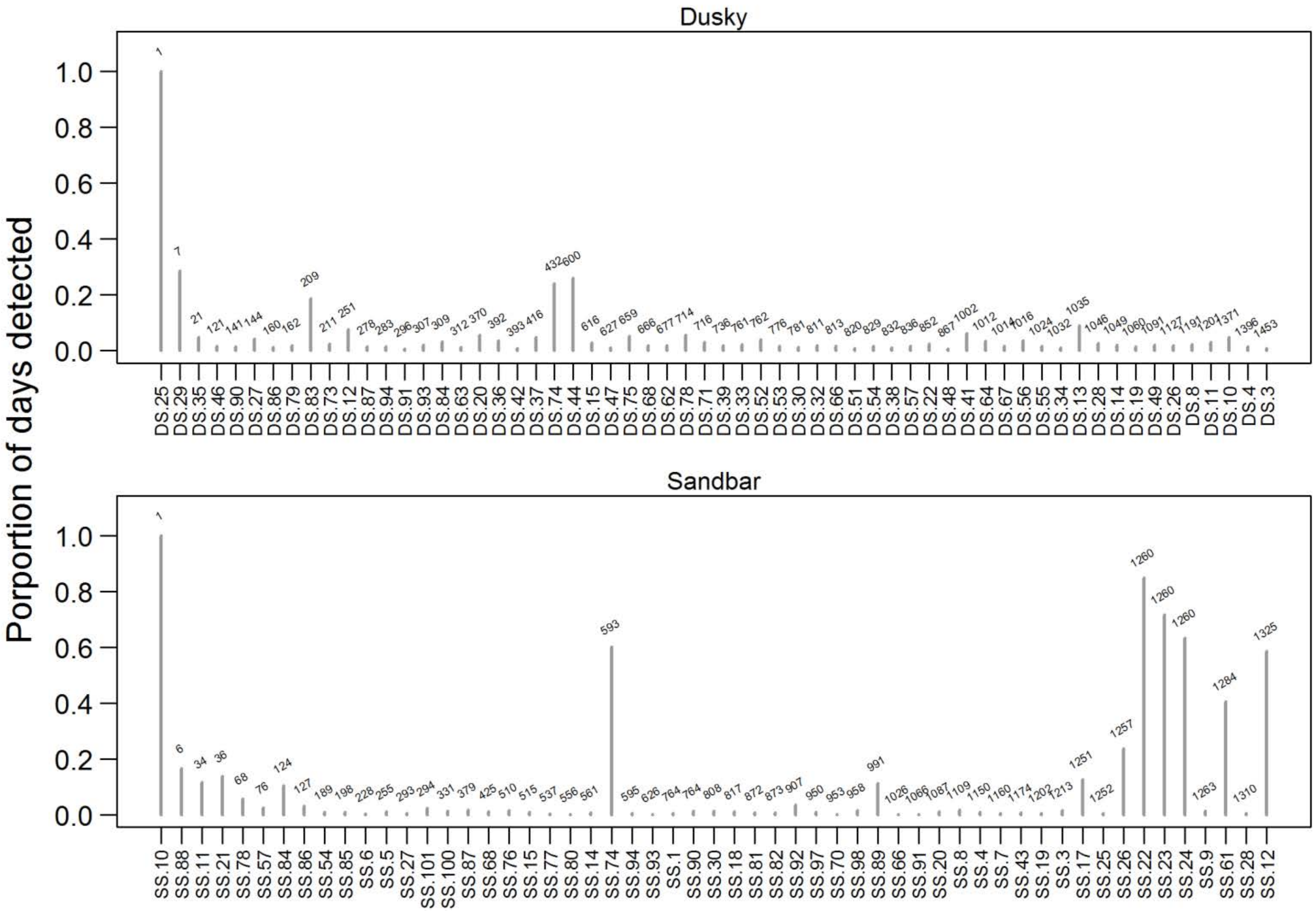


Figure 39. Proportion of time detected for dusky and sandbar sharks. The tag Identification Number (ID) is shown on the X-axis. The bars show the proportion of days detected within the monitored areas (i.e. the number of days between release and the last detection). The total number of days monitored are shown on top of each bar

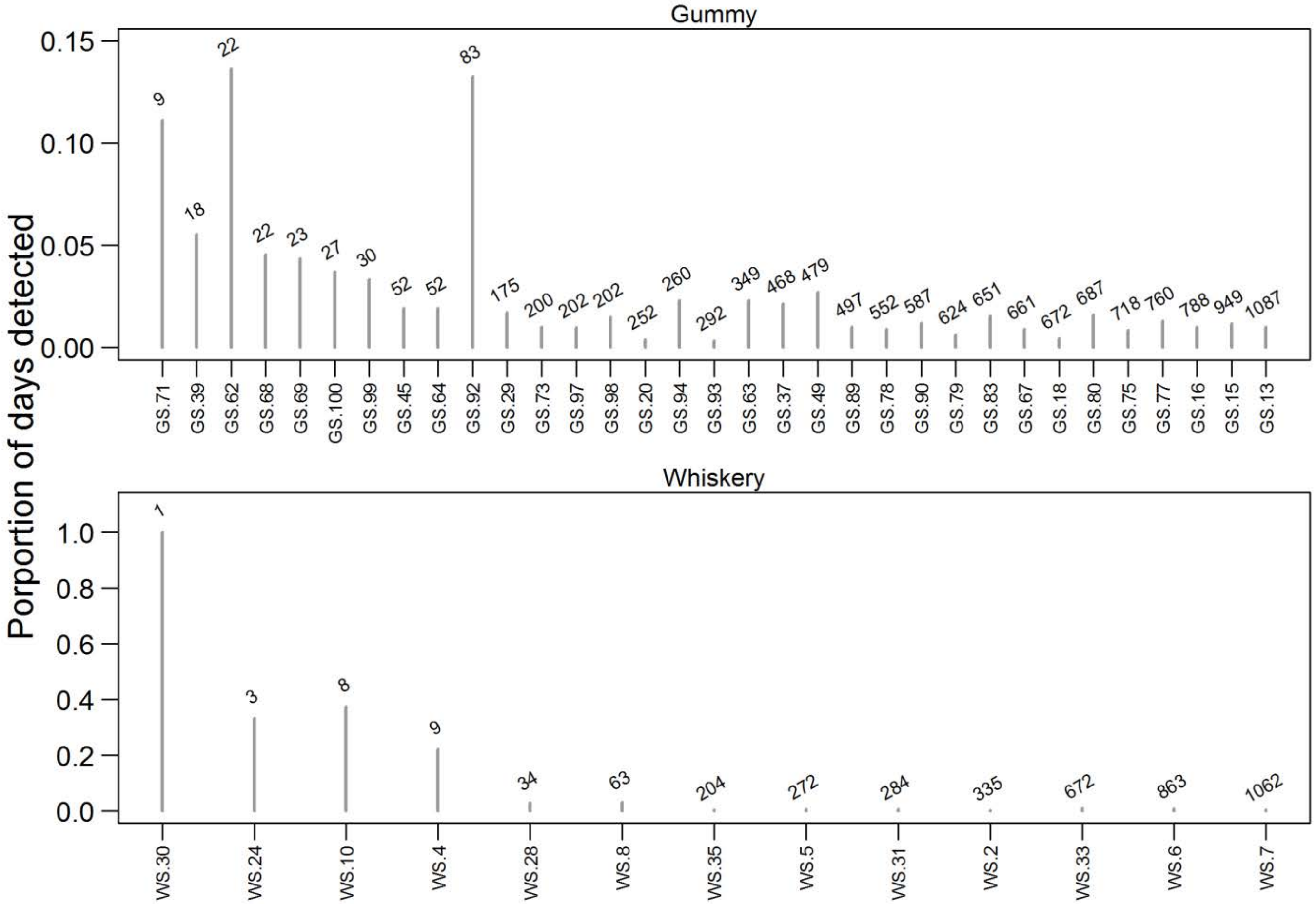


Figure 40. Proportion of time detected for gummy and whiskery sharks. The tag Identification Number (ID) is shown on the X-axis. The bars show the proportion of days detected within the monitored areas (i.e. the number of days between release and the last detection). The total number of days monitored are shown on top of each bar

Table 20. Number of days per month and total number of days detected in the Ningaloo array. Note that years were combined so the maximum number of days per month is ~120 (4 years)

Species	Tag ID	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Dusky	DS.35	0	0	0	0	0	0	0	1	0	0	0	0
	DS.93	0	0	1	0	0	0	0	0	0	0	0	0
	DS.29	0	0	0	0	0	0	0	0	0	2	0	0
	DS.67	2	0	0	0	0	0	0	0	0	0	0	0
	DS.83	0	0	0	2	0	0	0	0	0	0	0	0
	DS.86	0	0	0	0	0	0	0	0	2	0	0	0
	DS.26	0	2	0	0	1	0	0	0	0	0	0	0
	DS.38	0	2	1	0	0	0	0	0	0	0	0	0
	DS.42	0	0	0	0	0	0	0	2	0	1	0	0
	DS.79	0	0	0	2	0	0	0	0	0	0	0	1
	DS.20	0	0	0	0	1	0	0	0	0	3	0	0
	DS.47	2	0	0	0	0	0	0	3	0	0	0	0
	DS.73	2	0	0	0	1	0	0	2	0	0	0	0
	DS.27	3	0	0	3	0	0	0	0	0	0	0	0
	DS.48	2	0	0	3	0	0	0	1	0	0	0	0
	DS.34	2	0	0	0	0	2	0	2	0	0	1	0
	DS.51	3	1	0	0	1	0	0	2	0	0	0	0
	DS.49	6	0	1	0	0	0	0	1	0	0	0	0
	DS.30	3	0	0	0	4	0	0	0	0	3	0	0
	DS.84	0	0	3	5	0	0	0	2	0	0	0	0
	DS.15	3	1	7	0	0	0	0	0	0	0	0	0
	DS.36	0	0	0	4	0	0	0	8	0	0	0	0
	DS.33	2	0	4	0	0	0	0	4	0	3	0	0
	DS.39	0	0	0	0	0	0	1	4	2	5	1	0
	DS.53	4	0	0	0	2	0	0	3	4	0	0	0
	DS.28	7	0	2	1	2	0	0	3	0	0	0	0
	DS.32	0	13	0	0	0	0	0	2	0	0	0	0
	DS.14	10	0	0	0	0	0	0	2	6	0	0	0
	DS.12	0	4	8	5	0	2	0	0	0	0	0	0
	DS.37	9	1	0	0	3	0	0	7	0	0	0	0
	DS.8	2	6	1	3	4	0	2	2	0	0	0	0
	DS.11	4	4	12	2	0	0	0	0	0	0	0	0
	DS.52	7	0	3	4	0	0	0	12	0	0	0	0
	DS.75	0	0	0	0	0	9	9	0	5	2	9	0
	DS.10	6	25	13	3	1	0	0	0	0	0	0	0
	DS.41	13	6	6	15	1	0	0	8	0	2	0	0

Species	Tag ID	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	DS.13	9	11	32	25	0	6	2	7	0	0	0	0
	DS.74	12	12	6	6	7	5	11	18	7	9	5	6
	DS.44	27	2	17	35	20	0	3	16	20	3	1	12
Sandbar	SS.10	0	0	0	1	0	0	0	0	0	0	0	0
	SS.6	0	0	0	0	0	0	1	0	0	0	0	0
	SS.80	0	0	0	0	0	0	0	0	0	0	1	0
	SS.88	0	0	0	1	0	0	0	0	0	0	0	0
	SS.91	0	0	0	1	0	0	0	0	0	0	0	0
	SS.93	0	0	0	0	0	0	1	0	0	0	0	0
	SS.101	0	2	0	0	0	0	0	0	0	0	0	0
	SS.27	0	0	0	0	0	1	0	1	0	0	0	0
	SS.54	0	0	0	0	0	1	1	0	0	0	0	0
	SS.57	0	0	0	0	0	0	0	0	0	2	0	0
	SS.66	2	0	0	0	0	0	0	0	0	0	0	0
	SS.77	0	0	0	0	0	0	0	0	1	0	1	0
	SS.85	0	0	0	0	0	0	0	0	0	0	1	1
	SS.5	3	0	0	0	0	0	0	0	0	0	0	0
	SS.70	0	0	0	0	0	0	0	0	0	0	1	2
	SS.100	0	1	0	0	3	0	0	0	0	0	0	0
	SS.11	0	2	2	0	0	0	0	0	0	0	0	0
	SS.78	0	1	0	3	0	0	0	0	0	0	0	0
	SS.86	0	0	2	0	2	0	0	0	0	0	0	0
	SS.94	0	1	0	1	0	1	0	0	0	0	0	1
	SS.1	2	2	1	0	0	0	0	0	0	0	0	0
	SS.14	0	0	0	3	0	1	0	0	0	0	1	0
	SS.15	0	0	3	0	0	0	0	0	0	0	2	0
	SS.21	0	2	2	1	0	0	0	0	0	0	0	0
	SS.68	0	2	0	3	0	0	0	0	0	0	0	0
	SS.81	1	0	0	1	0	1	0	0	0	2	2	0
	SS.82	0	0	0	0	0	0	0	0	0	5	2	0
	SS.87	3	0	0	1	0	0	0	3	0	0	0	0
	SS.19	1	0	0	1	0	0	1	1	0	4	0	0
	SS.25	0	2	2	0	0	0	0	0	0	2	0	2
	SS.28	0	0	0	0	0	0	1	0	0	0	3	4
	SS.7	0	2	0	0	3	0	0	0	0	3	0	0
	SS.76	0	0	0	0	0	0	0	1	2	2	0	3
	SS.43	0	0	0	2	1	0	0	0	0	5	1	0
	SS.18	0	0	0	1	3	0	1	0	0	2	0	3

Species	Tag ID	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	SS.97	1	1	0	2	0	1	1	4	0	0	0	0
	SS.30	0	0	5	0	5	0	1	0	0	0	0	0
	SS.90	0	0	2	3	0	5	0	0	1	0	0	0
	SS.4	4	0	2	1	0	1	1	4	0	0	0	0
	SS.84	0	1	4	3	5	0	0	0	0	0	0	0
	SS.20	1	2	0	3	0	0	0	2	4	0	2	0
	SS.98	4	2	3	1	0	2	0	1	0	1	1	1
	SS.9	0	3	0	4	0	0	0	0	0	0	5	5
	SS.3	0	3	0	3	0	0	0	0	0	11	2	0
	SS.8	0	4	2	0	5	1	1	0	0	5	0	2
	SS.92	2	2	0	5	2	7	5	3	3	0	2	2
	SS.89	7	3	3	4	6	20	21	7	2	8	18	14
	SS.17	26	8	10	3	7	24	32	5	3	11	9	20
	SS.26	14	22	17	10	10	49	11	25	10	15	52	65
	SS.74	14	56	42	47	35	31	12	21	15	29	27	28
	SS.61	54	0	9	0	32	84	73	12	0	71	93	93
	SS.12	26	20	57	35	102	99	60	14	27	121	109	108
	SS.24	24	88	65	70	64	75	61	34	59	84	91	84
	SS.23	17	111	100	78	90	66	44	54	64	98	100	82
	SS.22	68	97	103	86	118	72	71	73	83	118	103	78

Male dusky sharks tagged in northern WA showed a range of different behaviours. Some individuals (e.g. DS.46, DS.87, DS.68, DS.64) were detected within the Perth and Southern Lines arrays only. Other individuals were only detected within the Ningaloo array (DS.27) or within the Ningaloo and Perth arrays (DS.47). Other individuals (DS.38) were detected in the Perth and Southern Lines arrays and then within the Ningaloo array. The most complex behaviours were shown by DS.11, DS.28 and DS.49. These sharks showed multiple detections between the Ningaloo, Perth and Southern Lines arrays. For example, DS.11 was first detected within the Ningaloo array, then detected within the Southern Lines array about a year after. Then, within a few months, it was detected in the Ningaloo, Perth and Southern Lines arrays. The next detection was about a year after within the Southern Lines and Perth arrays and it was finally detected within the Ningaloo array almost 3.5 years from the initial detection (Figure 41). Female dusky sharks tagged in northern WA showed similarly complex movement patterns. Some females were detected exclusively in the Ningaloo array on few occasions (e.g. DS.79 (a female below L_{50}) and DS.86 (a female above L_{50})) or consistently for long periods of time (e.g. two females above L_{50}: DS.13, detected for 3 years, and DS.44, detected for almost two years). Other individuals were detected within the Ningaloo and Southern Lines arrays, and then back in the Ningaloo array (e.g. DS.8), or within the Ningaloo and Perth arrays, and then back in the Ningaloo array (e.g. DS.36), or within the Ningaloo, Perth and Southern Lines arrays, and then back in the Ningaloo array (e.g. DS.33). Other individuals were detected only in the Perth and Southern Lines arrays (e.g. DS.66). Finally, other females (DS.10, DS.14, DS.41) showed multiple movements between the Ningaloo, Perth and Southern Lines arrays. For example, DS.41 was first detected within the Ningaloo array, then detected within the Southern Lines array about six months from the first detection in Ningaloo. Then, after several months, it was detected in the Ningaloo, Perth and Southern Lines arrays. The next detection was about six months after in the Ningaloo array with the final detection in the Perth array, almost 2.5 years from the initial detection (Figure 41).

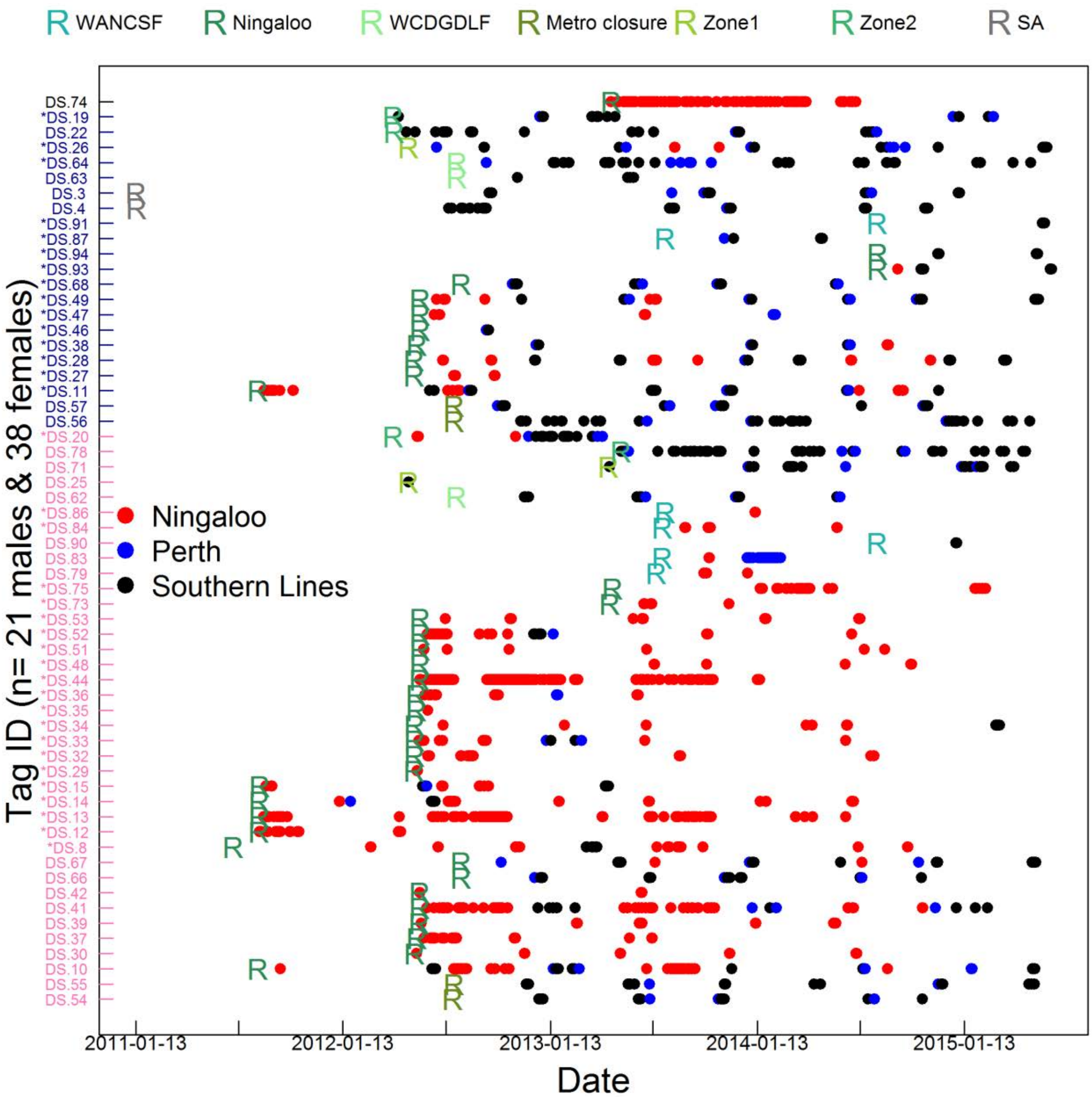


Figure 41. Daily presence/absence of tagged dusky sharks within the three arrays (colour coded). The ‘R’ indicates the management zone where the shark was released. Tag codes are split into males (blue) and females (pink) and ordered by release zone. The * next to the tag Identification Number (ID) indicates sharks with a Fork Length (FL) larger than the FL at 50% maturity. The date axis is labelled in steps of six months starting on the date the first shark was tagged

Table 21. Summary of long-distance (>100km) displacements between consecutive detections in different arrays or between detections and reported recapture

	Dusky	Sandbar	Gummy	Whiskery
Total number of trajectories	382	25	80	8
Total number of sharks	55	18	26	7
Mean distance (km)	409	301	238	241
Maximum distance (km)	2098	1091	969	374
Mean ROM (km/day)	33	14	23	15
Maximum ROM (km/day)	107	63	65	45

For individuals detected in multiple arrays, movements from the Ningaloo array to the Perth or Southern Lines arrays occurred mostly during the warmer months whereas movements from the Perth or Southern Lines arrays to the Ningaloo array occurred mostly during the cooler months (Figure 42).

For sandbar sharks, nearly all detections occurred at the Ningaloo array (Figure 43). However, 18 individuals (25 trajectories) undertook long-scale movements, each trajectory of up to 1,091 km at ROMs of up to 63 km per day (Table 21). Within the Ningaloo array, male and female sandbar sharks showed three different movement patterns: some individuals were detected continually within the Ningaloo array (e.g. SS.22, SS.23, SS.24). Other individuals were detected for long periods of time, interspersed with long periods of non-detection (e.g. SS.17, SS.61, SS.89). Finally, some individuals were only detected for a few days (e.g. SS.80, SS.82, SS.94). Two females above L_{50} were detected within the Ningaloo array and then within the Perth array (SS.100) or within the Perth and Southern Lines arrays (SS.101). These detection patterns occurred between February and April.

For gummy sharks, individuals have been sporadically detected in the Perth and South coast arrays (Figure 44). Twenty-six detected individuals (80 trajectories) undertook long-scale movements, each trajectory of up to 969 km at ROMs of up to 65 km per day (Table 21). Four females were detected travelling between the Southern Lines and Perth arrays (GS.75, GS.77, GS.83, GS.90). These detection patterns occurred throughout the year (Figure 45).

For whiskery sharks, individuals have been sporadically detected solely in the Southern Lines (Figure 46). Seven individuals (8 trajectories) undertook long-scale movements, each trajectory of up to 374 km at ROMs of up to 45 km per day (Table 21).

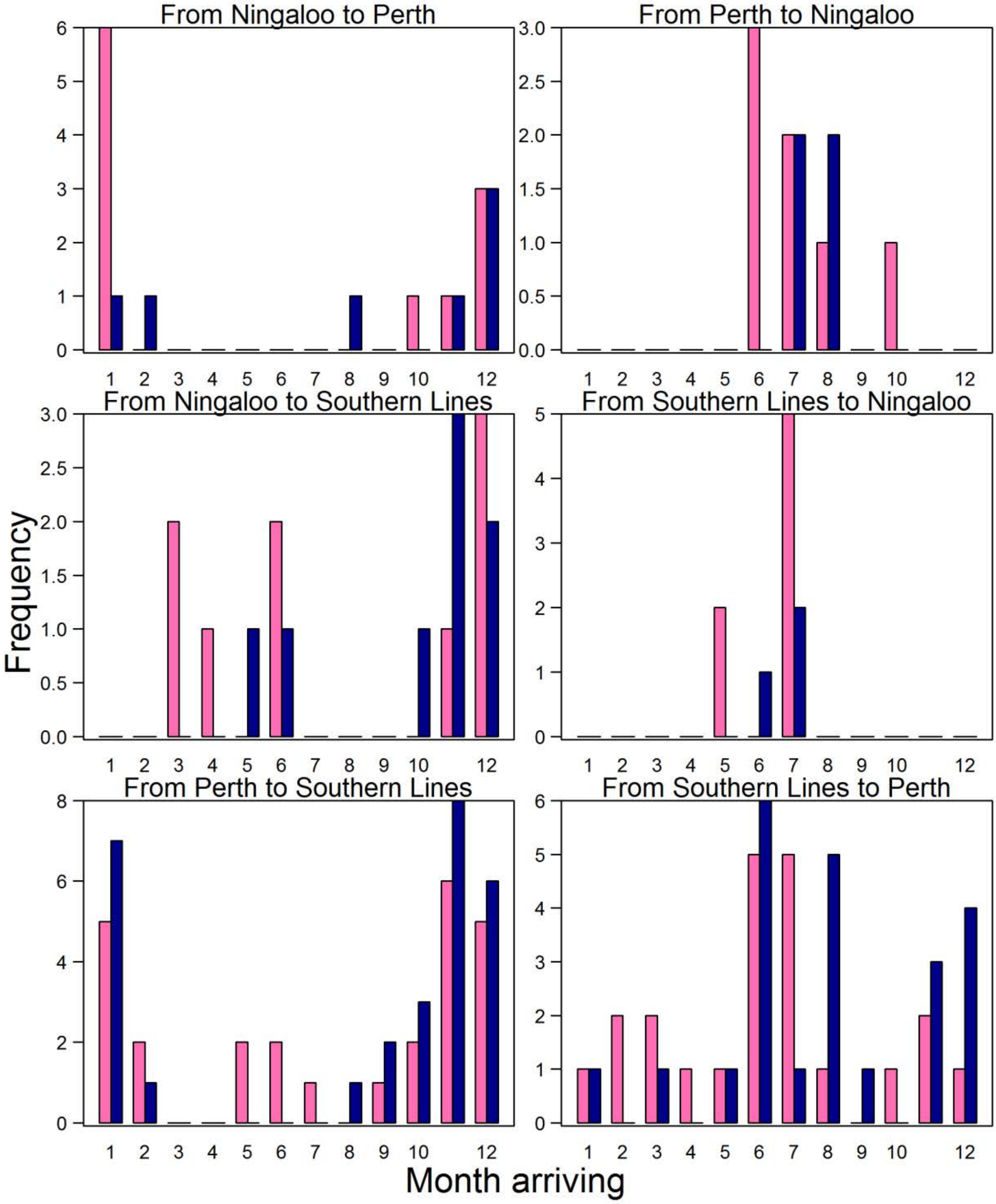


Figure 42. Frequencies of dusky shark displacements between arrays by month and sex (females are shown in pink and males are shown in blue)

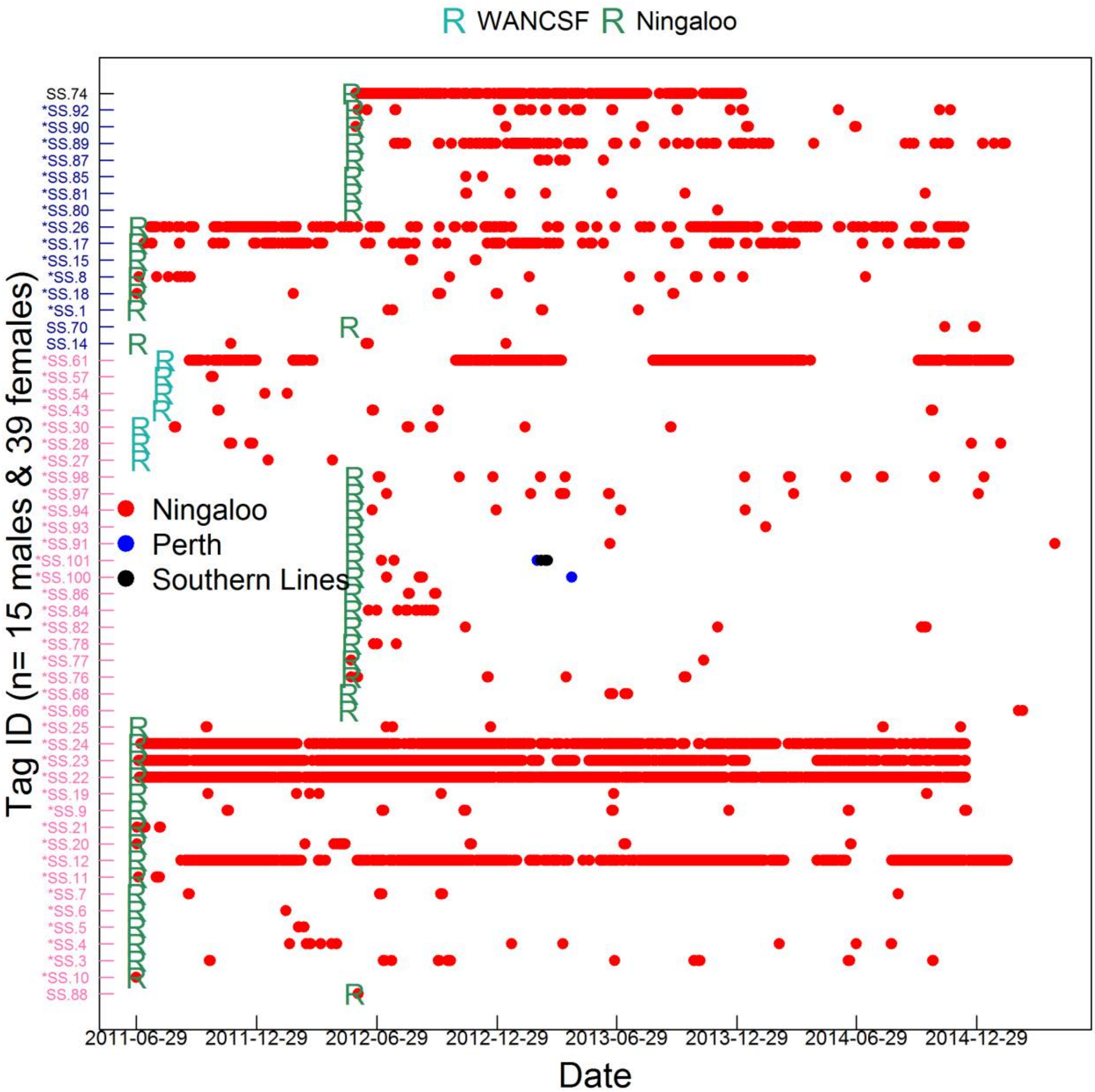


Figure 43. Daily presence /absence of tagged sandbar sharks within the three arrays (colour coded). The 'R' indicates the management zone where the shark was released. Tag codes are split in males (blue) and females (pink) and ordered by release zone. The * next to the tag Identification Number (ID) indicates sharks with a Fork Length (FL) larger than the FL at 50% maturity. The date axis is labelled in steps of six months starting on the date the first shark was tagged

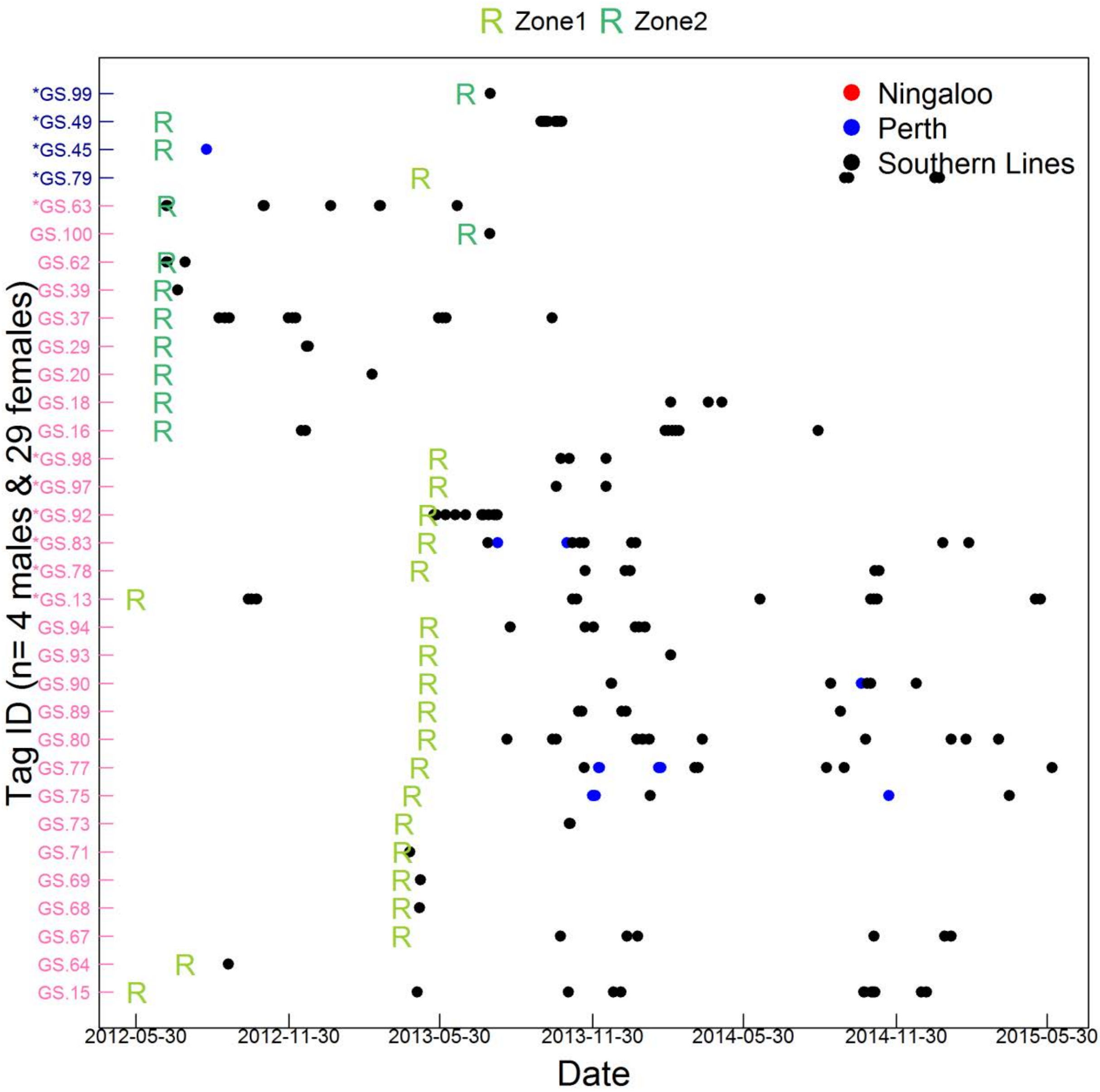


Figure 44. Daily presence /absence of tagged gummy sharks within the three arrays (colour coded). The 'R' indicates the management zone where the shark was released. Tag codes are split in males (blue) and females (pink) and ordered by release zone. The * next to the tag Identification Number (ID) indicates sharks with a Fork Length (FL) larger than the FL at 50% maturity. The date axis is labelled in steps of six months starting on the date the first shark was tagged

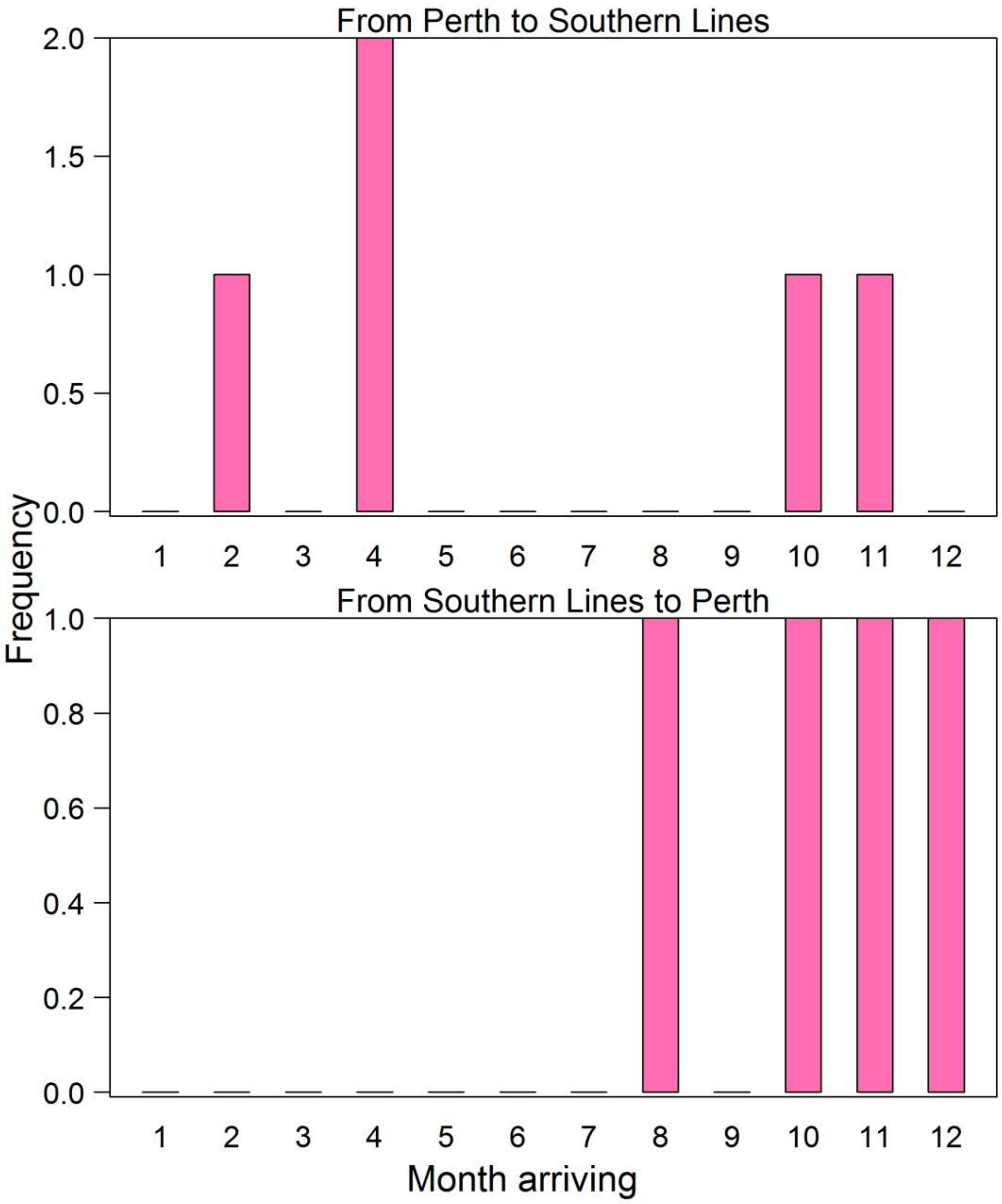


Figure 45. Frequencies of gummy shark displacements between arrays by month and sex (females are shown in pink and males are shown in blue)

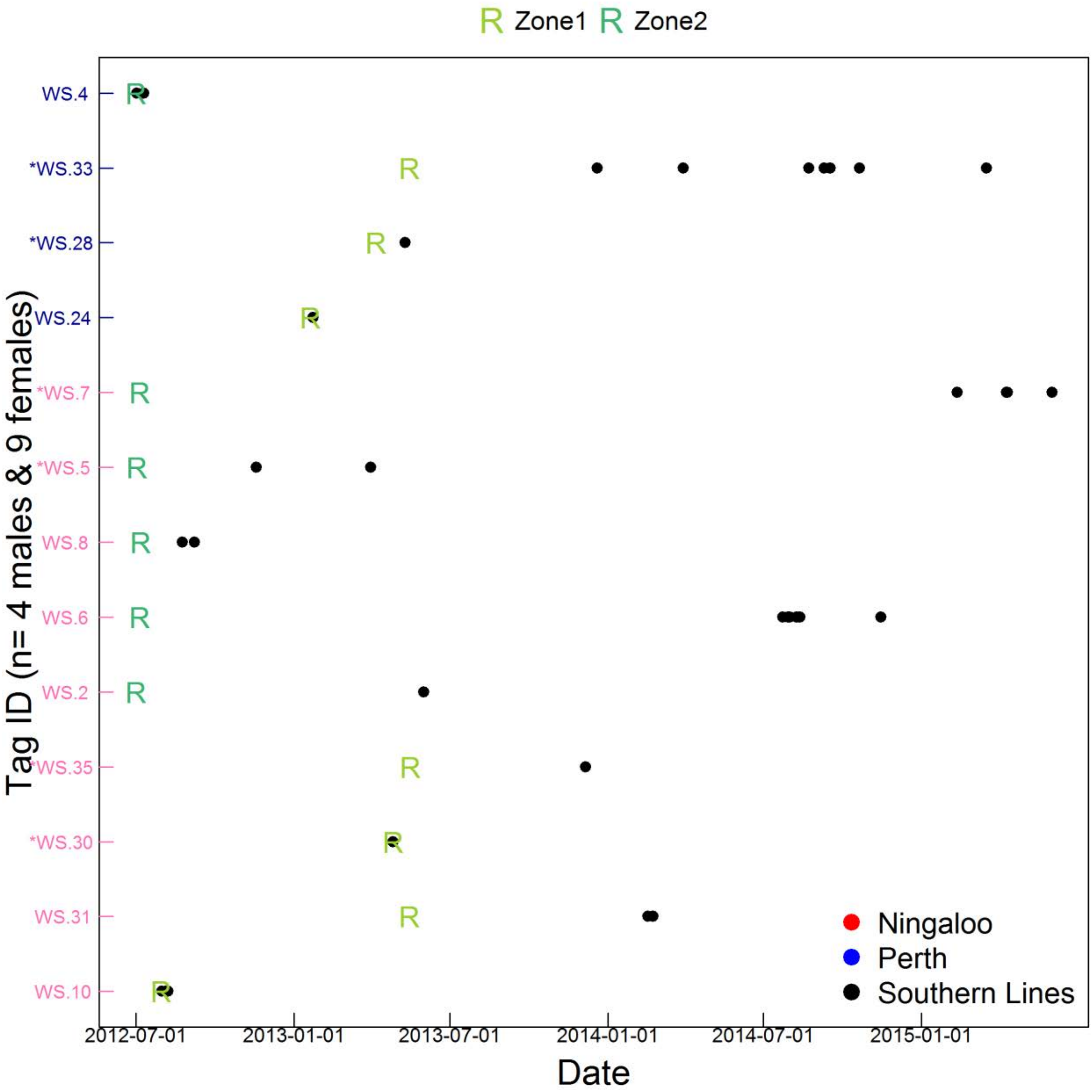


Figure 46. Daily presence /absence of tagged whiskery sharks within the three arrays (colour coded). The 'R' indicates the management zone where the shark was released. Tag codes are split in males (blue) and females (pink) and ordered by release zone. The * next to the tag Identification Number (ID) indicates sharks with a Fork Length (FL) larger than the FL at 50% maturity. The date axis is labelled in steps of six months starting on the date the first shark was tagged

Spatial detection patterns

Dusky and sandbar sharks were detected in all three Ningaloo lines (Figure 47). In the northern line of the array, sandbar sharks were largely detected by two of the inshore receivers whereas dusky shark detections were more evenly distributed. In the central line of the array, there was a large percentage of dusky shark detections whereas few detections of sandbar sharks were recorded. In the southern line of the array, dusky sharks were evenly detected by most receivers whereas sandbar sharks were mostly detected by the offshore or inshore receivers.

For the Perth array, detections of dusky sharks were fairly evenly distributed across the offshore receivers, (west of Rottnest Island and past the 50 m depth isobath), with a slightly higher number at the outermost receivers (Figure 48). For sandbar sharks, there were only six detection events, all at receivers west of the 50 m depth isobath. No detections for dusky or sandbar sharks were recorded east of Rottnest island. Detections were also fairly low for gummy sharks (n=45) and fairly uniformly spread across both shoreline receivers and receivers extending out to Rottnest island, as well as west of Rottnest up to approximately the 100 m isobath. Whiskery sharks were not detected in this array.

All species were detected in the Southern lines array, although detections were limited for sandbar (n=53) and whiskery (n=492) (Figure 49). For dusky, gummy and whiskery sharks, detections were distributed across the three receiver lines. Gummy sharks had a high number of detections on the eastern-most line (line 3) at receivers closest to the coast, just past the 50 m isobath. Sandbar sharks were only detected in the western-most line, adjacent to Augusta, at deepwater receivers.

For bronze whaler sharks, the spatial detection patterns observed are presented in Appendix 4: Spatial detection patterns for bronze whaler sharks.

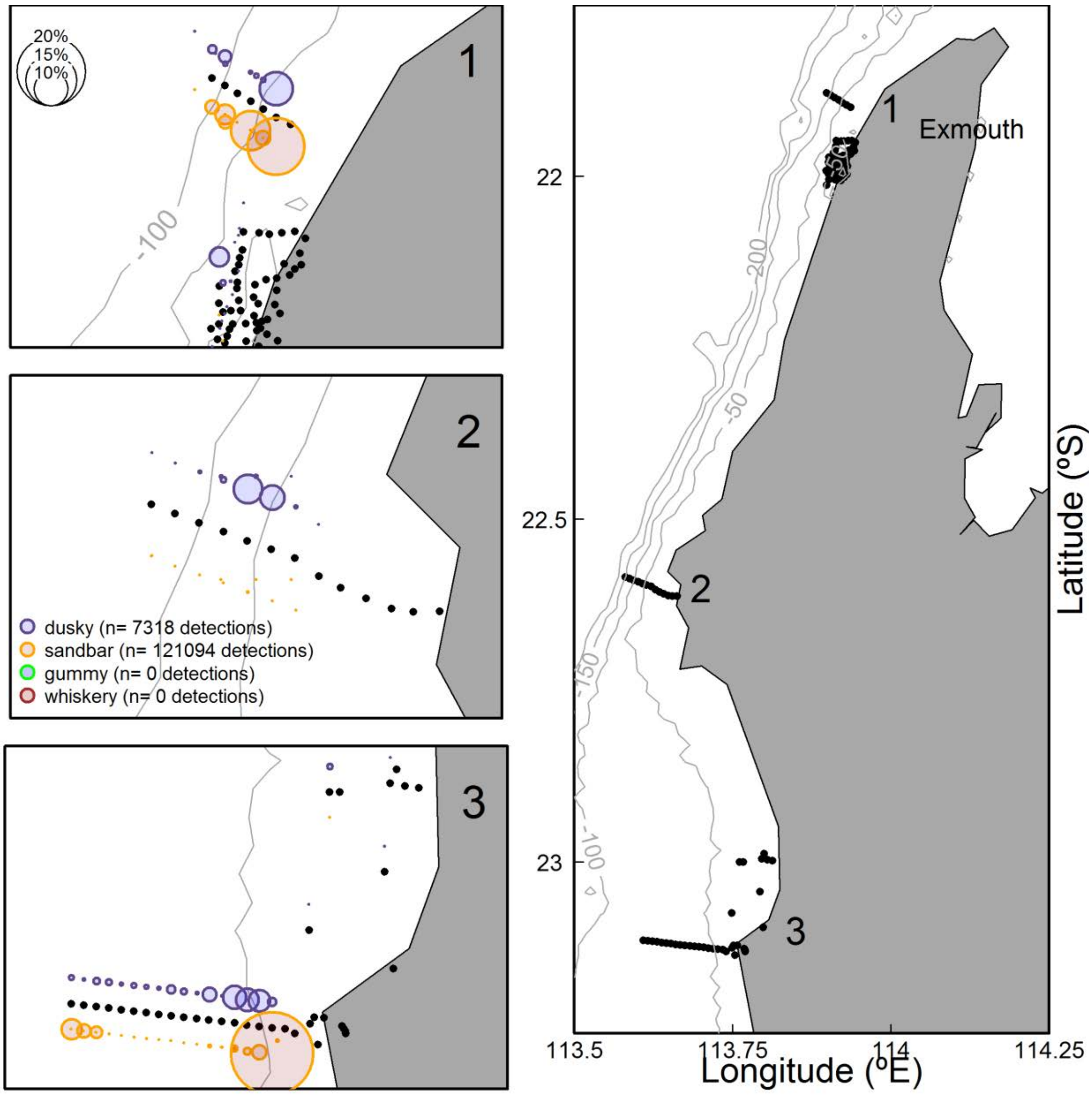


Figure 47. Spatial movement patterns. Bubble plot of percentage of detections per receiver within the Ningaloo array. The black dots represent actual receiver locations from which detection frequency bubbles are offset for clarity

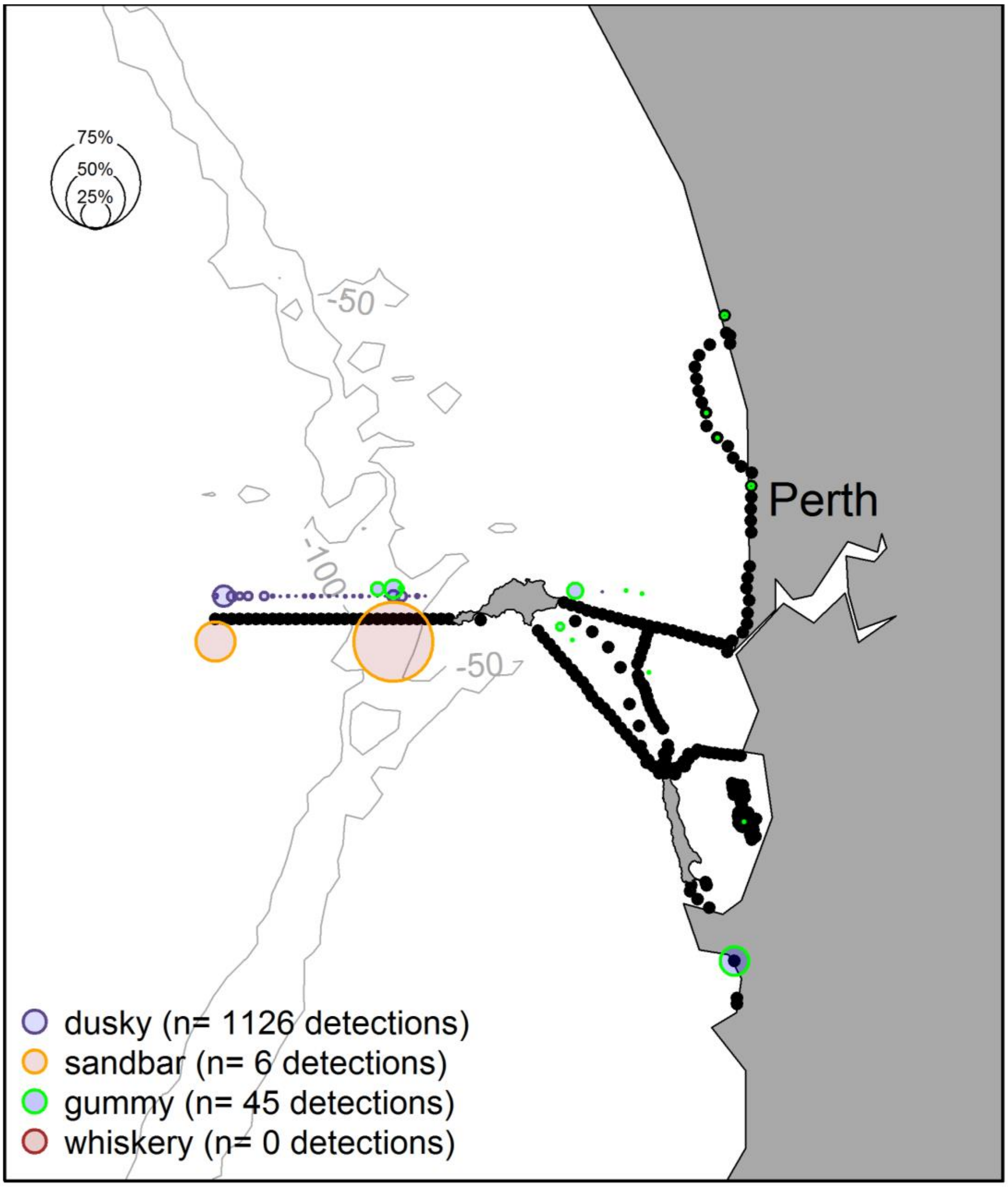


Figure 48. Spatial movement patterns. Bubble plot of percentage of detections per receiver within the Perth array. The black dots represent actual receiver locations from which detection frequency bubbles are offset for clarity

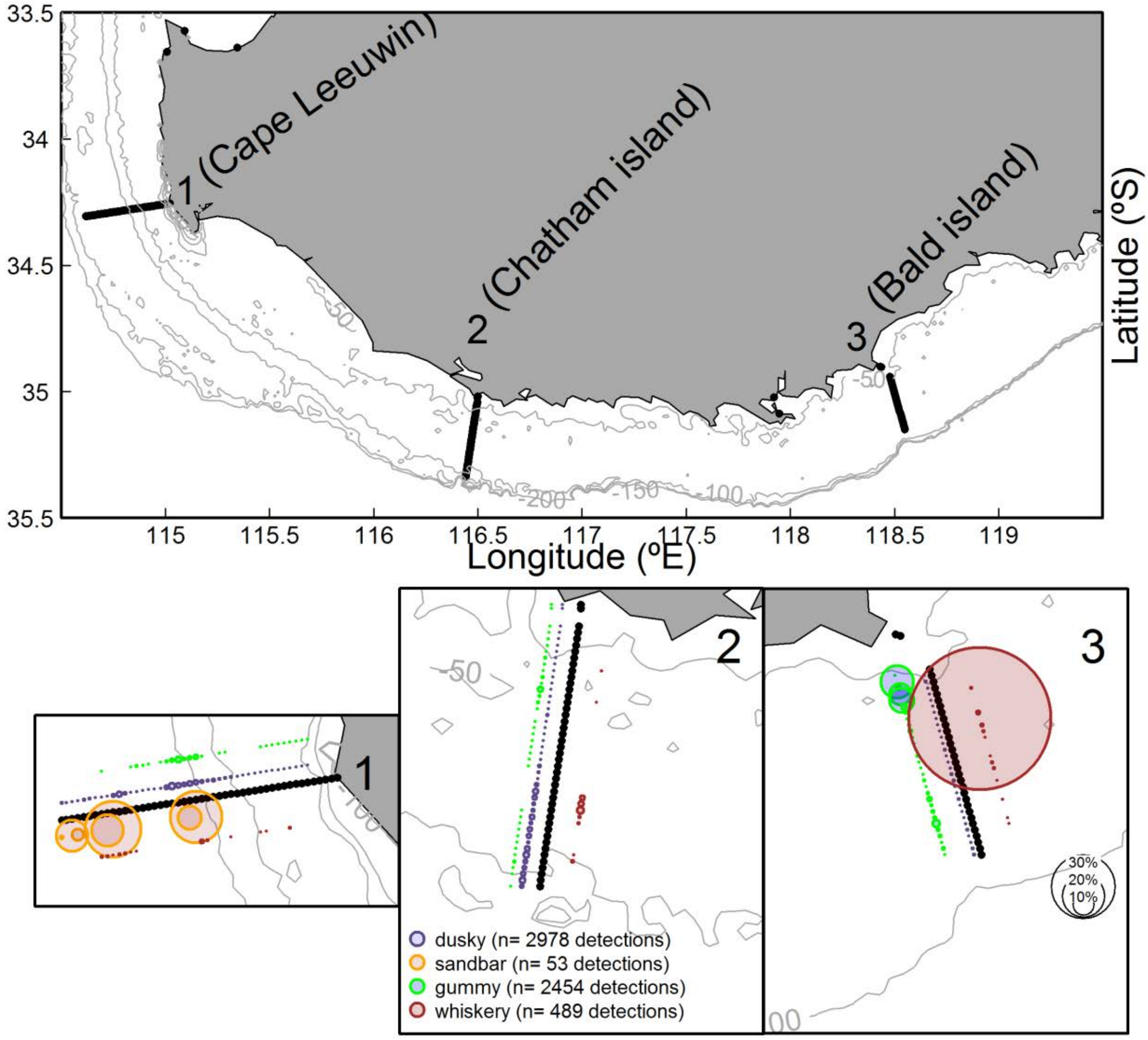


Figure 49. Spatial movement patterns. Bubble plot of percentage of detections per receiver within the Southern Lines array. The black dots represent actual receiver locations from which detection frequency bubbles are offset for clarity

4.1.3 Rates of movement

In general, for all species ROM increased with distance travelled (Figure 50). For small-scale displacements (<10 km) ROM was lower than for medium-scale displacements (between 10 and 50 km), which, in turn, showed lower ROMs than large-scale displacements (>50 km). Comparisons among species' ROMs showed that dusky sharks had the fastest ROMs for large-scale displacements, followed by sandbar, gummy and lastly whiskery sharks.

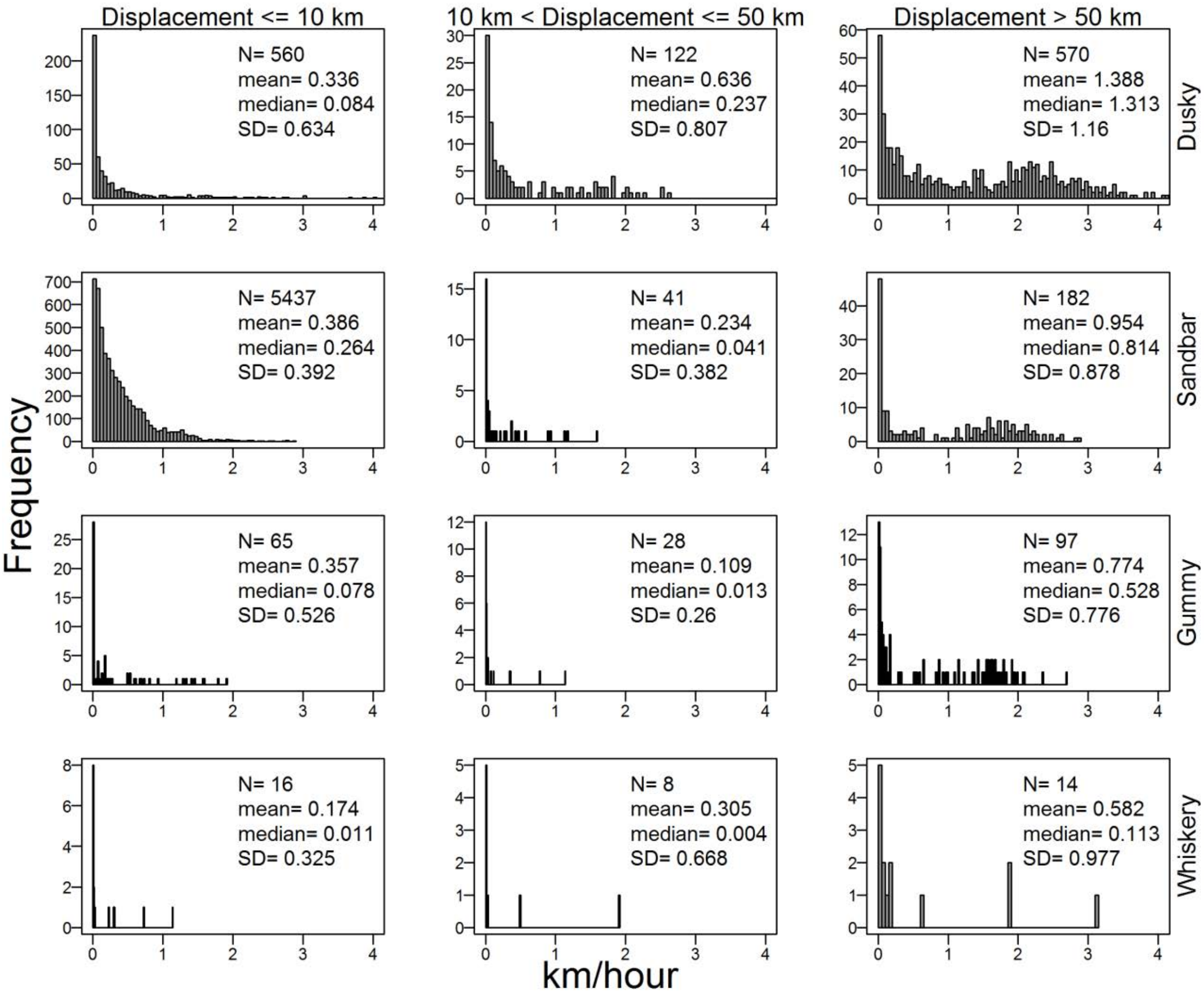


Figure 50. Rate of Movement distributions for different displacement distances for each species.

4.1.4 Daily patterns and co-detections

The proportion of detections by array and hour of day is shown in Figure 51. For sandbar and gummy sharks, the detections in the Perth and Southern Lines, and in the Perth arrays, respectively, were removed from this figure given the very few number of observations.

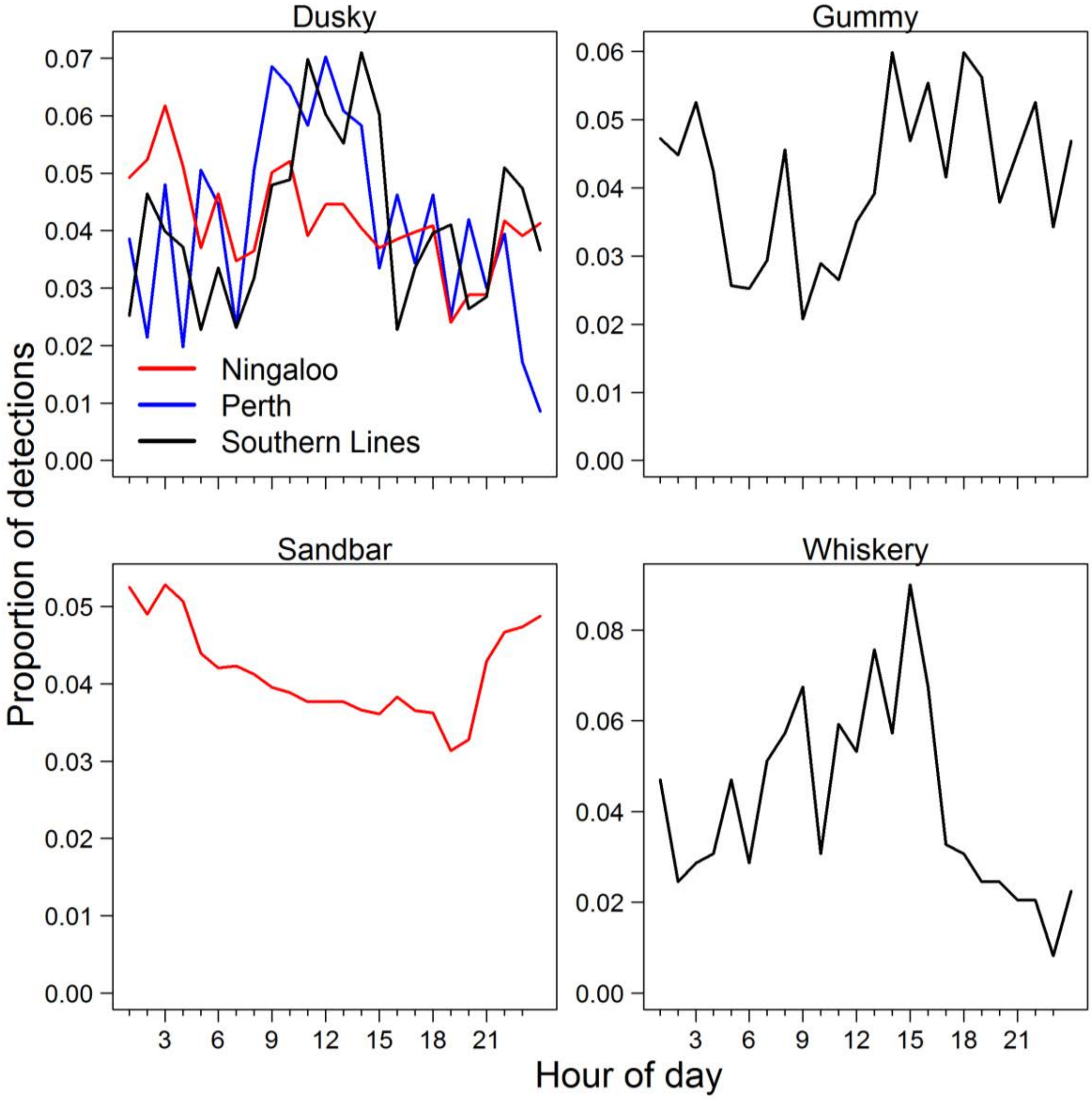


Figure 51. Proportion of detections by array and hour of day for each species

The pattern of co-detection of different individuals of the same species within the same date-hour is shown in Figure 52 and of different species is shown in Figure 53. For within species comparisons, up to two and three individuals of dusky and sandbar sharks, respectively, were detected within the same date-hour by the same receiver. For gummy and whiskery sharks, there were no co-detections (Figure 52). For between-species comparisons, up to four individuals of dusky and sandbar sharks were co-detected in the Ningaloo array whereas no co-detections of dusky and gummy, dusky and whiskery or gummy and whiskery were recorded in the Southern Lines array (Figure 53).

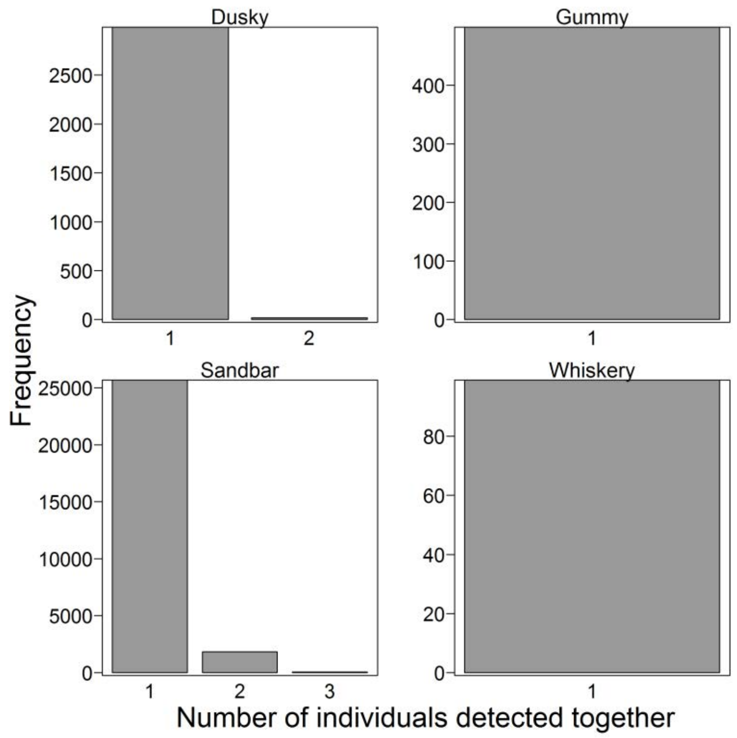


Figure 52. Number of individuals of the same species detected at the same location (receiver) within the same date-hour

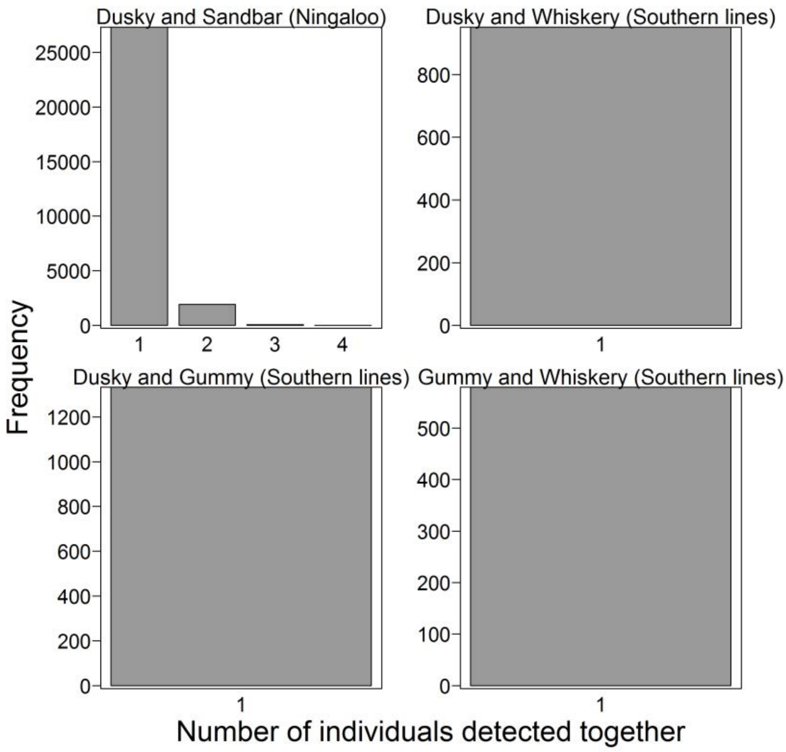


Figure 53. Number of individuals of the different species detected at the same location (receiver) within the same date-hour

4.1.5 Proportion of time per area

The proportion of monitored time spent by each detected dusky shark within each area is shown in Figure 54. Very few individuals remained exclusively within their release area, reflecting their high mobility and complex movement patterns. For example, several individuals released in the Ningaloo area spent a considerable proportion of the time in areas south of Ningaloo.

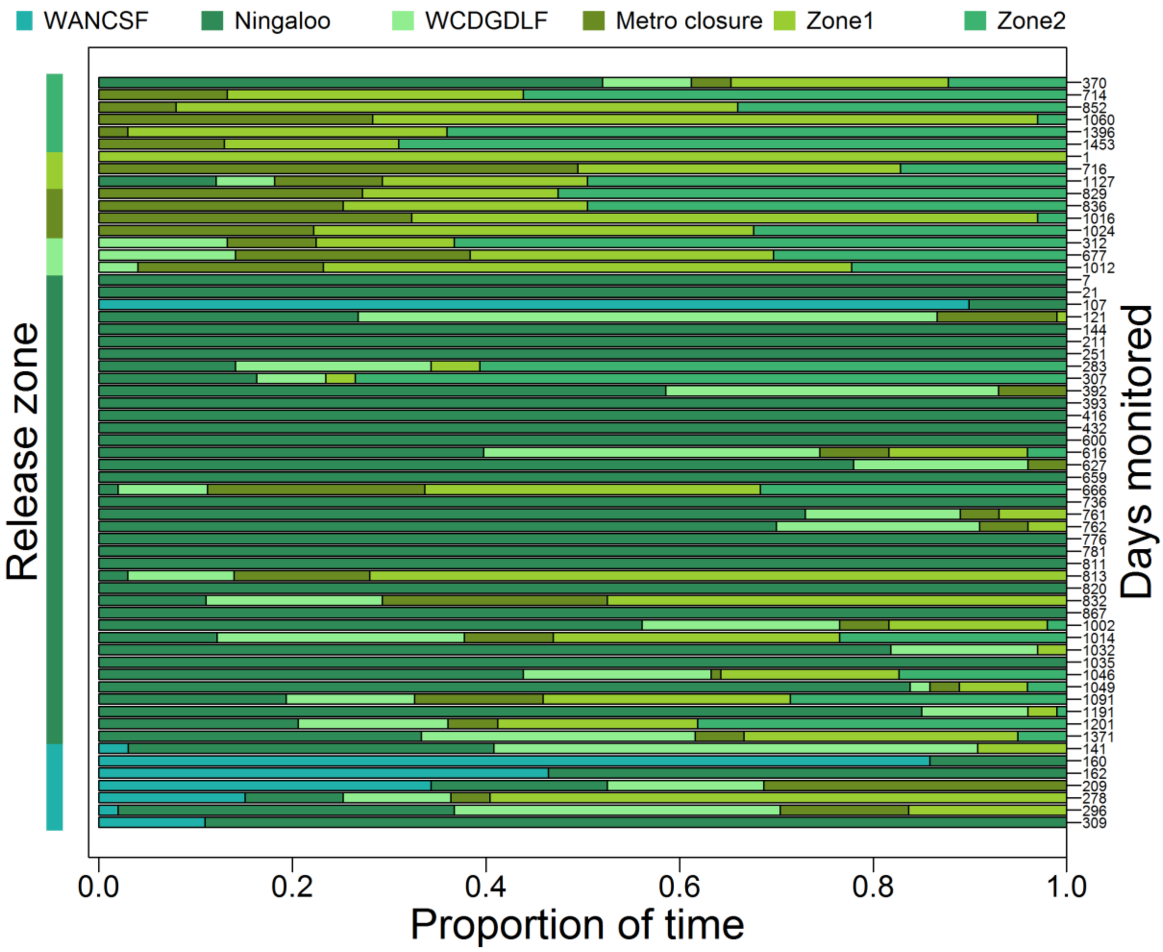


Figure 54. Proportion of the monitored time spent by tagged dusky sharks per area. This includes detected and non-detected sharks that were recaptured. Also shown is the number monitored days for each shark. Individuals are ordered by the release area (left Y axis) and within each release area, by the monitored days (right Y axis). WANCSF: Western Australia North Coast Shark Fishery; Ningaloo: Ningaloo closure; WCDGDLF: West Coast Demersal Gillnet and Demersal Longline (Interim) Managed Fishery; Zone 1: Zone 1 of the Joint Authority Southern Demersal Gillnet and Demersal Longline Managed Fishery; Zone 2: Zone 2 of the Joint Authority Southern Demersal Gillnet and Demersal Longline Managed Fishery

The proportion of monitored time spent by each detected sandbar shark within each area is shown in Figure 55. Most individuals remained within the release area though some individuals released off the north and north-west coasts spent most the monitored time in the Ningaloo area. In addition, one individual released in the Ningaloo area spent about 30% of the time in that array, whereas two individuals released in the Ningaloo area spent a considerable amount south of Ningaloo.

It must be remembered that this analysis assumes straight-line movements between consecutive detections (see Figure 2). Hence, if a tagged sandbar shark was detected by one of the Ningaloo receivers, then not detected for some time and then detected again by one of the Ningaloo receiver, the assumption is that the shark stayed within the Ningaloo area.

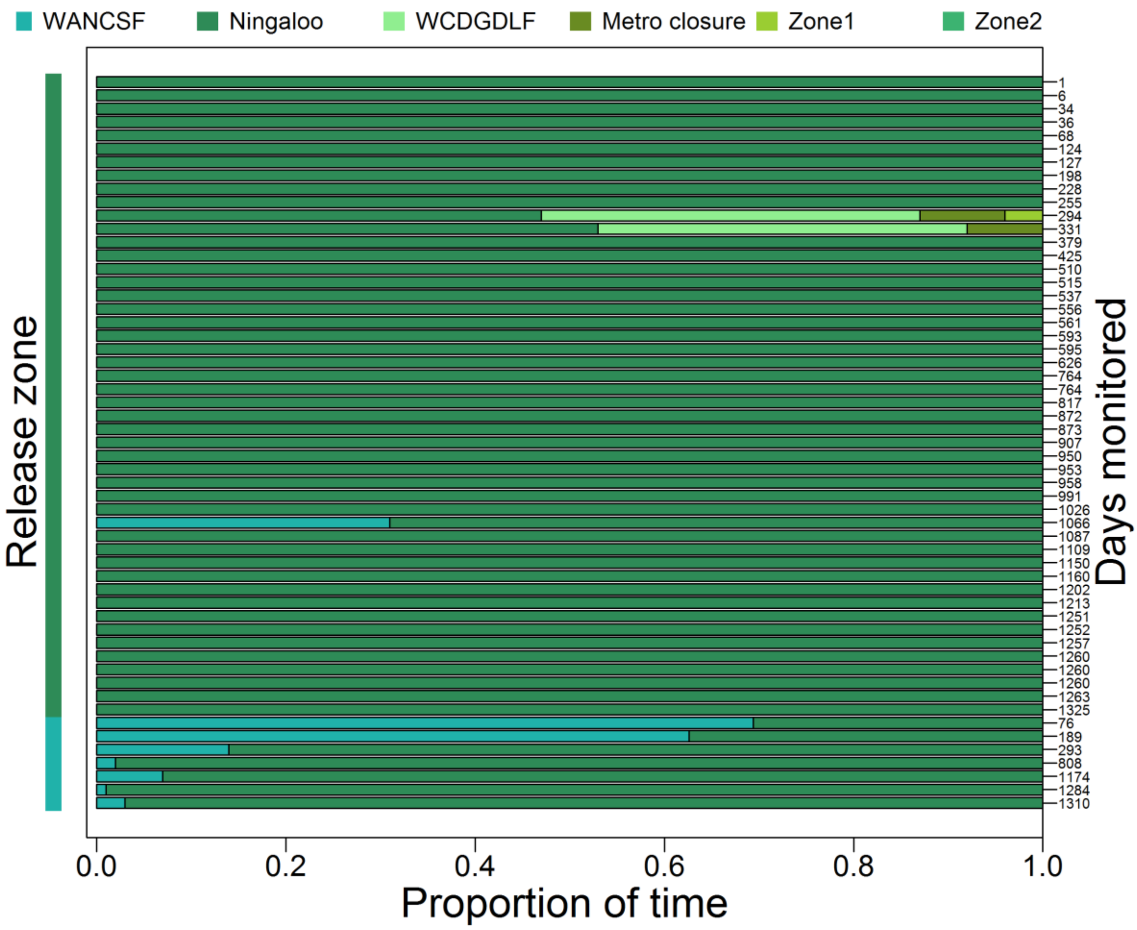


Figure 55. Proportion of the monitored time spent by tagged sandbar sharks per area. This includes detected and non-detected sharks that were recaptured. Also shown is the number monitored days for each shark. Individuals are ordered by the release area (left Y axis) and within each release area, by the monitored days (right Y axis). WANCSF: Western Australia North Coast Shark Fishery; Ningaloo: Ningaloo closure; WCDGDLF: West Coast Demersal Gillnet and Demersal Longline (Interim) Managed Fishery; Zone 1: Zone 1 of the Joint Authority Southern Demersal Gillnet and Demersal Longline Managed Fishery; Zone 2: Zone 2 of the Joint Authority Southern Demersal Gillnet and Demersal Longline Managed Fishery

The proportion of monitored time spent by each detected gummy shark within each area is shown in Figure 56. Most individuals released in Zone 2 remained within that area, with the exception of three individuals which were also detected in Zone 1 (two individuals) and the Metro closure (1 individual). Most individuals released in Zone 1, in contrast, spent a considerable amount of time in other areas.

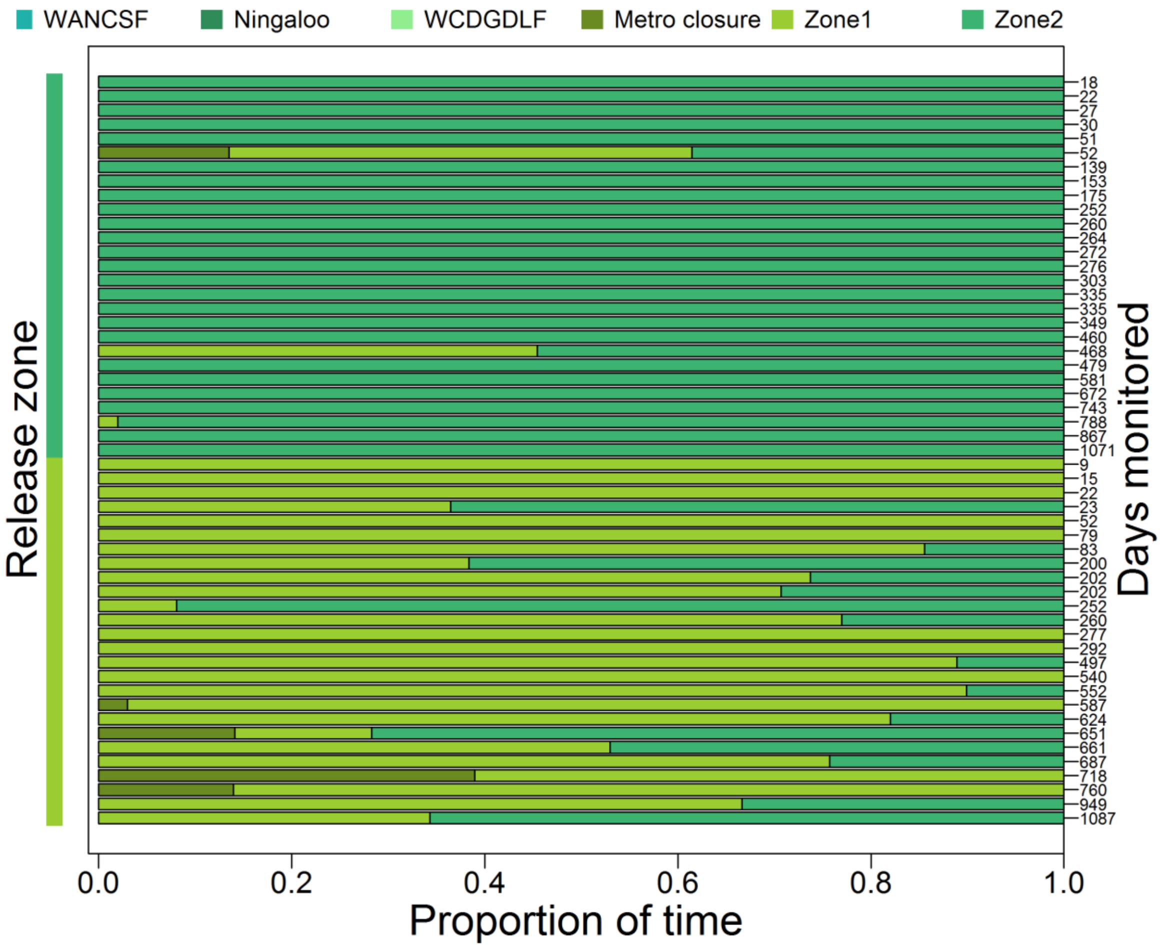


Figure 56. Proportion of the monitored time spent by tagged gummy sharks per area. This includes detected and non-detected sharks that were recaptured. Also shown is the number monitored days for each shark. Individuals are ordered by the release area (left Y axis) and within each release area, by the monitored days (right Y axis). WANCSF: Western Australia North Coast Shark Fishery; Ningaloo: Ningaloo closure; WCDGDLF: West Coast Demersal Gillnet and Demersal Longline (Interim) Managed Fishery; Zone 1: Zone 1 of the Joint Authority Southern Demersal Gillnet and Demersal Longline Managed Fishery; Zone 2: Zone 2 of the Joint Authority Southern Demersal Gillnet and Demersal Longline Managed Fishery

The proportion of monitored time spent by each detected whiskery shark within each area is shown in Figure 57. Almost all individuals remained within the release area, with the exception of two individuals released in Zone 1 which were detected in Zone 2 and two individuals released in Zone 2 which were detected in Zone 1.

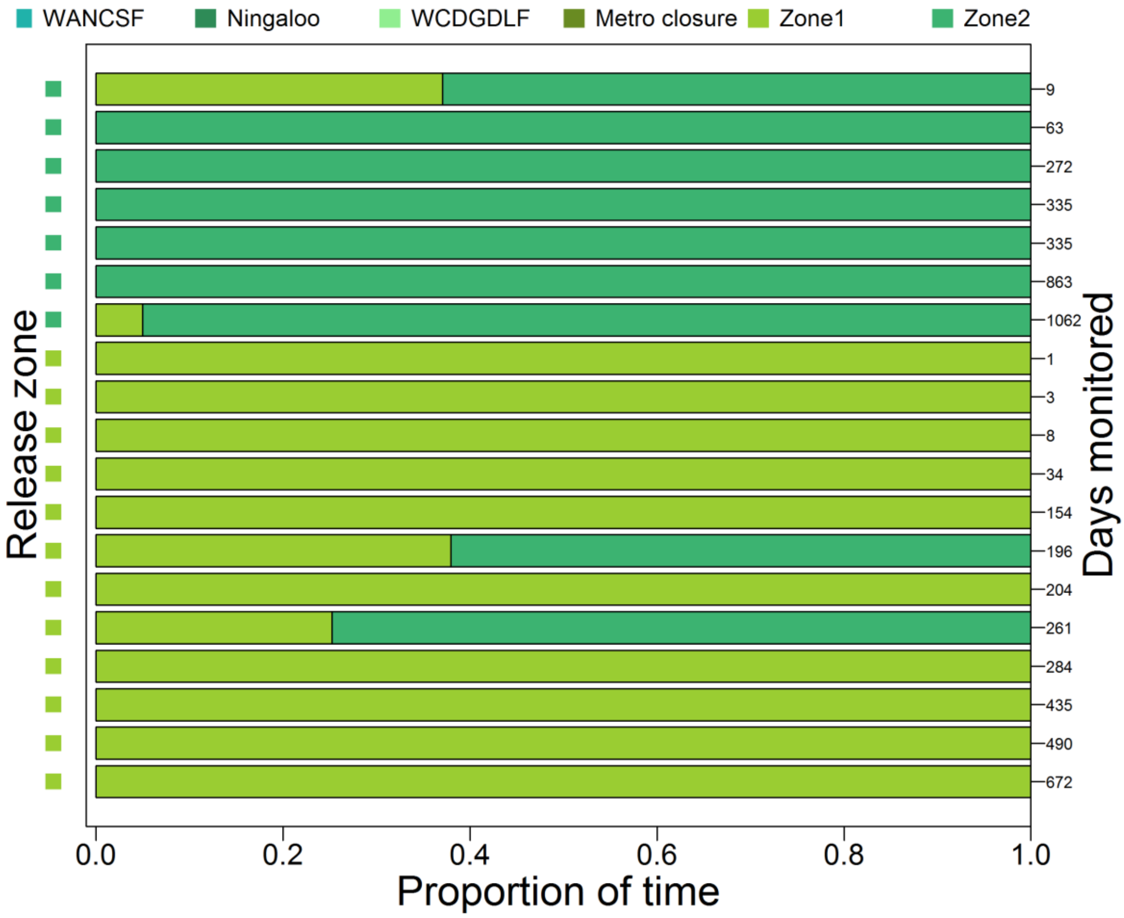


Figure 57. Proportion of the monitored time spent by tagged whiskery sharks per area. This includes detected and non-detected sharks that were recaptured. Also shown is the number monitored days for each shark. Individuals are ordered by the release area (left Y axis) and within each release area, by the monitored days (right Y axis). WANCSF: Western Australia North Coast Shark Fishery; Ningaloo: Ningaloo closure; WCDGDLF: West Coast Demersal Gillnet and Demersal Longline (Interim) Managed Fishery; Zone 1: Zone 1 of the Joint Authority Southern Demersal Gillnet and Demersal Longline Managed Fishery; Zone 2: Zone 2 of the Joint Authority Southern Demersal Gillnet and Demersal Longline Managed Fishery

The number of individuals of each species that moved to adjacent areas (Figure 58) and non-adjacent areas (Figure 59) at different time scales provides further information about species' mobility patterns. Dusky sharks showed the highest number of individuals moving to adjacent and non-adjacent zones. In addition, dusky sharks took considerable less time for undertaking those movements.

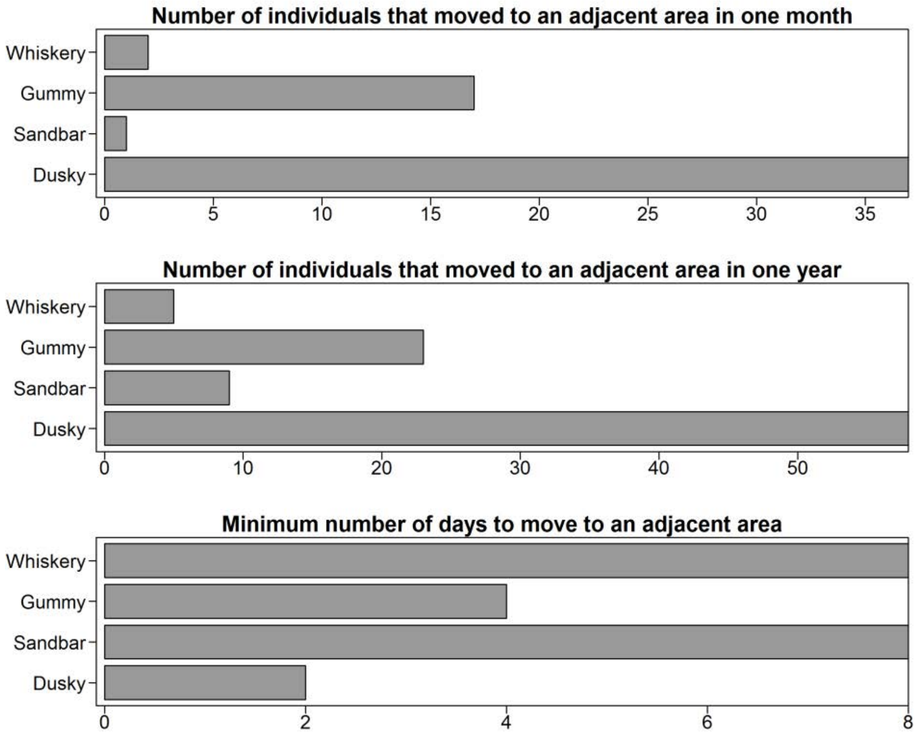


Figure 58. Movement among adjacent areas. The barplot shows the number of individuals of each species that moved to an adjacent area (top and centre panels) the minimum number of days these individuals took to move to an adjacent area (bottom panel)

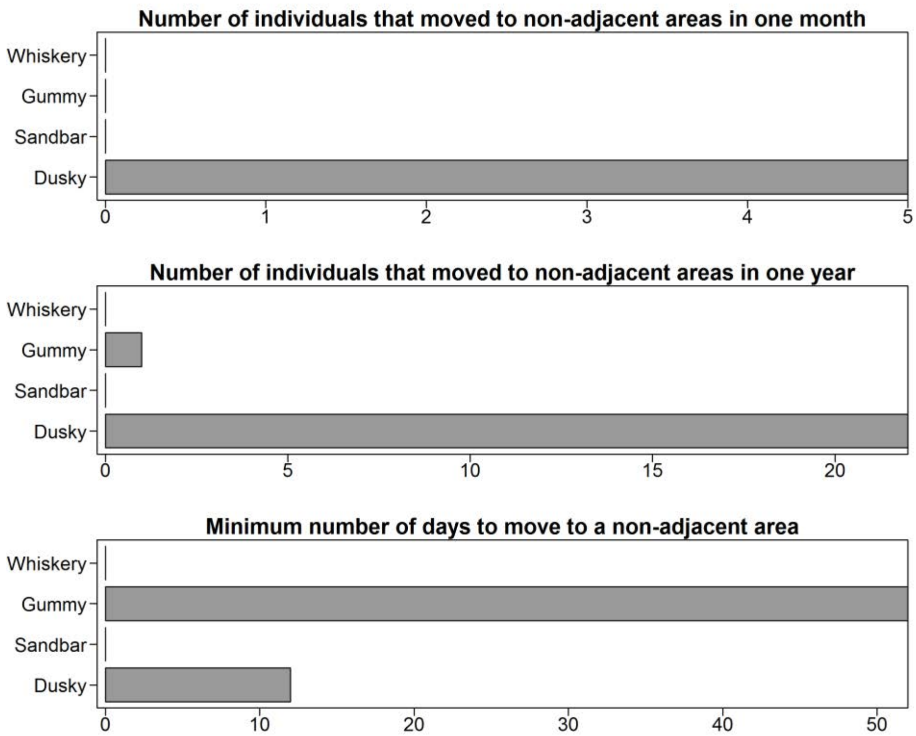


Figure 59. Movement among non-adjacent areas. The barplot shows the number of individuals of each species that moved to a non-adjacent area (top and centre panels) the minimum number of days these individuals took to move to a non-adjacent area (bottom panel)

4.1.6 Seasonal migration of dusky sharks

Larger dusky sharks showed regular displacements between the northern (Ningaloo array) and the southern (Perth and Southern Lines arrays) arrays. For both female (Figure 60) and male (Figure 61), most of the north to south and the south to north movements occurred within a year or less than a year (e.g. DS.41, DS.49). In WA, the lowest water temperature occurs during winter and spring whereas the highest water temperature occurs during summer and autumn (Caputi et al. 2009). Large males were detected at Ningaloo exclusively during winter and spring whereas during summer and autumn they were only detected in the Perth and Southern lines (Figure 61). Large females, however, showed a more complex pattern (Figure 60). Some individuals conformed to a 'north in winter–spring and south in summer–autumn' pattern (e.g. two individuals with a FL of 230 cm) whereas other individuals were consistently detected north in all seasons (e.g. individuals of 259 and 260 cm FL).

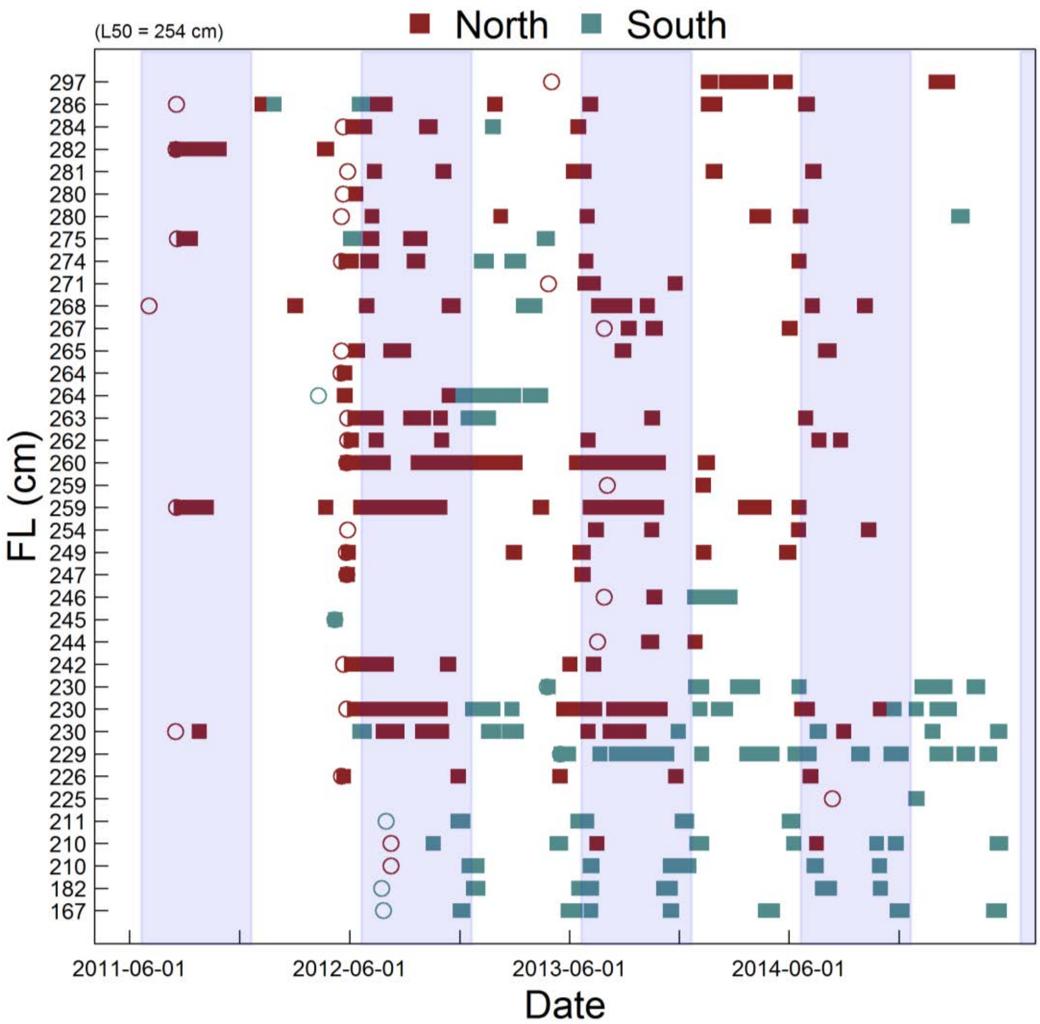


Figure 60. Daily presence/absence of tagged female dusky sharks in northern (Ningaloo array) and southern (Perth and Southern Lines arrays) Western Australia. Tagged individuals are sorted by fork length (FL). The Winter–Spring seasons are shaded in blue whereas the Summer–Autumn seasons are not shaded. The open circle shows the release location and date

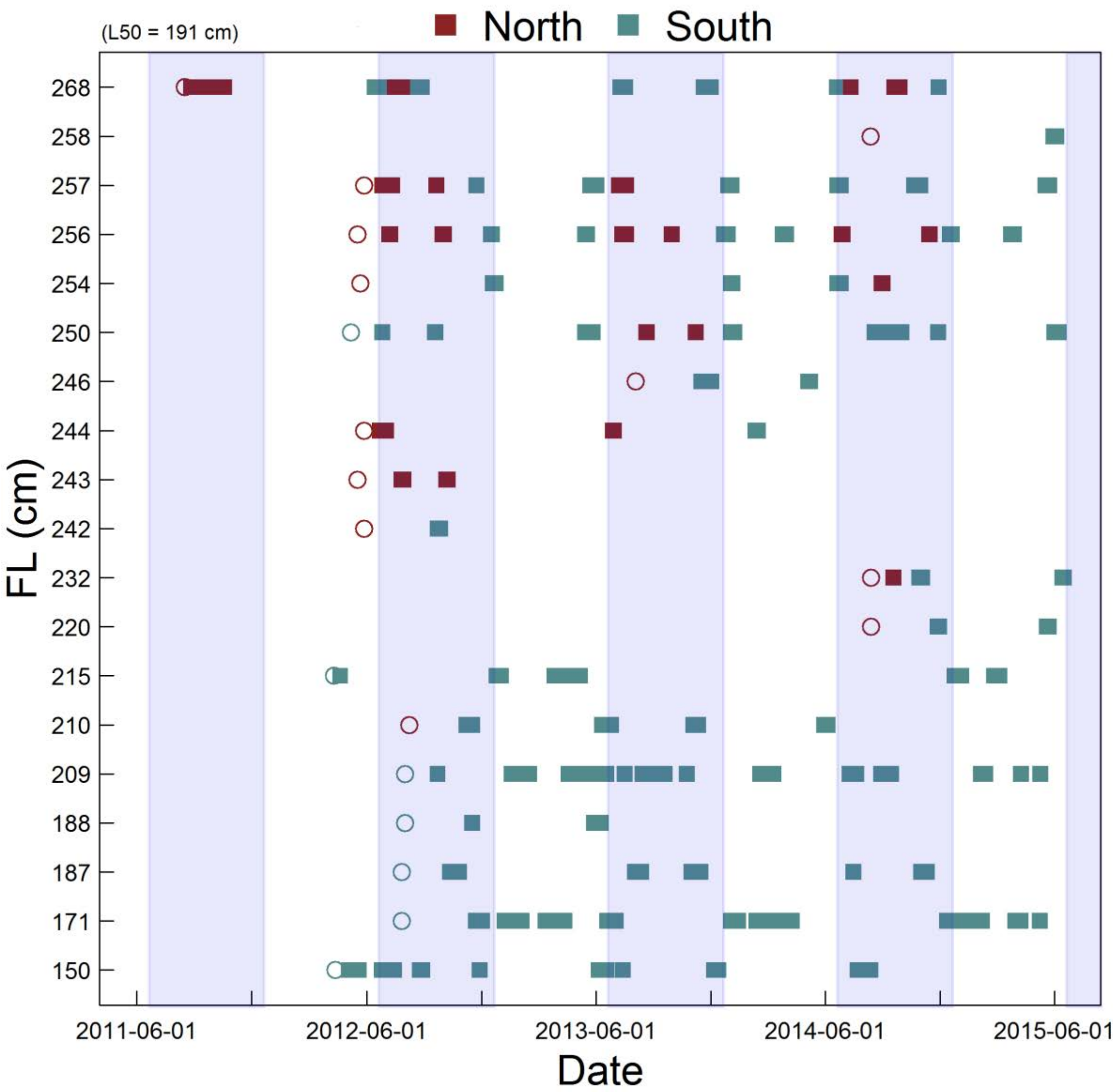


Figure 61. Daily presence /absence of tagged male dusky sharks in northern (Ningaloo array) and southern (Perth and Southern Lines arrays) Western Australia. Tagged individuals are sorted by Fork Length (FL). The Winter–Spring seasons are shaded in blue whereas the Summer–Autumn seasons are not shaded. The open circle shows the release location and date

Movement patterns were strongly related to sharks' sizes. Smaller individuals of both sexes were only detected by the Perth and Southern lines whereas larger individuals showed north–south displacements to and from Ningaloo Reef (Figure 60 and Figure 61). Mean (±95% credible intervals, CI) size at 50% migration of females and males was very similar (223 ± 6 and 222 ± 12 cm FL, respectively) (Figure 62). This pattern was consistent across all individuals, which displayed similar levels of variation in their migratory behaviour. The probability of occurring at Ningaloo varied with month and sex. There was a higher probability of being detected in the north during the austral winter/spring than during the austral summer/autumn (Figure 62). For the austral winter/spring period, the probability of occurring at Ningaloo was > 0.9 for females and 0.72 for males, whereas for the austral summer/autumn period, this probability was ~0.5 for both sexes. For males, model estimates had higher uncertainty (e.g. the lower limit of the 95% CI was close to zero between December and April, Figure 62) because there was little contrast in the presence/absence of sharks at Ningaloo Reef due to the limited number of detections in this location during summer/autumn (Figure 61).

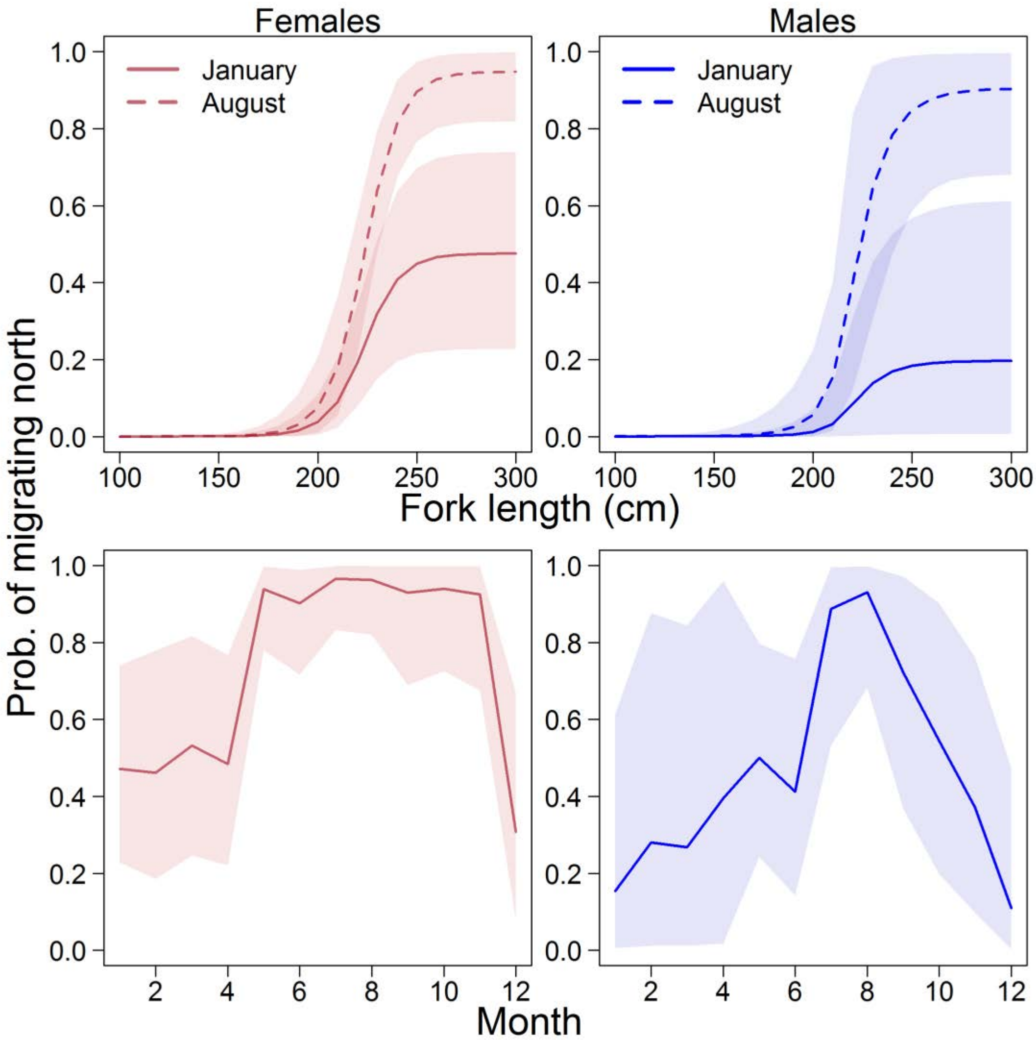


Figure 62. Dusky shark migration. The upper panel shows the probability of migrating north in January and August for different sizes of female and male dusky sharks with associated 95% Credible Intervals (CI). The lower panel shows the monthly probability of migrating north for female and male dusky sharks with associated 95% CIs.

4.1.7 Exchange rates of gummy and whiskery sharks

Annual movement rates among management zones were different between species and, for each species, also varied among zones (Figure 63). For gummy sharks, individuals occurring in the West Coast showed a high probability of moving to Zone 1 (0.46) and a moderate probability of staying in the West Coast (0.36). In turn, individuals occurring in Zone 1, showed a high probability of moving to Zone 2 (0.46) and a moderate probability of staying in Zone 1 (0.36). Finally, individuals occurring in Zone 2 showed a very high probability of not moving (0.97).

For whiskery sharks, there was a very high probability (0.83, 0.87, 0.94 for the West Coast, Zone 1 and Zone 2, respectively) of staying in the same zone. For all zones, there was a moderate (0.15 for individuals moving from the West Coast to Zone 1) to low probability (0.06 for individuals moving from Zone 2 to Zone 1) of moving to an adjacent zone. Finally, the probability of moving to a non-adjacent zone was negligible.

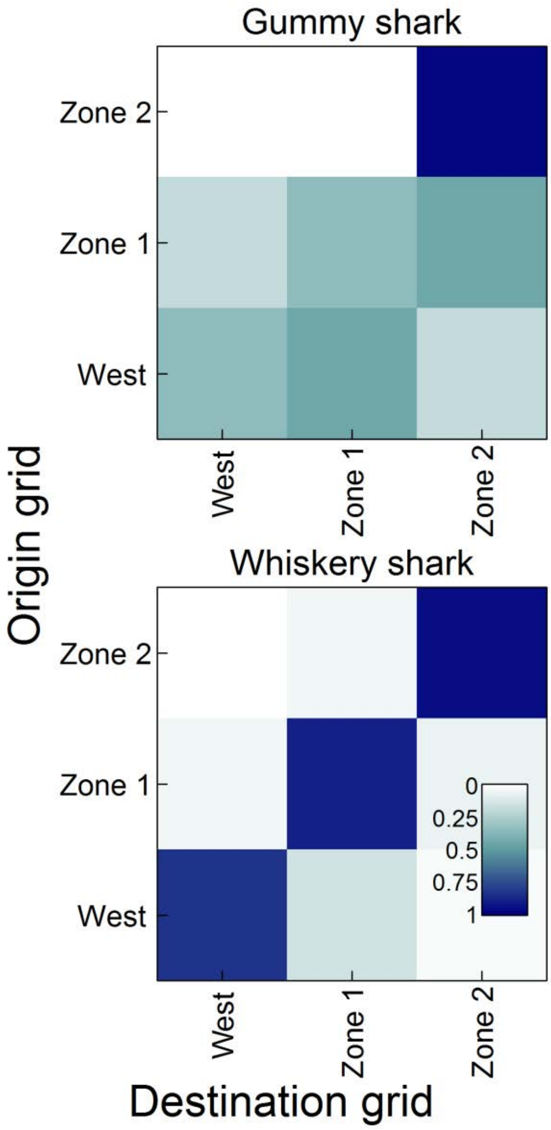


Figure 63. Movement transition matrix showing the annual probability of movement among management zones for gummy and whiskery sharks

4.2 Catch and effort standardisation

4.2.1 Data and model selection

The selection of indicative vessels removed several vessels from the total number of vessels providing 'good' records; however, the proportion of the total catch explained by the indicative vessels was very high (Figure 64). In all, the indicative vessels accounted for >80% of the total catch of each species.

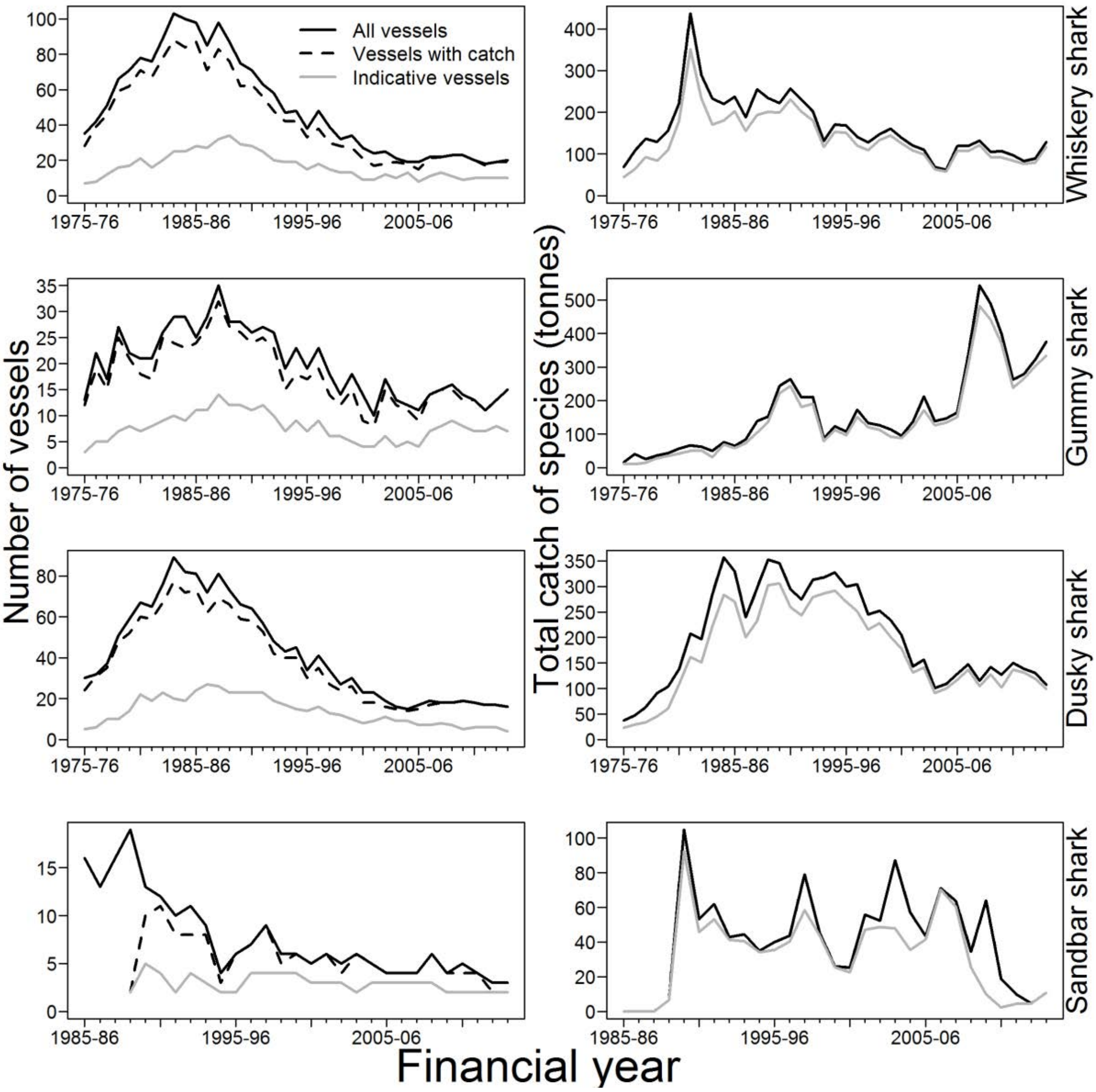


Figure 64. Annual trends in the number of vessels ('good' records only) within each species' effective effort areas. Also shown is the total annual catch of each species ('good' records only) within its effective effort areas

The summary statistics for the selected models are shown in Table 22. For the positive records, the AIC and percentage of deviance explained analyses selected the same model structure for the lognormal and gamma distributions. However, based on residual distributions and Box-Cox likelihoods the lognormal error provided the best fit for all species. This error structure was then used to standardise catch and effort. The selected models used to estimate the probability of positive catches explained between 37% and 86% of the deviance whereas for the positive catch records the selected models explained between 35% and 41% of the deviance (Table 22). For the positive catch records, diagnostic plots are provided in Figure 65. The q-q plots were generally consistent with the expected linear pattern of a lognormal distributed error (upper panel), which had a fairly normal distribution (mid panel). Finally, there were no systematic departures from the expected mean of zero and constant variance across the range of expected values (lower panel).

Table 22. Deviance explained for the best Generalized Linear Model and error structure fitted to the catch and effort data. Prob.Ktch, probability of positive catch

Model structure	**Deviance explained (%)**
Presence/absence	
Whiskery shark	37
Prob.Ktch~Yr+Block+Ves+log(Gummy_c)+log(Dusky_c)+log(km.gn.d)	
Gummy shark	72
Prob.Ktch~Yr+Block+Ves+Mn+log(Whiskery_c)+log(Dusky_c)+log(km.gn.d)	
Dusky shark	62
Prob.Ktch~Yr+Block+Ves+log(Gummy_c)+log(Whiskery_c)+log(km.gn.d)	
Sandbar shark	86
Prob.Ktch~Yr+Block+Ves+Mn+log(Gummy_c)+log(Whiskery_c)+log(Dusky_c) +log(km.gn.d)	
Positive records only	
Whiskery shark	40
log(Ktch)~Yr×Block+Ves+Mn+log(km.gn.d)	
Gummy shark	38
log(Ktch)~Yr×Block+Ves+Mn+log(km.gn.d)	
Dusky shark	41
log(Ktch)~Yr×Block+Ves+Mn+log(Whiskery_c)+log(km.gn.d)	
Sandbar shark	35
log(Ktch)~Yr×Block+Ves+Mn+log(km.gn.d)	

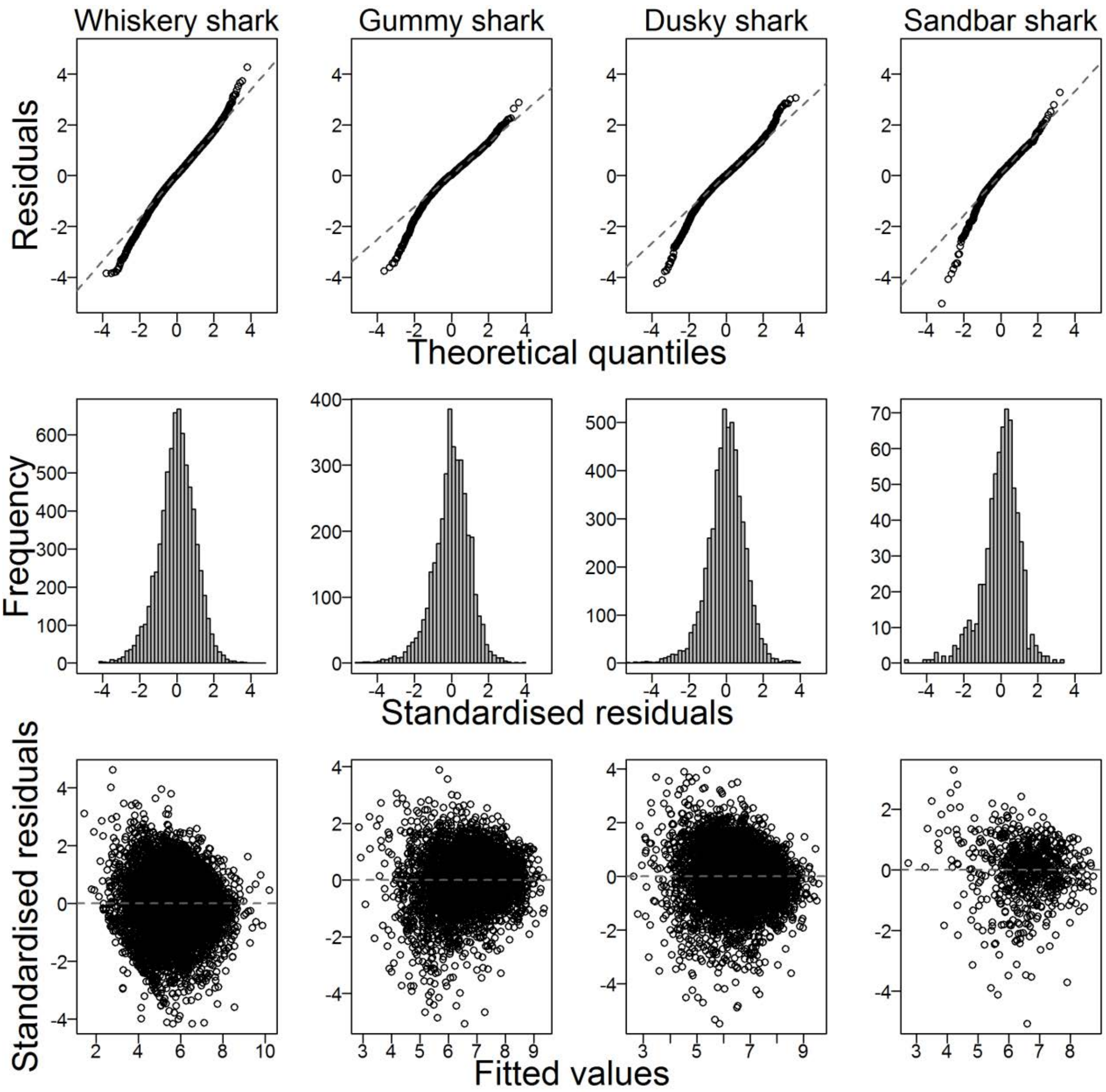


Figure 65. Model fit diagnostics for the postive catch records. q-q plots (upper panels); distribution of standardised residuals (middle panels); standardised residuals vs expected values (lower panels)

4.2.2 Construction of standardised CPUE time series

The effect of calculating nominal CPUE as the ratio of total annual catch to total annual effort [‘folly’ approach as per Walters (2003)] or as the annual average of each record’s CPUE is shown in Table 23. Only when catch is proportional to effort (Case 1) do the two methods for calculating CPUE yield the same value. In other cases, the ‘folly’ approach is not recommended (Walters 2003).

Table 23. Hypothetical example of the effect of calculating nominal Catch per Unit of Effort (CPUE) as the ratio of total annual catch to total annual effort or as the annual average of each record's CPUE

		Catch		
Vessel	**Effort**	**Case 1**	**Case 2**	**Case 3**
A	10	100	100	1000
B	20	200	200	2000
C	30	300	300	3000
D	40	400	0	400
E	50	500	500	500
F	60	600	0	600
G	70	700	700	700
H	80	800	0	800
I	90	900	900	900
J	100	1000	1000	1000

	CPUE		
Method	Case 1	Case 2	case 3
Mean	10	7	37
SD	0	4.83	43.47
Sum	10	6.73	19.82
SD	0	0	0

The standardised CPUE series resulting from application of the methods described above were reviewed at different spatial scales to assess their applicability as indices of each stock's relative abundance. Overall, like previous estimates of effective CPUE, standardisation model outputs indicated rapid increases in CPUE as fishing commenced, followed by equally rapid declines (Figure 66). However, unlike previous 'effective' CPUE series, apart from two spikes in the Zone 2 dusky shark data, standardised CPUE trends for whiskery and dusky sharks remained extremely stable in all zones since the mid-1980s. Another difference observed in the standardised data was the rapid decline in Zone 1 dusky and whiskery catch rates over the period spanning the introduction of new management and catch and effort reporting arrangements at the end of the 2005/06 fishing season. At a finer-scale, these differences were most-evident in blocks that had historically contributed large catches of these species to the overall catch (e.g. Figure 67) and therefore disproportionately influenced the overall trends for these species. These differences could not be readily explained but it is thought to be highly unlikely that they reflect real changes in the relative abundance of these stocks and are more likely a consequence of changes in management and/or reporting between these two years.

Another feature of the standardised data was a notable spike in the West Coast fishery's dusky shark CPUE in 2007/08. This corresponds to the year after fishing was prohibited in the metropolitan region, 35% of effort capacity was removed from the WCDGDLF through a Voluntary Fisheries Adjustment Scheme and the two largest and longest-term operators retired from fishing. Similarly, this feature (together with a smaller subsequent spike) is not thought to reflect an actual change in abundance but is more probably due to changes in the spatial re-distribution of effort, new operators entering the fishery, reporting behaviour, etc. Furthermore, the metropolitan closure and northward redistribution of effort resulted in missing years of data from what had traditionally been important dusky and whiskery shark fishing grounds. As a result, data for these blocks were imputed from the last year's coefficient value and the species' intrinsic growth rate.

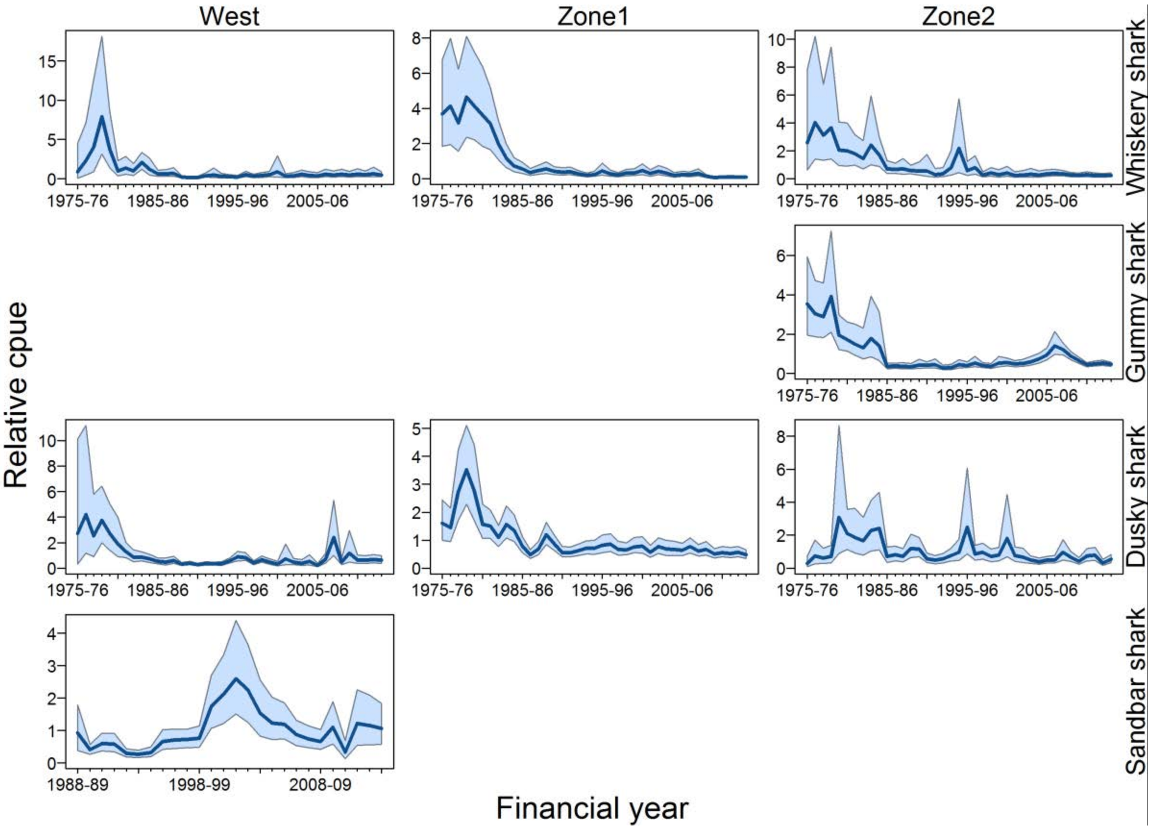


Figure 66. Time series of Catch per Unit of Effort (CPUE) standardisation model outputs (mean and 95% CI, shaded area) for each species and relevant management zone, normalised to a mean value of 1

Furthermore, there was a concern that by grouping daily records at a monthly level, information on changes in fishers' behaviour between fishing trips in the same month would be omitted. By combining daily records into a single monthly record, inter-trip variability would therefore be smoothed with the potential consequence of useful (i.e. a trip targeted at the species in questions) and misleading (i.e. a trip targeted at other species) information would be combined in the same record. Also, the transition from monthly returns to daily logbooks in combination with the implementation of several management measures (Borg and McAuley, 2004; DoF 2008) seem to have introduced bias(es) in the reported the catch and effort data.

For all of these reasons, there was a lack of confidence that standardised catch rate indices accurately reflected each stock's abundance. While these data were useful for the development of assessment models, model outputs based upon these data were considered unreliable representations of changes in stocks' abundance and have therefore not been presented. Further investigation of these issues and development of techniques to resolve them is required. As these analyses have re-emphasised the incompatibilities between monthly return and daily logbook data, resolution is likely to involve the use of two separate indices in future stock assessments.

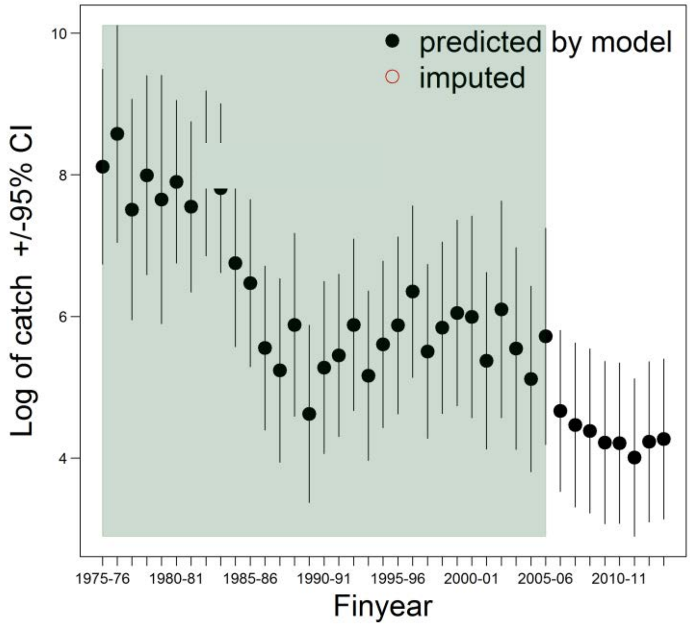


Figure 67. Example of the possible effect of changes in catch and effort reporting practices on the predicted catch of whiskery sharks in fishing block 3315. Period of monthly return data (1975-2006) is shaded.

4.3 Population dynamics of whiskery and gummy sharks

During construction of the population dynamics models, the models described in 3.3.7 (Modelling approach) were fitted to the effective CPUE historically used for the species assessments. However, no results are presented in this report because the construction of a standardised catch rate index that confidently reflects abundance was not achieved by the present study for the reasons detailed in 4.2.2 (Construction of standardised CPUE time series Once a reliable index of abundance is constructed, the models developed as part of the present study could be fitted to this and the other sources of information available described in 3.3.1 (Available data).

4.4 Risk assessment of dusky and sandbar sharks

4.4.1 Rationale for including issues

4.4.1.1 Impact of extractive fishing in WA

4.4.1.1.1 Temperate Demersal Gillnet & Demersal Longline Fisheries

Dusky and sandbar sharks are two of the four main shark species targeted by the TDGLDF which are by far the largest extractive fisheries for these species in WA. Catches of dusky and sandbar sharks by the TDGDLF in 2013/14 were 190t and 45t, respectively but previously exceeded 585t and 235t, respectively. Due to the size selectivity of mesh sizes used in these fisheries (typically 16.5cm and 17.8cm stretched) and their area of operation, catches are primarily composed of dusky sharks less than 2 years of age and sandbar sharks of between 6 and 9 years of age (Simpfendorfer and Unsworth, 1998b; McAuley et al., 2007a, b).

4.4.1.1.2 Recreational fishing

Recreational fishing is a popular activity in WA with an estimated 691,000 participants in 2011/12 (DoF 2012). Sharks are not specifically targeted but are still a component of the catch with reasonable quantities caught by boat-based fishers in the North Coast, Gascoyne Coast and West Coast bioregions (Ryan et al. 2013). Reliable, state-wide estimates of shore-based recreational catches are not currently available, although based on all available information, are not likely to be applicable to sandbar (or whiskery) sharks. An estimated 3958 whaler sharks (family Carcharhinidae, potentially including dusky and sandbar sharks) and an estimated 590 sandbar sharks were caught in 2011/12. Of these, 3513 whaler sharks and 504 sandbar sharks were released. The accuracy of species identification in these data is unclear and it may be more reliable to consider these catches of 'whaler' and 'sandbar' sharks in combination.

4.4.1.1.3 Northern Shark Fisheries

The NSF comprise the state-managed WA North Coast Shark Fishery (WANCSF) and the Joint Authority Northern Shark Fishery (JANSF), which operated in the Pilbara/western Kimberley and eastern Kimberley, respectively, until 2009 (Molony et al. 2013). Historically, the primary fishing method used was demersal longline with a sporadic and relatively small amount of pelagic gillnetting in the JANSF. Between 1994 and 2009, the NSF targeted various species of shark including sandbar (*C. plumbeus*) and blacktip whaler sharks (*Carcharhinus limbatus and Carcharhinus tilstoni*) and hammerheads (*Sphyrna* spp.).

4.4.1.1.4 Other WA Fisheries

The wide distribution and movements of both dusky and sandbar sharks means there is the potential for interaction with many WA-managed marine fisheries. Successive quantitative assessments of fishing mortality on these stocks (McAuley et al. 2007a) demonstrated the importance of considering all potential sources of mortality beyond target fisheries, especially those that impact adult age-classes.

4.4.1.1.5 Cumulative WA fishery impacts

Dusky and sandbar sharks are potentially exposed to multiple threats that, cumulatively, may have greater an impact on the stock than individual threats. This category includes all sources of extractive fishing mortality (targeted and non-targeted) on dusky sharks under Western Australia's management jurisdiction.

4.4.1.2 Impact of external influences

4.4.1.2.1 Non-WA extractive fisheries

The areas occupied by western Australian populations of dusky and sandbar sharks overlap with most WA-managed fisheries. Although the extent of these populations' overlap with other management jurisdictions is not fully understood, they are understood to be relatively minor and possibly intermittent. The boundaries and linkages of these and other populations (e.g. Indonesia or eastern Australia) are also not entirely resolved. Although the magnitude of catches from these stocks in other jurisdictions has not been quantified, past and present sources of external mortality are known or suspected to include the Commonwealth managed Western Tuna and Billfish Fishery (WTBF) and Southern and Eastern Scalefish and Shark Fishery (SESSF), the South Australian Marine Scalefish Fishery (MSF) and Northern Territory Offshore Net and Line Fishery (ONLF), as well as illegal catches by Foreign Fishing Vessels near or within the Australian Exclusive Economic Zone (EEZ).

4.4.1.2.2 Coastal and offshore development

Coastal development and the increasing population of WA, potentially pose risks to a range of aquatic resources through loss or degradation of habitats and indirectly through increasing fishing pressure. While offshore development of WA's petroleum and natural gas resources poses some potential risks, particularly in the North Coast Bioregion where there is a high level of exploration and development currently occurring, it is noted that dusky and sandbar sharks occupy very large ranges, across multiple habitats and are not known to exhibit any particular habitat or prey-specificity. Therefore, the risks of coastal and offshore development are only considered here for the sake of completeness.

4.4.1.2.3 Environmental influences

Oceanographic dynamics, in particular the influence of the warm, oligotrophic waters of the Leeuwin Current, are of major importance to the distribution and ecology of most marine species in WA (Caputi et al. 1996). A widespread and sustained period of unprecedented warm ocean temperatures ('marine heat wave') around the WA coast between 2011 and 2013 had major consequences for a large number of the state's aquatic resources (Pearce et al. 2011, Wernberg et al. 2013), with some suggestion that this event may have altered the distribution of some shark species.

4.4.2 Dusky shark

4.4.2.1 Impact of extractive fishing in WA

4.4.2.1.1 Temperate Demersal Gillnet & Demersal Longline Fisheries

Issue	C	L	Score	Risk Rating
Impact of TDGDLF neonate/juvenile catches	2	3	6	LOW
Impact of TDGDLF juvenile/sub-adult catches	3	2	6	LOW
Impact of TDGDLF adult catches	5	1	5	LOW

Justification: Dusky sharks are born in WA waters south of the Abrolhos Islands between February and June at a mean length of 75.3 ±3.8 cm FL (Simpfendorfer et al 1999). The species does not use discrete coastal nursery areas and the range over which birthing occurs is thought to vary depending on the strength of the Leeuwin Current. Young are typically born in Zone 1 of the JASDGDLF or the west of Zone 2 in years with a stronger Leeuwin Current (Department of Fisheries, unpublished data). The 16.5 to 17.8cm gillnet mesh sizes that are predominantly used in the TDGDLF, are highly size-selective for this species (Simpfendorfer and Unsworth 1998);

landings are mainly comprised of 0+ individuals and 91% of sharks are <100cm FL (< 2 years old; McAuley and Simpfendorfer 2003). At lengths below 100 cm FL, juvenile dusky sharks primarily inhabit inshore waters of the continental shelf <100m depth (Braccini et al. in prep). Conventional tag-recapture data indicate that as they grow, juvenile dusky sharks undertake a gradual northwestern movement (Figure 33 and Figure 34; Simpfendorfer et al. 1999). In South Australia, juvenile dusky sharks of between 100 and 250 cm FL begin to traverse the continental shelf more widely using both shallow, protected waters including inner gulfs and embayments, and deeper waters out to the shelf-break (Rogers et al., 2013a). Assuming dusky sharks behave similarly in Western Australian waters, these factors may result in decreased susceptibility to capture by TDGDLF operators, who mostly operate in waters shallower than 100m and use fishing gear that is highly selective for smaller sharks.

Since 2005/06, the trend in TDGDLF effective CPUE of dusky sharks has been variable but increasing (Braccini et al. 2014). Prior to this, management changes led to substantial rationalisation and reduction in fishing scale and intensity. Notable management events have included: a more than 60% reduction in the gear capacity of transferrable effort units and subsequent shift to an hourly effort management system; closure of waters <250m deep off the Perth metropolitan area between 31° S and 33° S and consequential removal of 33% of WCDGDLF units through a Voluntary Fisheries Adjustment Scheme (VFAS); annual 2 month seasonal closure of the fisheries west of 118°E between 2006 and 2014 and introduction of a maximum size limit (70cm interdorsal fin length, IDL) for dusky sharks. The number of vessels in the TDGDLF decreased from >100 during the 1980s to 26 presently (McAuley et al. 2015, Figure 7), the footprint of the fishery has stabilised from 58 to ~45 1 degree blocks/year (Figure 7), and effort has decreased to around 35% of peak levels. Accordingly, the total catch of dusky sharks has been reduced from a peak of 585t in 1988/89 to190 t in 2013/14 (Braccini et al., 2014).

In addition to the increasing effective CPUE for dusky sharks since 2005/06, there is no evidence of changes in length or weight composition (Figure 25 and Figure 31) or the proportions of 0+ sharks within the catch (Figure 30). As such, it was considered that TDGDLF catches of neonate and juvenile dusky sharks pose a remote (L1) likelihood of causing major (C4) or catastrophic (C5) consequences to the stock. Given the substantial reduction in scale and intensity of fishing compared to historical levels (which, based on analyses of empirical fishing mortality estimates, were sustainable in 1994/95 and 1995/96, Simpfendorfer, 1999; McAuley et al., 2007a), unacceptably high levels of fishing (C3) are also considered unlikely (L2). However, as biomass estimates are not available for neonate/juvenile dusky sharks and fishing mortality rates have not been estimated for over 20 years (Braccini et al 2015), it is still possible (L3) that the current, relatively low levels of fishing are at the maximum acceptable level (C2). In consideration of these assessments, the risk of TDGDLF catches of neonate/juvenile dusky sharks compromising the population's sustainability is low.

Due to the selectivity characteristics of the TDGLDF and measures to prohibit retention of dusky sharks with interdorsal length of over 70cm (approximately 1.8m TL), juvenile/sub-adult and adult fishing mortality in the TDGDLF is low. Incidental entanglement of larger sharks in demersal gillnets is presumed to be proportional to effort in the fishery and so is expected to have decreased over the last 20+ years, due to substantial effort reductions in the fisheries. Despite the overall reduction in WCDGDLF units from the VFAS, closure of Perth metropolitan waters in November 2007, concentrated fishing effort northward where there is a greater overlap with the distribution of larger sharks. However, given the lower overall level of effort expended in the WCDGDLF since these changes, the effects of any changes in size composition are thought to be minimal. The movements of acoustically-tagged sub-adult dusky sharks also confirms that these age classes spend little time within TDGDLF fishing grounds. The larger dusky sharks that were detected on the Perth or Southern Lines arrays, typically remained outside the 100m isobath (Figure 48, Figure 49), where TDGDLF fishing effort is relatively low, further reducing their likelihood of capture by the fishery. Based on available evidence, it was therefore considered unlikely (L2) that TDGDLF catches of juveniles/sub-adults are occurring at unacceptable levels (C3), so the risk to stock sustainability is low.

It was also considered unlikely (L2) that the TDGDLF could have a minor (C1) impact on adult dusky sharks, with all other consequences considered a remote probability (L1). Thus, the risk to adult sharks by the TDGDLF is also low under current management arrangements.

4.4.2.1.2 Recreational fishing

Issue	C	L	Score	Risk Rating
Impact of recreational neonate/juvenile catches	1	2	2	NEGLIGIBLE
Impact of recreational juvenile/sub-adult catches	1	1	1	NEGLIGIBLE
Impact of recreational adult catches	1	1	1	NEGLIGIBLE

Justification: The quantity of recreationally-caught dusky sharks in WA is minor compared to the commercial catch (Figure 23). Although the size composition of recreational catches is unknown, it has historically been assumed to be similar to the commercial fishery, comprising mainly neonates/juveniles with an average weight of 5kg (DoF 2008). There are anecdotal reports of land-based targeting of larger whaler sharks in WA, although it is unclear whether these are dusky sharks or sympatric species, especially bronze whaler sharks. Acoustic tagging data collected during the course of the current and associated studies, suggest that bronze whaler sharks are more common in nearshore waters around the lower West and South coasts of WA (*Appendix 4: Spatial detection patterns for bronze whaler sharks.*) than dusky sharks. Although dusky sharks may be a minor component of land-based recreational catches of large whaler sharks, until accurate records and species identification of these catches are available, these catches are assumed to comprise equal quantities of bronze whaler and dusky sharks. Although beach-caught whaler sharks are generally reported to be released alive and a maximum size limit of 70cm IDL prevents recreational fishers from legally retaining any large individuals, their eventual fate is uncertain. Irrespective of uncertainty about post-release mortality, the likelihood of recreational catches of juvenile/sub-adult or adult dusky sharks having any impact on stock sustainability (C1) is considered remote (L1), and it is considered unlikely (L2) that the level of recreational fishing of younger age classes would have a measurable impact on the stock (C1). Recreational fishing was therefore assessed as posing a negligible risk to all age groups of dusky sharks.

Table 24. Overview of risk scores and risk ratings for issues relating to the ecological sustainability of Western Australia's dusky shark resource

Component	Sub-component	Issue Group	Issue	Likelihood of Consequence 1	2	3	4	5	Risk score	Risk rating
Dusky shark	Neonate/juvenile (0 – 5 yrs)	Impact of extractive fishing in WA	Temperate Demersal Gillnet & Demersal Longline Fishery	5	3	2	1	1	6	Low
			Recreational fishing	2	1	1	1	1	1	Negligible
			Northern Shark Fishery	1	0	0	0	0	1	Negligible
			Other WA fisheries	1	0	0	0	0	1	Negligible
			Cumulative WA fisheries	5	3	2	1	1	6	Low
		Impact of external influences	Non-WA extractive fisheries	1	0	0	0	0	1	Negligible
			Coastal and offshore development	1	0	0	0	0	1	Negligible
			Environmental influences	1	0	0	0	0	1	Negligible
	Juvenile/sub-adult (5 – 25 yrs)	Impact of extractive fishing in WA	Temperate Demersal Gillnet & Demersal Longline Fishery	3	2	2	1	1	6	Low
			Recreational fishing	1	0	0	0	0	1	Negligible
			Northern Shark Fishery	1	0	0	0	0	1	Negligible
			Other WA fisheries	1	0	0	0	0	1	Negligible
			Cumulative WA fisheries	3	2	2	1	1	6	Low
		Impact of external influences	Non-WA extractive fisheries	4	3	2	1	1	6	Low
			Coastal and offshore development	1	0	0	0	0	1	Negligible
			Environmental influences	1	0	0	0	0	1	Negligible

Adults (> 25 yrs)	Impact of extractive fishing in WA	Temperate Demersal Gillnet & Demersal Longline Fishery	2	1	1	1	1	5	Low
		Recreational fishing	1	0	0	0	0	1	Negligible
		Northern Shark Fishery (current conditions)	1	0	0	0	0	1	Negligible
		Northern Shark Fishery (resumption of fishing)	3	3	3	2	1	9	Medium
		Other WA fisheries	1	0	0	0	0	1	Negligible
		Cumulative WA fisheries (current conditions)	1	0	0	0	0	1	Negligible
		Cumulative WA fisheries (resumption of NSF)	3	3	3	2	1	9	Medium
	Impact of external influences	Non-WA extractive fisheries	5	4	3	2	2	10	Medium
		Coastal and offshore development	2	2	1	1	1	4	Low
		Environmental influences	1	0	0	0	0	1	Negligible

4.4.2.1.3 Northern Shark Fisheries

Issue	C	L	Score	Risk Rating
Impact of NSF neonate/juvenile catches	1	1	1	NEGLIGIBLE
Impact of NSF juvenile/sub-adult catches	1	1	1	NEGLIGIBLE
Impact of NSF adult catches (current conditions)	1	1	1	NEGLIGIBLE
Impact of NSF adult catches (resumption of fishing)	3	3	9	MEDIUM

Justification: The combination of existing fishery-dependent and -independent data, previous conventional tagging and new acoustic monitoring data collected during this project provides the most accurate and complete picture of the life cycle of dusky sharks off Western Australia. As dusky sharks grow they gradually move northward through the West Coast Bioregion, before joining sub-adult and adult dusky shark stock components in the Gascoyne and Northern Bioregions. However, sub-adults and adults remain highly mobile and undertake periodic southward movements, usually (but not always) during warmer months (Figure 60 and Figure 61). The frequency of southward movement based on acoustic data suggests that, at least for females, these movements are probably linked to natal migrations, as has been suspected.

Since the closure of the western portion of the WANCSF (114°-118°E and South of 18°S) in 2005 and the termination of the NSF EPBC Act accreditations as approved Wildlife Trade Operations (WTOs) in 2008 and 2009, operators have elected not to fish since early 2009 (Figure 23, Molony et al. 2013). However, as fishing could theoretically resume in these fisheries, they are considered here for completeness. Notwithstanding the potential for a future resumption of the NSF, the closure of the WANCSF off the Pilbara coast to protect adult sandbar sharks, along with the previous (1993) prohibition on the commercial use of "shark fishing gear" throughout the rest of the Gascoyne Bioregion, has currently eliminated targeted shark fishing across most of the known distribution of sub-adult dusky sharks off northern WA. As a result, the consequence of zero juvenile/sub-adult dusky shark catches (C1) was assessed as being remotely likely (L1) to compromise stock sustainability under current management arrangements (i.e. negligible risk). As neonates/juveniles are primarily distributed in the south-west of the State and were never caught in appreciable quantities by this fishery, the risk associated with catches of these stock components are also negligible (C1, L1).

Although the northern and north-eastern extent of adult dusky sharks' distribution is not clearly defined and the magnitude of previous catches is uncertain due to potential misreporting issues, catches would resume if the NSF fishing recommenced with the previously-permitted gear types. As protection of whaler sharks with inter-dorsal fin lengths >70cm does not apply north of 27°S latitude, it is assumed that those catches would result in close to 100% mortality. Dusky sharks have an exceptionally low biological productivity (Smith et al., 1998; Simpfendorfer, 1999) and recruitment is sensitive to even very low levels (0.01-0.02y^{-1}) of adult mortality (McAuley et al. 2007a).

On this basis, the catch of adult dusky sharks that occurred during the late 1990s to mid-2000s, while poorly quantified, was likely (L4) to have been unacceptable (C3) (i.e. constituted a high risk to stock sustainability). However, the management changes implemented in response to unsustainable exploitation of sandbar sharks indirectly led to a complete cessation of fishing by the NSF in early 2009. As a result, there has been no catch of adult dusky sharks for nearly eight years and the likelihood of any consequence (C1) resulting from adult fishing mortality is, therefore, remote (L1) and the current risk to the stock is negligible. Any future resumption of fishing by the NSF (within the five year scope of this risk assessment), however, would increase this risk. Noting the sensitivity of the adult stock to even low rates of fishing mortality (1-2%), without effective safeguards, it was considered possible (L3) that, following a resumption of NSF activity, adult catches could recur at unacceptable (C3) levels, in which case the fisheries would pose a medium risk to this stock.

4.4.2.1.4 Other WA Fisheries

Issue	C	L	Score	Risk Rating
Impact of other WA fisheries' neonate/juvenile catches	1	1	1	NEGLIGIBLE
Impact of other WA fisheries' juvenile/sub-adult catches	1	1	1	NEGLIGIBLE
Impact of other WA fisheries' adult catches	1	1	1	NEGLIGIBLE

Justification: Dusky sharks were historically caught and retained by other WA fisheries, with potentially significant quantities caught by "wetline" hook methods, particularly in the West Coast Bioregion (Figure 23). Since 2006, commercial landings of sharks and rays have been prohibited in non-target fisheries throughout WA, as has the use of wire traces and large hooks, previously used to target large sharks for their fins. Furthermore, the practice of shark-finning (retaining fins and discarding the rest of the shark) was effectively prohibited in 2006. Nevertheless, because of the longevity of this species, the impacts of this previous source of mortality may still be suppressing recruitment to the stock and, despite the significant penalties for illegally landing shark fins, there is potential for this activity to resume in the future. The risks associated with these activities are therefore included here for completeness.

Catches of sharks, including dusky shark, are known to have occurred in numerous other State-managed commercial fisheries prior to their commercial protection in 2006, although records of these catches are patchy and generally unspecified (Borg and McAuley, 2004). These fisheries included the open access 'wet-line' sector (now partially managed as the West Coast Demersal Scalefish Interim Managed Fishery), numerous trawl fisheries, the Kimberley Gillnet and Barramundi Fishery and the South and West Coast Estuarine Managed Fisheries. Despite the 2006 prohibition on retention of shark catches in (most of) these fisheries, incidental bycatches are likely to have continued since then, although these have presumably been discarded when they occurred. Although neither the quantity nor size composition of dusky sharks' contribution to these poorly documented catches cannot be reliably quantified, even small catches of sub-adult and adult dusky sharks have the potential to affect recruitment and should, therefore, be considered. However, based on current management arrangements and the remote likelihood (L1) that relatively minor (C1) historical catches (in comparison to the target shark fisheries), other fisheries were assessed as posing negligible risk to the stock.

4.4.2.1.5 Cumulative WA Fisheries

Issue	C	L	Score	Risk Rating
Cumulative impact of neonate/juvenile catches	2	3	6	LOW
Cumulative impact of juvenile/sub-adult catches	3	2	6	LOW
Cumulative impact of adult catches (current conditions)	1	1	1	NEGLIGIBLE
Cumulative impact of adult catches (resumption of NSF)	3	3	9	MEDIUM

Justification: Current management arrangements have resulted in negligible-low risk ratings for the majority of issues, and the cumulative impacts of multiple issues is not expected to materially increase the risks to dusky sharks. In keeping with the precautionary principle of ESD, therefore, the highest risk for each particular age group was therefore chosen to reflect the cumulative risk to dusky sharks.

4.4.2.2 Impact of external influences

4.4.2.2.1 Non-WA extractive fisheries

Issue	C	L	Score	Risk Rating
Impact of non-WA neonate/juvenile catches	1	1	1	NEGLIGIBLE
Impact of non-WA juvenile/sub-adult catches	2	3	6	LOW
Impact of non-WA adult catches	5	2	10	MEDIUM

Justification: Given available catch and conventional tagging data, which suggest that neonates/juveniles occur almost exclusively within nearshore waters off the WA coast (Figure 33 and Figure 34), there was considered to be a remote (L1) likelihood of minimal consequences (C1) to the sustainability of the dusky shark stock from non-WA fisheries' catches of these age groups. The risk of neonate/juvenile fishing mortality from non-WA fisheries was therefore considered to be negligible.

Older juvenile and sub-adult dusky sharks are, however, known to be caught by the MSF and the Gillnet Hook and Trap (GHAT) sector of the SESSF that operates off the South Australian coast. Rogers et al. (2013b) found that in 2007-2010 dusky sharks comprised around 20% of the whaler shark catch (previously assumed to be entirely bronze whaler sharks), which has averaged ~70 t annually since 1990. Fishery-dependent sampling indicated that the dusky shark component of these catches is/was comprised predominantly of juvenile/sub-adults. Satellite and acoustic tagging shows that individuals move between SA and WA waters (Rogers et al. 2013a, 2013b). Although the quantity of South Australian MSF catches is quite small relative to the TDGDLF, given the inherent sustainability risks of applying fishing mortality to older dusky sharks than are assessed and managed in the TDGDLF, it is possible (L3) that catches may be at the maximum acceptable level (C2). Based on this, the risk of extra-jurisdictional catches of juveniles/sub-adults was assessed as low.

Sub-adult and adult dusky sharks are known and suspected to have been historically caught by other fisheries outside of WA's jurisdiction. In particular, the development of the Commonwealth WTBF during the mid-late 1990s (then known as the Southern and Western Tuna and Billfish Fishery) is believed to have led to substantial incidental catches of adult sharks along the edge of the continental shelf, which at the time were estimated to have amounted to 1400 – 2100 individuals in 1999 (Rose and McLoughlin 2001; Borg and McAuley 2004). Acoustic telemetry data from the current study support previous assumptions that outer continental shelf and (presumably) proximal oceanic waters are commonly utilised by adult and larger sub-adult dusky sharks during migrations along the West coast of Australia. A code of conduct was developed for the WTBF in 2003 to reduce the potential impacts of this fishery on shark stocks, which included shark bycatch trip limits and a handling protocol (AFMA 2008). However, by then, the fishery had moved further offshore into oceanic waters where dusky shark bycatch was likely to be negligible. In recent years fishing activity in the WTBF has been extremely low. However, as it is uncertain if and how the fishery might redevelop in the future, its potential future risk is considered here for completeness.

In addition to catches by domestic fisheries, adult dusky sharks are potentially vulnerable to capture by foreign fishing vessels, both legally in international jurisdictions and within the MOU box off the Kimberley coast, as well as illegally within the Australian Exclusive Economic Zone (EEZ). As part of a bilateral Memorandum of Understanding (MOU) between Indonesia and Australia, traditional Indonesian fishers are allowed to capture sharks, including dusky sharks, using traditional methods in an area of Australia's Northwest Shelf (Stacey 2001). Illegal fishing for sharks has also occurred (and may be continuing) throughout Australia's northern waters (Field et al. 2009). However, the magnitude of Illegal, Unregulated and Unreported (IUU) fishing, including by foreign fishing vessels, of dusky sharks is not well understood and the risk from this activity is assumed to fluctuate through time in response to social, economic, and political factors. Indonesia has the highest global production of sharks and rays and although much of this catch is likely to come from waters outside of Indonesia's territorial waters, emerging data suggest that a genetically shared stock of dusky sharks exists in Indonesian waters (Junge et al, in review). Thus, the potential impacts of adult dusky shark catches outside of the Australian Exclusive Economic Zone (EEZ), also need to be considered.

Although the magnitude and composition of historical, current and potential future levels of foreign fishing pressure on adult dusky sharks is uncertain, given the inherent vulnerability of this critical stock component, it was considered that, extraneous fishing pressure could conceivably lead to permanent or widespread depletion (C5), at least under exceptional circumstances (L2). Thus the risk to the dusky shark stock from these sources of fishing is thought to be medium.

4.4.2.2.2 Coastal and offshore development

Issue	C	L	Score	Risk Rating
Impact of development on neonates/juveniles	1	1	1	NEGLIGIBLE
Impact of development on juveniles/sub-adults	1	1	1	NEGLIGIBLE
Impact of development on adults	2	2	4	LOW

Justification: Coastal development and associated human population growth in the southwest region could indirectly lead to impacts on neonate/juvenile and juvenile/sub-adult dusky sharks through increased commercial and recreational fishing pressure and impacts of habitat degradation on prey species with flow-on trophic cascade effects to dusky sharks. Since this species does not use discrete inshore nursery areas, impacts of habitat degradation do not directly pose a significant risk. Therefore, especially within the timeframe of this risk assessment, the likelihood of any impact (C1) from development impacts to neonate/juvenile age classes appears remote (L1) and risk to these age groups were considered to be low. Development of WA's offshore petroleum and natural gas resources on the Northwest Shelf, however, overlaps with the core area of adult distribution of dusky sharks. However, it is considered unlikely (L2) these activities could be having any more than a moderate impact (C2). Therefore, the risk from coastal and offshore development was considered to be low.

4.4.2.2.3 Environmental influences

Issue	C	L	Score	Risk Rating
Environmental influences on neonates/juveniles	1	1	1	NEGLIGIBLE
Environmental influences on juveniles/sub-adults	1	1	1	NEGLIGIBLE
Environmental influences on adults	1	1	1	NEGLIGIBLE

Justification: Given their widespread distribution, mobility, wide temperature-range tolerance, apparent lack of habitat-specificity and relatively broad diets (Simpfendorfer et al., 2001), it was assumed that dusky sharks have an inherently low vulnerability to environmental influences (Chin et al., 2010). At least anecdotally, the range over which dusky sharks give birth appears, however, to shift in relation to the strength of the Leeuwin current. A risk assessment for chondrichthyans in the Great Barrier Reef Marine Park also found dusky sharks to have low vulnerability to the effects of climate change (Chin et al. 2010). Given the apparently high adaptive capacity of dusky sharks, any consequence (C1) is considered remote (L1) and the risk from environmental influences was therefore assessed to be negligible.

4.4.3 Sandbar shark

4.4.3.1 Impact of extracting fishing in WA

4.4.3.1.1 Temperate Demersal Gillnet & Demersal Longline Fisheries

Issue	C	L	Score	Risk Rating
Impact of TDGDLF neonate/juvenile catches	1	1	1	NEGLIGIBLE
Impact of TDGDLF juvenile/sub-adult catches	3	2	6	LOW
Impact of TDGDLF adult catches	1	1	1	NEGLIGIBLE

Justification: Relatively little is known about the early life history of sandbar sharks as only a small number of neonates have been recorded from a wide area of continental shelf waters off WA (McAuley et al 2007b). Due to their smaller size at birth relative to dusky sharks, the size selectivity of 16.8cm and 17.5cm mesh sizes used in the TDGDLF results in catches primarily comprising older juvenile and sub-adult age classes (McAuley et al., 2007a). Birth occurs at 40–45 cm FL after a 12 month gestation (McAuley et al 2007b). The timing of parturition seems to be protracted, peaking during summer and autumn. Neonates have been captured throughout WA waters in depths 28 to 119 m suggesting that, unlike other parts of the world, coastal embayments are not used as nursery areas by sandbar sharks (McAuley et al 2007b). Based on the lack of neonates and younger juveniles in TDGDLF catches, there was assessed to be a remote (L1) risk of even minimal consequences (C1) from TDGDLF fishing mortality impacts on these age groups. The West Coast Bioregion is the core range of larger juveniles/sub-adults and is where targeted fishing by the TDGDLF developed during the mid-1990s and continues to be focused. Juvenile sandbar sharks begin recruiting to the TDGDLF around 60 cm FL. Gillnet selectivity was estimated to peak at 80–100 cm FL (McAuley et al. 2007b), with a broader range of age classes (3–12 year olds) being vulnerable to the fishery, relative to dusky sharks (McAuley et al 2007a). Catch rates are greatest in depths of 80 to 120m. Conventional tagging data and TDGDLF catch records suggest that sandbar sharks of these sizes remain resident within the West Coast Bioregion year-round and do not undertake extensive movements or migrations (Figure 35 and Figure 36, McAuley et al. 2005).

Targeting of sandbar sharks by the TDGLDF commenced in the mid-1990s and increased steadily through the late 1990s and early 2000s (Figure 24) as effort shifted offshore in response to declining catch rates of target stocks, particularly dusky sharks. From 2000 to 2005 catches fluctuated between 158 and 215 t, corresponding to age-specific fishing mortality rates of 0.1–0.28 yr-1 (McAuley et al. 2007a). Demographic analysis indicated increasing catches in the early 2000s were likely to be unsustainable, particularly due to the high level of concurrent adult fishing mortality in the NSF (see below). Since then there has been a major reduction in effort in the West Coast Bioregion, where the majority of juvenile/sub-adult catch was taken, with commensurate reductions in catch (45 t in 2013/14). This is well-below the management trigger of 120 t that was developed to accommodate a low level of ongoing NSF catch in the mid-2000s (McAuley et al., 2005).

The time-series of effective sandbar shark CPUE showed a fluctuating trend that is thought to reflect fishing behaviour rather than trends in abundance (McAuley et al., 2005). Neither length (Figure 27) nor weight (Figure 32) compositions suggest a shift in the catch composition towards larger sharks, and fishery-wide fluctuations in the mean weight of sandbar sharks, derived from logbook records, are assumed to be due to the natural variability in the distribution of multiple co-occurring age-classes and/or artefacts of catch reporting behaviour (Figure 32). It is therefore considered unlikely (L2) that fishing will occur at unacceptable (C3) levels unless there is a major shift in fishing behaviour, e.g. shifting from gillnets to longlines as began to occur in the mid-2000s. The risk of juveniles/sub-adult exploitation by the TDGDLFs is therefore low.

Acoustic tagging data (Figure 55) confirm the inference from fishery-dependent and –independent catch composition data that West Coast and South Coast Bioregions are not core areas of distribution for adult sandbar sharks. Furthermore, the selectivity characteristics of 16.5 and 17.8cm mesh sizes are not effective at catching these larger-sized sharks. It was therefore concluded that there is limited potential for the TDGDLF to catch appreciable quantities of adult sandbar sharks and that there is a remote (L1) risk of any consequence (C1) occurring (i.e. a negligible risk).

4.4.3.1.2 Recreational fishing

Issue	C	L	Score	Risk Rating
Impact of recreational neonate/juvenile catches	1	1	1	NEGLIGIBLE
Impact of recreational juvenile/sub-adult catches	1	1	1	NEGLIGIBLE
Impact of recreational adult catches	1	1	1	NEGLIGIBLE

Justification: Sandbar sharks are not targeted by recreational fishers but are known to be caught by anglers around the State (McAuley et al., 2005; Ryan et al., 2013). Even allowing for an unknown quantity of unidentified sandbar shark catch, the quantity of recreational catches in WA is minor compared to the commercial catch (Figure 24). Additionally, juvenile sandbar sharks' preference for deeper waters is thought to reduce their relative susceptibility to capture. Despite this, conventional tags have been recovered from recreational fishers, particularly off North-West Cape and in North-West Shelf waters, indicating that some recreational catch of sub-adults and adults occurs. However, in the West Coast Bioregion and to a lesser extent, in the South Coast Bioregion, sandbar sharks in the named and unspecified recreational whaler shark catches are assumed to be mainly juveniles/sub-adults, although adults and young juveniles and neonates may also occasionally be caught. For all bioregions the annual reported catch of sandbar sharks by recreational fishers is < 1 tonne (Figure 24, Ryan et al. 2013), however the species is also likely to account for an additional unknown portion of the 3,958 unidentified whaler sharks retained in 2011/12. Based on the relatively minor magnitude of these catches, there was considered to be a remote (L1) likelihood of any consequence (C1) arising from recreational exploitation of any life stage, so these risks were assessed to be low.

Table 25. Overview of risk scores and risk ratings for issues relating to the ecological sustainability of Western Australia's sandbar shark resource

Component	Sub-component	Issue Group	Issue	Consequence 1	2	3	4	5	Risk score	Risk rating
Sandbar shark	Neonate/juvenile (0 – 6 yrs)	Impact of extractive fishing in WA on juveniles	Temperate Demersal Gillnet & Demersal Longline Fishery	1	0	0	0	0	1	Negligible
			Recreational fishing	1	0	0	0	0	1	Negligible
			Northern Shark Fishery	1	0	0	0	0	1	Negligible
			Other WA fisheries	1	0	0	0	0	1	Negligible
			Cumulative WA fisheries	1	0	0	0	0	1	Negligible
		Impact of external influences on juveniles	Non-WA extractive fisheries	1	0	0	0	0	1	Negligible
			Coastal and offshore development	1	0	0	0	0	1	Negligible
			Environmental influences	1	0	0	0	0	1	Negligible
	Juvenile/ sub-adults (6 – 15 yrs)	Impact of extractive fishing in WA on sub-adults	Temperate Demersal Gillnet & Demersal Longline Fishery	3	2	2	1	1	6	Low
			Recreational fishing	1	0	0	0	0	1	Negligible
			Northern Shark Fishery (current conditions)	1	0	0	0	0	1	Negligible
			Northern Shark Fishery (resumption of fishing)	5	4	4	3	3	15	High
			Other WA fisheries	1	0	0	0	0	1	Negligible
			Cumulative WA fisheries (current conditions)	3	2	2	1	1	6	Low
			Cumulative WA fisheries (resumption of NSF)	5	4	4	3	3	15	High

	Impact of external influences on sub-adults	Non-WA extractive fisheries	1	0	0	0	0	1	Negligible
		Coastal and offshore development	1	0	0	0	0	1	Negligible
		Environmental influences	1	0	0	0	0	1	Negligible
Adults (> 15 yrs)	Impact of extractive fishing in WA on adults	Temperate Demersal Gillnet & Demersal Longline Fishery	1	0	0	0	0	1	Negligible
		Recreational fishing	1	0	0	0	0	1	Negligible
		Northern Shark Fishery (current conditions)	1	0	0	0	0	1	Negligible
		Northern Shark Fishery (resumption of fishing)	5	4	4	3	3	15	High
		Other WA fisheries	1	0	0	0	0	1	Negligible
		Cumulative WA fisheries (current conditions)	1	0	0	0	0	1	Negligible
		Cumulative WA fisheries (resumption of NSF)	5	4	4	3	3	15	High
	Impact of external influences on adults	Non-WA extractive fisheries	5	4	3	2	2	10	Medium
		Coastal and offshore development	2	2	2	1	1	6	Low
		Environmental influences	1	0	0	0	0	1	Negligible

4.4.3.1.3 Northern Shark Fishery

Issue	C	L	Score	Risk Rating
Impact of NSF neonate/juvenile catches	1	1	1	NEGLIGIBLE
Impact of NSF juvenile/sub-adult catches (current conditions)	1	0	1	NEGLIGIBLE
Impact of NSF juvenile/sub-adult catches (resumption of fishing)	5	3	15	HIGH
Impact of NSF adult catches (current conditions)	1	0	1	NEGLIGIBLE
Impact of NSF adult catches (resumption of fishing)	5	3	15	HIGH

Justification: All available evidence indicated that, like dusky sharks, sandbar sharks comprise a single biological stock in WA, with juveniles concentrated in the West Coast and Gascoyne Bioregions and adult biomass concentrated between the Abrolhos Islands and the Kimberley. Conventional tag recaptures demonstrated that, like dusky sharks, juveniles gradually migrate up the West Coast as they grow before joining the adult stock in the Gascoyne and North Coast Bioregions (McAuley et al., 2005). Based on observations of seasonal catches of adult sandbar sharks by the TDGDLF (typically during autumn), it was previously hypothesised that adults undertake north-south seasonal migrations, although, given the limited and dispersed observations of neonate sandbar sharks, it was unclear whether parturition was the main driver of these migrations. However, unlike dusky sharks, previous DNA microsatellite analysis, suggested a finer-scale bioregional structuring within the sandbar population (McAuley et al. 2005). The acoustic tagging data collected during the current study, provide further evidence of functional stock-structuring that require further resolution but which may have important implications for future assessment and management of this stock. Nonetheless, as neonate and juvenile life stages do not commonly occur in the area that the NSF operated, there was considered to be a remote (L1) likelihood of any possibility (C1) that these fisheries will impact the stock through catching neonate, juvenile and sub-adult sandbar sharks. Thus these risks were assessed as low.

The predominantly sub-adult and adult sharks tagged within the Gascoyne and North Coast Bioregions showed a relatively high degree of occupancy in the Ningaloo area (Figure 43), which is contrary to a hypothesis of them undertaking regular long-distance southerly migrations from the North-West of the State. Although, a small number of sandbar sharks from the Ningaloo array were detected in deeper waters off Perth and the South-West of the State (Figure 48 and Figure 49), it seems increasingly unlikely that adult sandbar sharks are generally as mobile as previously believed. If this Bioregional separation of functional stock sub-units is characteristic of sharks in the northern Bioregion, then not only might breeding biomass have been more heavily impacted than previously estimated (McAuley et al. 2005) but measures to recover this key stock component may have been more effective than expected. However, their low detection rates off Perth and to the South might indicate that the majority of sandbar sharks do not regularly travel that far South.

Following the introduction of restrictions on the use of shark fishing gear ("shark longlines," "shark droplines" and pelagic gillnets) off the north coast of WA in 1993, catch of sandbar sharks was initially low (< 20 t, Figure 24). However, during the late 1990s and early 2000s, a rapid escalation in targeting occurred with reported catch peaking at 763 t in 2004/5. Conflicting sources of CPUE data also suggested substantial underreporting of catch may have occurred (McAuley et al. 2005). Demographic analysis incorporating empirically-derived fishing mortality rates, indicated that these catches of predominantly sub-adult and adult sharks (Figure 28) were increasingly unsustainable (McAuley 2009). These model predictions were supported by a concurrent 58% decline in a fishery-independent CPUE abundance index between 2002 and 2005. Demographic modelling further suggested that in addition to TDGDLF catches, this stock could sustain as little as 1–2% fishing mortality of adult age classes, which at the time could have been in the order of 20-40t (McAuley *et al.* 2007a, DoF, unpublished data).

Based on current understanding of the inherent vulnerability of sandbar sharks it is almost certain (L5) that the intensity of fishing during the early 2000s had a major (C4) impact, implying that the risk to the stock at that time was Severe. As a result of the strong management intervention commensurate with this level of risk, catch was greatly reduced after 2005 and there has been zero catch of sandbar sharks in the NSF since 2009. It is important to point out that the current risk to the stock is and has been negligible since 2009 (C1, L1) and will likely remain low if catch of sub-adults and adults by the NSF stays below the suggested sustainable levels for the target fisheries (i.e. TDGDLF and NSF; McAuley 2006). However, resumption of fishing by even a small number of vessels could rapidly reverse any recovery that may have occurred since fishing ceased. Based on prior experience, there is clear evidence to suggest that widespread and long-term depletion (C5) is possible (L3) within five years. As such the risk to the sandbar shark stock from a resumption of NSF activities is considered high.

4.4.3.1.4 Other WA Fisheries

Issue	C	L	Score	Risk Rating
Impact of other WA fisheries' neonate/juvenile catches	1	1	1	NEGLIGIBLE
Impact of other WA fisheries' juvenile/sub-adult catches	1	1	1	NEGLIGIBLE
Impact of other WA fisheries' adult catches	1	1	1	NEGLIGIBLE

Justification: The Pilbara Fish Trawl Fishery (PFTF) historically retained 20 to 30 tonnes of predominantly adult female sandbar sharks during the early 2000s (Figure 29, McAuley et al. 2005). A range of other prawn trawl fisheries operating in the North Coast Bioregion also have the potential to interact with adult sandbar sharks. Together with strong anti-finning penalties and state-wide commercial protection of all sharks in 2006, the introduction of bycatch reduction devices in WA trawl fisheries is understood to have reduced the mortality of sandbar sharks posed by these fisheries to very low levels. Although sandbar sharks are distributed widely throughout the West Coast, Gascoyne and North Coast Bioregions, they are generally distributed outside the range of most other WA-managed commercial fishing methods that they are vulnerable to. Based on these current management arrangements, the likelihood of any consequence (C1) occurring due to other fisheries' catches of sandbar sharks at any life stage was considered remote (L1) and the associated risk to the stock as low.

4.4.3.1.5 Cumulative WA Fisheries

Issue	C	L	Score	Risk Rating
Cumulative impact of neonate/juvenile catches	1	1	1	NEGLIGIBLE
Cumulative impact of juvenile/sub-adult catches (current conditions)	3	2	6	LOW
Cumulative impact of juvenile/sub-adult catches (resumption of NSF)	5	3	15	HIGH
Cumulative impact of adult catches (current conditions)	1	1	1	NEGLIGIBLE
Cumulative impact of adult catches (resumption of NSF)	5	3	15	HIGH

Justification: For neonates/juveniles the cumulative likelihood of any consequence (C1) was assessed as remote (L1). Thus, based on the current management arrangements and precautionary principal of ESD, the cumulative risk to sandbar sharks was chosen to reflect that of the TDGDLF for juveniles/sub-adults and the NSF for adults.

4.4.3.2 Impact of external influences

4.4.3.2.1 Non-WA extractive fisheries

Issue	C	L	Score	Risk Rating
Impact of non-WA neonate/juvenile catches	1	1	1	NEGLIGIBLE
Impact of non-WA juvenile/sub-adult catches	1	1	1	NEGLIGIBLE
Impact of non-WA adult catches	5	2	10	MEDIUM

Justification: Because of the size selectivity of target fishing gear, little is known about the distribution of neonates/juvenile sandbar sharks, however they are assumed to occur primarily within continental shelf waters of WA, South of 26^{o} 30'. Thus it was concluded that the likelihood of any consequence (C1) arising from external fishing mortality of these age groups is remote (L1). Likewise, as the core distribution of juvenile/sub-adult sandbar sharks appears to be within WA waters, the likelihood of any consequence (C1) is also remote (L1). Thus the sustainability risk of non-WA fisheries' catches of neonates/juvenile and juvenile/sub-adult sandbar sharks is negligible.

Like dusky sharks, adult sandbar sharks have historically been caught and retained in other fisheries outside of WA's jurisdiction. In particular, sandbar sharks are known to have been caught during the development of the Commonwealth WTBF during the mid-late 1990s (Borg and McAuley 2004). During the 2000s, a range of management measures were introduced to reduce the impacts of shark bycatch in this pelagic longline fishery, including trip limits and gear restrictions (AFMA 2008). In recent years fishing activity in the WTBF has been low; however, there remains uncertainty about the extent to which adult sandbar sharks could be impacted in the future.

In addition to capture by domestic fisheries, for the reasons given for dusky sharks above, adult sandbar sharks are known to be vulnerable to capture by foreign vessels, fishing both legally (in the MOU box, where tagged sandbar recaptures have been reported) and illegally in Australian and neighbouring waters. However, given sandbar sharks' more northerly distribution, higher fin values, and smaller size, adult sandbar sharks may be at relatively higher risk of Foreign Fishing mortality than dusky sharks. Despite the high level of uncertainty about current and potential fishing of adult sandbar sharks by non-WA fisheries and the inherent vulnerability of this stock to adult fishing mortality, it is still considered unlikely (L2) that fishing could lead to permanent or widespread depletion (C5) within the five year scope of this risk assessment. Thus, the risk arising from adult sandbar shark catches by non-WA managed fisheries was considered to be medium.

4.4.3.2.2 Coastal and offshore development

Issue	C	L	Score	Risk Rating
Impact of development on neonates/juveniles	1	1	1	NEGLIGIBLE
Impact of development on juveniles/sub-adults	1	1	1	NEGLIGIBLE
Impact of development on adults	3	2	6	LOW

Justification: For the same reasons outlined for dusky sharks, the likelihood of any impact (C1) from development to neonate/juvenile and juvenile/sub-adult age groups was judged to be remote (L1). In regards to the more northerly-distributed adult stock components, it was considered unlikely (L2) that coastal and offshore development could have a high impact on stock sustainability within the timeframe of this risk assessment (C3), resulting in a low risk.

4.4.3.2.3 Environmental influences

Issue	C	L	Score	Risk Rating
Environmental influences on neonates/juveniles	1	1	1	NEGLIGIBLE
Environmental influences on juveniles/sub-adults	1	1	1	NEGLIGIBLE
Environmental influences on adults	1	1	1	NEGLIGIBLE

Justification: For the same reasons outlined for dusky sharks any consequence resulting from environmental influences (C1) was considered remote (L1) and the resulting risks as negligible.

5. Discussion

5.1 Acoustic tagging

This study internally implanted 344 *C. obscurus* (n=103), C. *plumbeus* (n=101), *F. macki* (n=40) and *M. antarcticus* (n=100) with acoustic transmitters and includes data from another 53 internally-tagged *C. brachyurus* tagged during the associated Shark Monitoring Network project (McAuley et al., 2016). By July 2015, 207 of these individuals had been detected along the western Australian coastline. Tagged individuals were monitored for a period of up to 1,453 days. In general, acoustic tagging studies have typically been done at more limited spatial and temporal scales and have been focused on species that exhibit stronger aggregation/residency to an area. Recently, however, acoustic receiver networks have started to be used for monitoring the broad-scale movements of sharks (Heupel et al. 2015; Espinoza et al. 2016). In this study, the four most commercially-important shark species of WA were monitored across multiple temporal and spatial scales (from hours to 100s of days and even >1000 days and from 10s to 1,000s of km). This allowed the construction of a more complete picture of each species' movement behaviours than has been obtained from small-scale acoustic tagging studies. It must be noted, however, that the larger species, dusky and sandbar sharks, had a higher detection rate (58 and 55%, respectively) than gummy and whiskery sharks (33%) which could be due to a combination of the intrinsic movement patterns of these species, the spatial distribution of the receiver arrays and those species' higher rates of recapture by targeted fishing.

An important aspect of the current study is that most individuals were large juveniles or adults, which allows the first detailed understanding of these life history stages' movement ecology around the WA coast. In the case of dusky and sandbar sharks, such detailed data could not have been obtained from fishery-dependent methods because adult dusky and sandbar sharks predominantly reside in areas closed to commercial fishing, are naturally lower in abundance than juveniles, are rarely and unpredictably captured by TDGDLF operators and (in the case of dusky sharks) are commercially protected. Thus, obtaining sufficient quantities of conventional tag recapture data to describe their movements would have been unrealistic. Further, because conventional tagging studies are dependent on recapture information provided by fishers, there are multiple sources of potential biases, which may arise from the distribution and behaviour of fishing, gear selectivity, reporting behaviour, etc. While the results from this study partially confirmed that these stock components undertake seasonal migrations into commercial fishing grounds as predicted by Simpfendorfer et al. (1996, 1999) and McAuley et al. (2005, 2007b), the current data also revealed features of these stocks' spatial and temporal dynamics that were inconsistent with the previous inferences about them. The information generated in our study was also used to incorporate fishery-independent movement data into population dynamics models for gummy and whiskery stocks.

Dusky sharks showed the most extensive displacements throughout WA and were not detected within any detection array for extensive periods. Smaller individuals were only detected in the south and larger individuals showed north-south and south-north displacements with 15 individuals completing round-trip long-distance north-south migrations. Satellite and conventional tagging studies in South Australia (Rogers et al. 2013a), the Gulf of Mexico (Hoffmayer et al. 2014) and South Africa (Hussey et al. 2009) also indicate that dusky sharks undertake long-distance displacements in other parts of the world, in the order of 100s to 1000s of km at maximum speeds (based on minimum linear displacement) in the order of 10s to 100 km per day (Hussey et al. 2009; Rogers et al. 2013a; Hoffmayer et al. 2014,; present study). Hence, the present and previous studies strongly indicate that dusky sharks are a highly mobile species with broad-scale movements.

Most dusky shark individuals undertaking migratory movements completed one migratory event within a year though up to 3.5 migratory events were detected during the monitored period. The north-south displacements occurred mostly during the warm months (summer and autumn) and the south-north displacements occurred mostly during the cooler months (winter and spring). This pattern was clear in larger males. The larger females, however, showed a more complex pattern. Some individuals conformed to the 'North in winter-spring and South in summer-autumn' pattern whereas other individuals were consistently detected North during both the warmer and cooler months. Also, the GLM predicted that about half of the tagged female population would move south in a given year. These findings would support the 2-year reproductive cycle hypothesis (McAuley et al. 2007a). However, it is still unclear if all migrating individuals actually reproduce and a potentially longer reproductive cycle should not be entirely disregarded.

Sandbar sharks were exclusively tagged in the north of the state and were mostly detected at the Ningaloo array, where both males and females showed three different movement patterns: some individuals resided within the Ningaloo array and were detected continually, other individuals were detected and then not detected for long periods of time and other individuals were only detected for a few days. These patterns may suggest 'behavioural polymorphism', where seemingly comparable individuals of a population exhibit very different behavioural patterns (Rees et al., 2010). Behavioural polymorphism has been reported for some teleost species, where some individuals exhibit regular patterns and defined movements while others display irregular and nomadic movements (e.g. Grüss 2015) or when only a fraction of the population undertakes regular reproductive migrations, while another fraction show fidelity to an area throughout the year (e.g. Willis et al. 2003). High levels of behavioural polymorphism have direct implications for the effectiveness of spatial management (Grüss 2015). However, at least in part, these results also reflect the disparate receiver coverage between Perth and Ningaloo Reef and complete lack of receivers off the North Coast of WA. Movements of 12 sandbar sharks (22% of those detected) from Ningaloo to Perth and the Southern Lines array (n=2) and from release locations in the Kimberley (n=3), North West Shelf (n=4) and Shark Bay (n=3) into the Ningaloo array demonstrate that sandbar shark movements extend far beyond the Ningaloo Reef region. It may therefore be that migration does occur to the South, but not always as far South as Perth or that the Ningaloo region itself is close to the southern extent of adult's migrations from the North-East. Unlike sandbar sharks, dusky sharks were generally detected for very brief periods within the arrays so no overall patterns of differences in movement among individuals could be inferred. For gummy and whiskery sharks, which were less mobile, a receiver array with a higher spatial resolution would be required to test the 'behavioural polymorphism' hypothesis.

The apparent preference of sandbar sharks for deeper continental shelf and upper slope waters, may also account for the non-detection of some sharks. Nevertheless, in addition to the two sharks detected off Perth, ten of the 54 detected sandbar sharks did demonstrate extraneous movements from the Kimberley (n=3), North West Shelf (n=4) and Shark Bay (n=3) into the Ningaloo. Thus it is likely that equivalent movements also occur in the opposite directions, which might have underrepresented movements of sharks between the Kimberley and Pilbara coasts to the southern Gascoyne and northern West Coast bioregions.

Natal philopatry is common in shark species, and it has been identified for juvenile sandbar sharks in the West Atlantic population, where pups occupy estuaries and embayments (Grubbs et al. 2005). In WA, adults are thought to migrate south to pup and neonates are most often found south of the Houtman Abolhos Islands (McAuley et al. 2005, 2007b). Based on conventional tagging, these authors hypothesised that juveniles remain in temperate waters for several years and slowly migrate northwards to join the breeding stock while adults migrate south to temperate waters to give birth. Several reported recaptures of conventionally-tagged adults and sub-adults partly support this hypothesis (McAuley et al. 2005). In North America, sandbar sharks are highly migratory (Kohler et al. 1998) with adults annually migrating along the eastern coast from overwintering areas as far south as the Gulf of Mexico to summer nurseries as far north as Great Bay, New Jersey(Rechisky and Wetherbee 2003) . In our study, however, only two individuals (two females larger than L_{50}) were detected in southern WA. These detections were recorded between February and April by receivers located in deep water. The lack of detections in arrays south of Ningaloo Reef may be an artefact of the limited depth distribution of the receivers (<200 m), as large sandbar sharks have been caught to depths of 334m off North West Cape during fishery-independent surveys (Department of Fisheries unpublished data). Alternatively, the limited number of detections off the southern half of WA may be an indication of more complex population structuring than previously thought or the lack of receiver coverage for more than 1,000km to the south of the Ningaloo array. Therefore, it is unclear to what extent these observations are representative of the broad-scale movements of sandbar sharks in WA and few inferences on migratory movements can be drawn for this species.

Gummy and particularly whiskery sharks were less mobile than sandbar and dusky sharks. Conventional mark-recapture studies have reported movements from Tasmania to WA (Walker 2010) for gummy sharks and between Cape Leeuwin in WA and Spencer Gulf in South Australia for whiskery sharks (Department of Fisheries, unpublished). Gummy sharks in south-eastern Australia showed average displacements in the order 100–250 km with a maximum displacement of >2,500 km (Brown et al. 2000). Comparably, in this study gummy sharks showed average displacements of 238 km with a maximum displacement of >900 km. For whiskery sharks, conventional tagging in south-western WA showed that most tagged individuals were either detected or recaptured within 50 km of the point of release, even after long periods at liberty, although six individuals showed displacements to South Australia, of between 940km and 2,035km (Department of Fisheries, unpublished). In our study, average long-distance displacements were larger (> 240 km) but the maximum displacement recorded was similar (374 km) to the 384 km (Simpfendorfer et al. 1996). These differences in movement behaviour resulted in higher exchange rates among management zones for gummy sharks than for whiskery sharks.

The calculated exchange rates must, however, be interpreted with caution. Recorded displacements are a function of receiver location. The location of the receiver lines for the Southern array did not align with the West Coast/JASDGDLF Zone 1 boundary and sharks were not tagged evenly or randomly within each of the zones (e.g. no individuals were tagged in the WC). In addition, individuals released in Zone 2 were tagged near the boundary with Zone 1, possibly introducing a positive bias in the calculated exchange rates from Zone 2 to Zone 1 and therefore in the probability of staying within Zone 2 for those sharks released within this zone. However, integrating the conventional tagging data (generated by previous FRDC-funded projects) into the estimation of exchange rates among zones would minimise the biasing effects described above. Finally, by integrating the estimation of exchange rates in the population dynamics models (base case scenario), the effects of other sources of information that reflect population dynamics (abundance, size composition, etc.) would balance the potential biasing effects of the acoustic tagging data.

5.2 Catch and effort standardisation

We applied best-practices for the standardisation of commercial catch and effort data. First, catch and effort data were manipulated following agreed business rules for improving data quality. An R script that clearly implements these rules in a logical and easy to follow manner was developed (https://github.com/JuanMatiasBraccini/Catch_and_effort_manipulation). Next, these data were standardised using GLM models. Finally, missing observations were imputed based on explicit criteria, an index was constructed, and its corresponding uncertainty was quantified. At present, the derived indices are not considered to be reliable representations of abundance. Although catch rate standardisation attempts to remove confounding effects of variables not related to abundance, this does not necessarily result in CPUE being proportional to abundance. Factors such as targeting behaviour, management changes and changes in fishing efficiency may not be fully accounted for as the information required for this may not be available (Punt et al. 2000). For the TDGDLF daily logbooks, fishing trips (potentially targeted at different species) undertaken within the same year-month-block had to be grouped into a single record in order to combine these data with the monthly returns, which comprise the vast majority of the catch and effort records (1975-76 to 2005-06). In addition, the implementation of a range of management measures (Borg and McAuley 2004, DoF 2008, McAuley et al. 2015) and the transition from monthly returns to daily logbooks affected the reporting of catch and effort data. Hence, there seems to be a disjunct between the standardised catch rate series derived from monthly and daily logbook records. As this effect is not related to abundance, it is recommended that the two data series are treated separately and two indices are constructed for future assessments. Once these indices are available, the population dynamics models developed in this study can be calibrated and used to re-assess the status of whiskery and gummy shark stocks.

5.3 Population dynamics of whiskery and gummy sharks

This study developed a range of population dynamics models (from biomass dynamics to spatial size-based and age-structured models) to reassess the stocks of whiskery and gummy sharks. The base case model was designed to capture the movement patterns quantified using the acoustic tagging information in addition to movement information collected as part of previous FRDC-funded conventional tagging studies. As pointed out above, the models will be calibrated once a reliable index of abundance is available.

5.4 Risk assessment of dusky and sandbar sharks

Although the TDGDLF is the only active fishery currently targeting dusky and sandbar sharks in WA, eight distinct issues were identified as potential risks to achieving the sustainability objectives for these resources. Each issue was further subdivided to evaluate the risk to three life stages, resulting in a total of 54 issues being considered in the risk assessment. The large number of possible issues highlights the complexities of managing wide-ranging and migratory marine species with spatially-segregated life stages. The consequence-likelihood risk assessment method used here provided a framework for screening this large number of potential issues. In the absence of a population dynamics model, it provided a flexible and rapid qualitative method for integrating the outcomes of this research project into scientific management advice for these species.

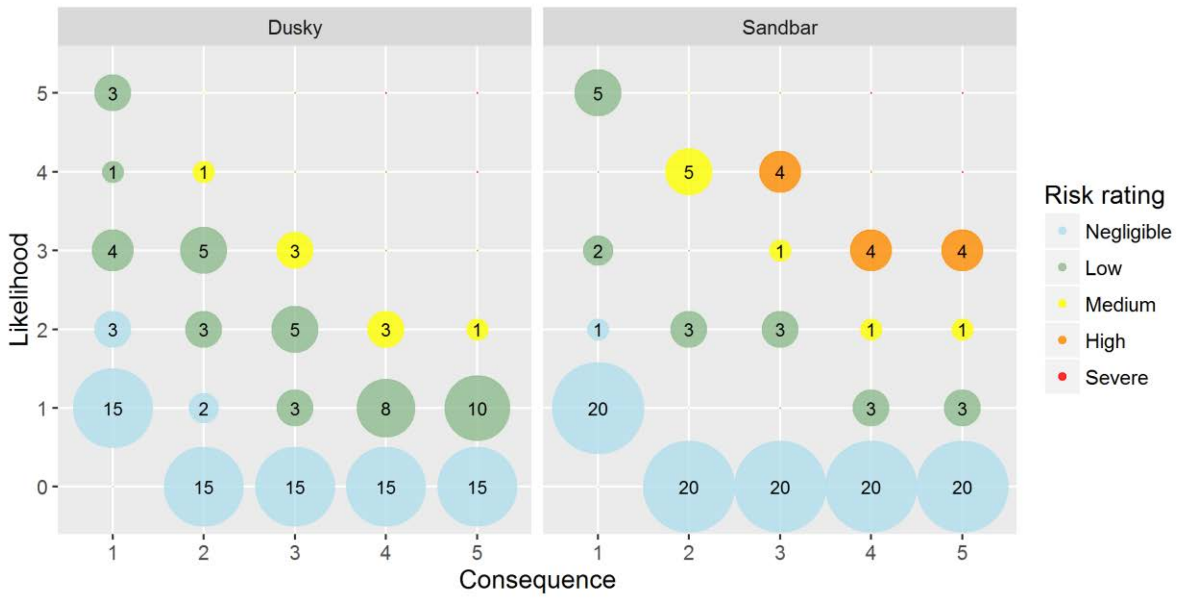


Figure 68. Risk profile of all individual consequence likelihood scores (5 pairs × 54 issues) for dusky and sandbar sharks from the risk assessment (see Table 24 and Table 25). The size of bubbles is proportional to number of pairs, and the colour denotes the corresponding risk rating

A key finding of this assessment was that risk ratings for the vast majority of issues — 46 out of 54 — were at or below the acceptable level of ‘Medium’ risk (Figure 68). Furthermore, all but 2 of the 34 issues for neonates/juvenile and juvenile/sub-adult life stages were assessed as negligible or low risk. The two high risk issues for these age groups both related to a resumption of sub-adult sandbar catches in the NSF (see below). This outcome was due to the large number of management changes that have been introduced for all extractive fisheries that catch or may catch sandbar and dusky sharks in WA over the past two decades. In the main commercial fishery, the TDGDLF, this has included large reductions in target fishing effort, spatial closures, seasonal closures, commercial protection, gear restrictions and size-limits. These measures have reduced landings by non-target fisheries, in most cases to zero and limited the potential impacts on critical life history stages of dusky and sandbar stocks. Although population dynamics models do not currently exist for these species, all available information from the TDGDLF was congruent with acceptable levels of depletion (C1-2) and therefore negligible or low risk ratings.

For both dusky and sandbar sharks the risks were greatest for the adult components of the stocks, and two issues were identified as posing an unacceptable risk to adult sandbar sharks. Specifically, a resumption of fishing by the NSF was identified as the only source of adult mortality that could potentially pose a medium to high risk to any component of these stocks. It is important to note that these fisheries have been inactive (zero catch) since 2009 and the current risks from this fishery are negligible (Molony et al. 2013). Should catches remain at zero or below the 20 t level considered sustainable for sandbar sharks (McAuley, 2006), the risk to sub-adult and adult sandbar sharks would remain negligible although, without additional safeguards, risks to adult dusky sharks may not be ameliorated to below medium. Based on the inherent vulnerability and low biological productivity of these long-lived a low productivity sharks, a rapid escalation in fishing activities, as occurred in the early 2000s, could still lead to unacceptable risks within 5 years. This is based on prior evidence of rapid escalation in targeting of, in particular, adult sandbar sharks by the NSF. In contrast to previous analysis of conventional tagging data (McAuley et al., 2005), acoustic tagging of adult sandbar sharks in this study found that a proportion of individuals showed high fidelity to the Ningaloo Reef area. As telemetry data were not collected from north of Ningaloo, this study was unable to provide information about the northern boundary of the stock or potential northward movements. As such, there is still the potential for the stock to be impacted should fishing recommence by the JANSF in the Kimberley region, even if the WANCSF remains closed.

While the vast majority of risks to dusky and sandbar sharks by extractive fisheries in WA are now negligible-low, non-WA fisheries still pose a medium risk to the sustainability of these stocks by virtue of their known or expected catches of adults. These fisheries include a range of domestic and legal and illegal foreign fishing fleets, for which, accurate species-specific catch records and size composition data are generally lacking. Although some of these sources of fishing mortality are currently at low levels (eg. WTBF, illegal fishing in the Australian Fishing Zone by foreign vessels), sustainability risks could rapidly escalate if activity returns to previous levels in future.

Direct comparison of these assessments with previous risk assessments is not straightforward since the latter were undertaken at the fishery (rather than the stock) level and did not distinguish threats to specific life stages. A 2002 ESD risk assessment of the TDGDLF (DoF, Unpublished) assessed dusky sharks as high risk, primarily due to unquantified cryptic mortality occurring on adults at the time. As a result of multiple factors (e.g. specific management measures in WA and Commonwealth fisheries, economic pressures and increased maritime border surveillance), dusky shark catches by both WA and non-WA managed fisheries are now believed to be much lower. Therefore, while the reduction in assessed risk to currently negligible to low levels over the last 14 years appears justified, it is acknowledged that without adequate safeguards, a resumption of targeted fishing of large demersal sharks by the NSF could elevate the sustainability risk to dusky sharks to an unacceptable level. The medium risk assessed here also acknowledges that the NSF could have a greater impact on dusky sharks than was assessed in 2002 as data collected since then indicates that the stock has a more northerly distribution than was previously considered.

The 2002 risk assessments of sandbar sharks in the TDGDLF and NSF (DoF Unpublished) rated the risks to the sustainability of this stock as medium ('moderate'). This assessment was based on preliminary (2 year) estimates of fishing mortality derived from FRDC project no 2000/134 and deterministic demographic modelling of published biological parameters, which indicated that 2000/01 and 2001/02 catch levels in the TDGDLF and NSF were sustainable. However, when demographic analyses were subsequently updated with additional years' fishing mortality rate estimates and empirically-derived biological parameters, these preliminary estimates were found to be overly-optimistic. Before the partial-closure of the NSF and loss of export approvals, reported catches ultimately peaked at 763 t, nearly 40 times the level estimated to have been sustainable (in addition to TDGDLF catches of 120t).

The current catch of sandbar sharks in the NSF has been zero since 2009/10 (inclusive) and catches in the TDGDLF have declined to less than 50t per annum for the last three years for which data are available. Should catches of sub-adults and adults by the NSF remain zero (or close to zero) and catches of the TDGDLF remain below 120t, future risks to the sustainability of this stock are likely to remain negligible-low. However, the current assessment recognises the potential for rapid escalation of risks to sandbar sharks to unacceptable (high) levels within five years from a resumption of previous levels of fishing in the NSF.

Conclusion

This project successfully tagged and monitored a large number of commercially-fished shark species, around a large extent of the WA coastline. Acoustic telemetry from these sharks revealed a variety of movement dynamics at different temporal and spatial scales. Significantly, because data were collected from regions and depths of the TDGDLF that are largely unfished or closed to fishing and from age classes that are not subject to targeted fishing in WA, it is unlikely that these insights into stocks' temporal and spatial dynamics could have been obtained from conventional tagging studies. As such, the movement parameters derived from acoustic tag detections provide unique fishery-independent inputs to the new gummy and whiskery shark population dynamics models, re-assessments of contemporary risks to the recovery of dusky and sandbar sharks and to future assessments of these commercially-important stocks.

Acoustic telemetry results provided evidence to largely confirm previous hypotheses about the movements of sub-adult and adult dusky sharks, with both males and females demonstrating clear migratory displacements between northern and southern WA. While most individual dusky sharks remained in the northern extent of the study area during winter and spring before moving to southern receiver arrays in summer–autumn, not all large females undertook such movements each year. This observation is also consistent with previous assumptions of a non-annual parturition cycle in this species (Simpfendorfer, 1999; McAuley et al., 2007a) however it could not be determined whether these patterns were more likely to represent a 2- or 3-year reproductive cycle. Description of these movement patterns has effectively 'closed the loop' in terms of explaining the ontogenetic-segregation of this stock in WA waters. As previously reported, dusky sharks are born around the South-West of the State before gradually migrating northwards along the West coast (Simpfendorfer et al., 1996; 1999) to join the breeding stock as sub-adults or adults. The observation of regular southerly migrations of both males and females, provides the first direct evidence of the mechanism by which parturition occurs more than 1000km to the south of what is considered to be the core distribution of adult dusky sharks in the North-West of WA.

There was no strong supporting evidence for similar assumptions about adult sandbar sharks' migration into temperate waters to give birth as suggested by McAuley et al. (2005). A small proportion of sandbar sharks (n=6) showed high levels of regional fidelity within the Ningaloo array but most were only detected intermittently. Despite extended periods of non-detection, only 2 sandbar sharks were detected away from Ningaloo, one in the metropolitan OTN array and another in the Cape Leeuwin array. The large distance between the Ningaloo receivers and first acoustic array south of this location (Perth) almost certainly affected the number detections elsewhere.

Together with existing FRDC-funded conventional tag-recapture data, new acoustic telemetry data were used to inform qualitative consequence–likelihood assessments of the remaining sustainability risks facing dusky and sandbar sharks. Risk ratings for the majority of issues were at acceptable levels, including for the main target fishery, the TDGDLF, and most other WA fisheries. These results reflect the outcomes of the evidence-based management changes that have been introduced over the last 20 years in the fisheries that continue to regulate the exploitation of these stocks.

The only potential high risk identified was if excessive fishing mortality of adult sandbar shark occurred from a potential resumption of fishing in the NSF. This situation would also pose a medium risk to dusky sharks. Under current practices, in which all shark fishing only occurs in the south and west coast bioregions, the risks to both species are negligible-low. Should fishing recommence in the north coast region, alternative management arrangements would need to be developed to minimise catch of these two species' breeding stocks to avoid impacting recruitment of juveniles to the TDGDLF and the consequential sustainability and economic risks to those fisheries.

Gummy and particularly whiskery sharks showed relatively less movement than dusky and sandbar sharks, although individuals were still capable of relatively large-scale displacements.

The quantitative data about their movements between TDGDLF management zones, however, provides a valuable basis for including and assessing these stocks' spatial and temporal characteristics in a variety of population dynamics models that were developed through this project. Once the issues with developing relative abundance indices for these stocks can be resolved, these models will be used to re-assess their status and the potential implications of differential implementation of management measures in the fisheries over the last 25 years. Further work is still required to understand how changes in management and reporting behaviour have affected the catch rates reported by the fisheries over the history of these fisheries. Work to generate a time series of standardised CPUE data that more-accurately reflect trends in these stocks' abundance is therefore still ongoing.

This study has demonstrated how acoustic telemetry can be used to determine the movement patterns of species at the scale of fisheries management. This information has already been used to inform updated assessments of the status and future risk profiles of these important shark species.

Implications

This study took advantage of a unique opportunity provided by national and international collaborations to concurrently install more than 300 passive acoustic receivers around the WA coast between North-West Cape and the Recherche Archipelago. As the majority of these receivers have now been removed (though the Perth OTN line and the AATAMS Ningaloo array are still operating), it may be unlikely to collect a similar set of large-scale movement data for these stocks again. Thus, the telemetry data collected through this project are likely to remain the best available source of information on dusky, sandbar, gummy and whiskery shark movements for many years to come.

Although problems with standardising CPUE data across monthly and daily reporting periods could not be overcome before preparation of this report, the models that have been developed will be used to provide new gummy and whiskery shark stock assessment advice for management of the TDGDLF. By incorporating stock movement information, these models will be of particular benefit in assessing how these stocks may be impacted by the potential introduction of additional spatial management arrangements designed to exclude demersal gillnet fishing effort around colonies of Australian Sea Lions. As the displacement of fishing effort resulting from these exclusion areas will result in changes to spatial and temporal patterns of fishing behaviour, industry and fishery managers will require more spatially-explicit assessment advice that can be facilitated through these models.

Confirmation of adult dusky shark movement patterns has enabled a more refined assessment of Resource sustainability risks to this stock. While previous FRDC-funded research quantified the risks of fishing mortality on sub-adult and adult stock components, quantifying the cryptic sources of fishing of those age classes was regarded as unfeasible. Thus, management measures were introduced in the early-mid 2000s to mitigate these known sustainability risks. The movements of adult dusky sharks recorded in this project, assisted in qualitatively re-assessing the risks associated with sub-adult and adult sharks' movements through fisheries they are known to be susceptible to capture in. Results of this assessment suggested that the measures introduced to mitigate the risks associated with adult fishing mortality are likely to have been successful. These conclusions should provide industry and fishery managers with confidence that existing management arrangements are providing adequate protection for the breeding stock, allowing it to recover from any previous level of depletion. Similarly, the data collected on movements of adult sandbar sharks was less conclusive but still suggested that existing spatial management, especially the prohibition of commercial shark fishing off the Gascoyne and Pilbara coasts, has dramatically reduced the sustainability risks to this stock.

Risk assessments did, however, emphasise that resumption of fishing in the NSF would pose medium to high risks to dusky and sandbar shark stocks, respectively, if they resumed in a similar manner to the mid-2000s. As the potential to reactivate these fisheries is currently under consideration, these results dictate that methods for mitigating these risks need to be developed before fishing resumes. Although this study was not designed to describe these stocks' spatial overlap with the NSF, the internal implantation of acoustic transmitters ('tags') with expected battery lives of up to ten years during this project, does provide an option for further studies into their distribution and movements in NSF fishing grounds.

Recommendations

Recommendations for further steps that may be taken to develop the results and outcomes from this project include:

- Development of standardised CPUE indices that take into account the nature of commercial catch and effort data reporting and spatio-temporal resolution and use these to calibrate the population dynamics models developed in the present study
- Develop reference points that align with different life history traits of the species (e.g. Braccini et al. 2015) and with DoF guidelines for developing harvest strategies (DoF 2015). Clear species-specific reference points are essential for accurate stock assessments.
- More generally, develop a harvest strategy for the TDGDLF where decision rules that determine appropriate harvest levels are clearly defined for meeting the fisheries' objectives.
- Consideration should be given to the potential of medium to high Resource sustainability risks to dusky and sandbar sharks in determining future arrangements for the NSF if these fisheries recommence.
- Consideration should be given to utilising internally-tagged sharks from the present project in further studying the spatial overlap of these species with NSF fishing grounds.

Further development

A key area that needs further development is the constructing of abundance indicators, particularly for whiskery and gummy sharks as this is required in their stock assessments.

A reliable index of abundance needs to be constructed in order to calibrate the population dynamics models developed and inform management. For this, the monthly return and daily logbook data must be treated separately. This will allow analyses at a higher resolution level for the daily logbook data. For example, targeting behaviour can be explored at the level of shot or trip, rather than at a monthly-aggregated level.

Once these indices are developed, all available information should be used in the species' assessments. The base case model (3.3.7.3 Base case model and models S7–S11) provides the platform for integrating additional information (conventional and acoustic tagging data, catch size composition, age and length data). The incorporation of these data could aid parameter estimation and also better account for structural uncertainty. The base case model provides a further improvement to the current model used for assessing these stocks by incorporating CPUE uncertainty in the models' objective function. An alternative to dealing with unrepresentative abundance indices could be to exclude/down weight this data series. Specifically for dealing with the observed spike in gummy shark catches and catch rates in the late 2000s, the effect of effort saturation/gear competition (e.g. Punt et al. 1999; Tuck 2011) could be incorporated.

These observations highlight the importance of further exploring options for constructing the most reliable abundance index for whiskery and gummy sharks and for using all available information, not just commercial catch and effort, for assessing these stocks.

Finally, species-specific biological reference points are needed to assess model estimates of current biomass and exploitation levels. Currently, assessment of stock status is based on a single target biomass reference point (40% unfished biomass) applied to all species. However, Braccini et al. (2015) showed that different life histories result in different reference points for whiskery, gummy, dusky and sandbar sharks. In addition, limit (an unacceptable boundary which, if breached, triggers immediate significant management actions) and threshold (an intermediate level between targets and limits used as an 'early warnings' so an appropriate management response is generated before limit levels are breached) reference points must be defined as part of the requirements for development a harvest strategy for the TDGDLF (DoF 2015).

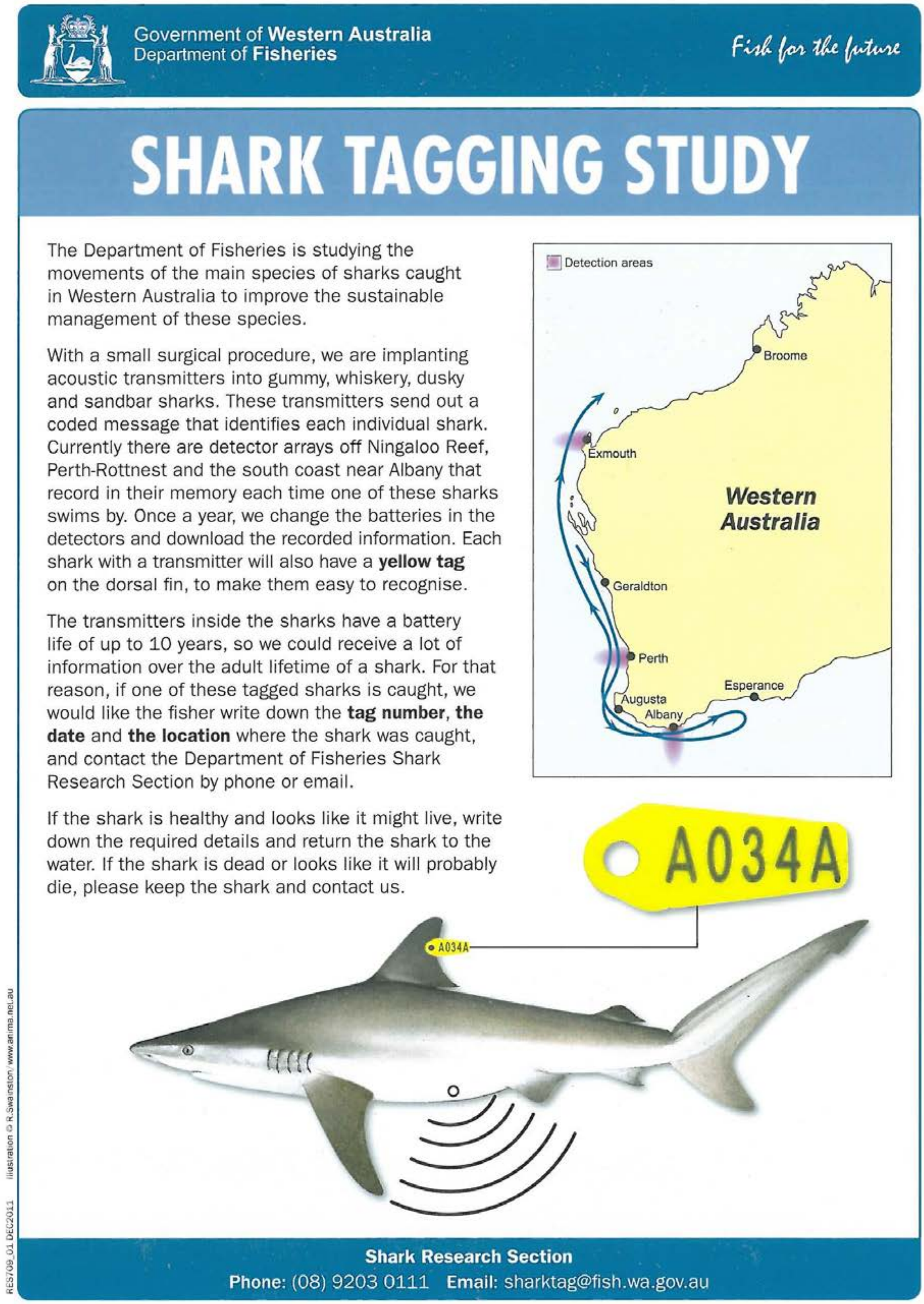
Extension and Adoption

Some of the earlier results were presented at the TDGDLF Annual Management Meeting in September 2013, and in several international conferences (2012 ASFB Annual Conference, Adelaide, VIII *Jornadas Nacionales de Ciencias del Mar*, Comodoro Rivadavia, Argentina, 2012, and Sharks International, Durban, South Africa, 2014). The data chapters and population dynamics modelling chapter will be written up as scientific papers. The draft final report was presented to industry, managers and other stakeholders at the TDGDLF Annual Management Meeting in October 2016.

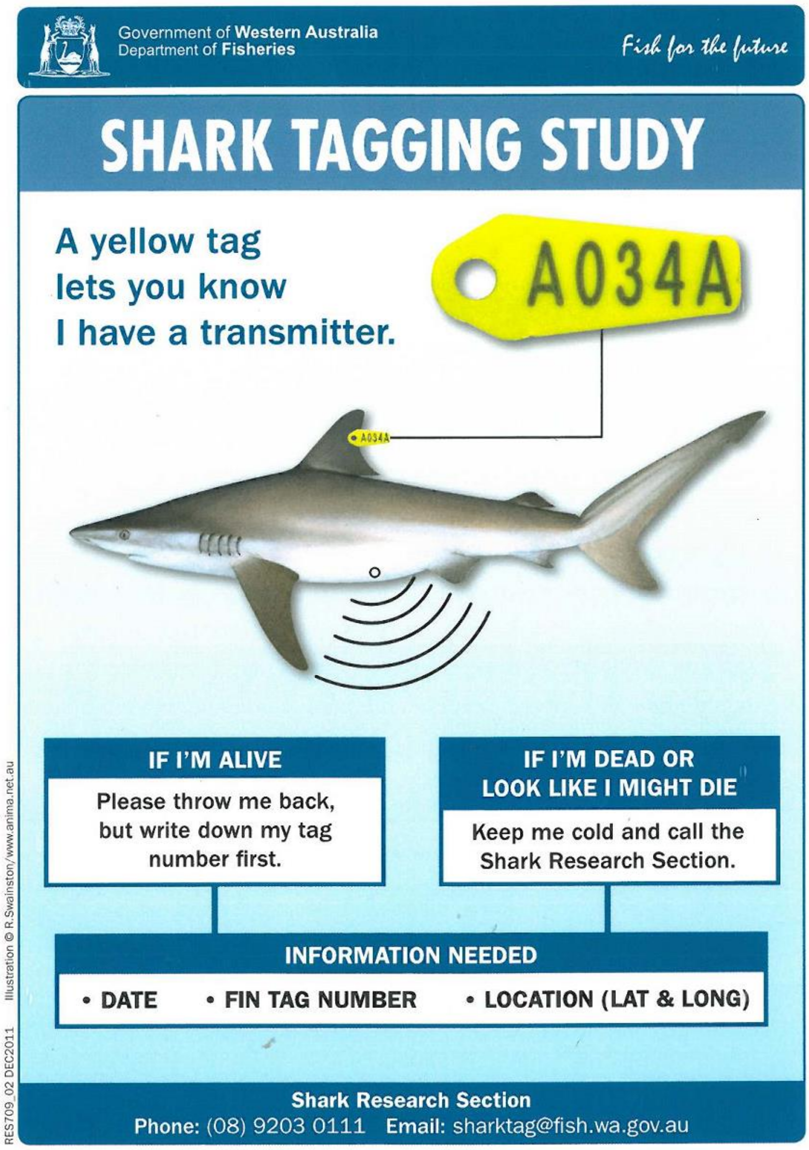
Project coverage

None relating to the outputs of this project.

Project materials developed



Example of the posters distributed among fishers



Example of the fridge magnets distributed among fishers

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Displaying uncertainty in the biological reference points of sharks

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ABSTRACT

Variability in life-history traits influences biological reference points (BRP). For data-poor species such as sharks, BRP have commonly been set at arbitrary values with little consideration of life-history variability. The temperate shark fisheries of Western Australia were used as a case study to develop species-specific limit, threshold and target BRP that consider life history uncertainty and population dynamics. Shark species with higher biological productivity had lower biomass BRP and higher fishing mortality BRP (F_{BRP}) than less productive species. The interplay of gear selectivity and variability in life history traits influenced BRP uncertainty, particularly for F_{BRP}. Traditionally, stock status is determined by comparing a stock-performance indicator (SPI) to a BRP point estimate based on a set probability of SPI exceeding the point BRP. We proposed an alternative approach where we considered distributions for both SPI and BRP and compared the proportion of overlap between those distributions. In practice, we consider this an improvement to characterizing both uncertainties and an easier-to-grasp concept than a probability of exceeding a point estimate.

1. Introduction

Ecologically sustainable development is a primary goal for fishery management. In practice, this high-level objective must be translated to an operational level where specific management actions are defined and their performance evaluated. In recent years, this has started to be formalised into Harvest Strategy Policies (HSP), where the actions needed for achieving agreed objectives, the monitoring and assessment processes, and the rules that control fishing intensity are specified (Smith et al., 2009). At the core of HSP is the clear definition of biological reference points (BRP) because stock status is defined by comparing these benchmarks to stock-performance indicators (SPI, e.g. spawning biomass and fishing mortality). If the SPI exceeds the BRP, management actions are triggered to control different aspects of the fishery or stock (Anonymous, 1995).

BRP are commonly expressed in terms of biomass (B_{BRP}) or fishing mortality (F_{BRP}) and consist of targets (representing the optimum state to deliver economic and/or social objectives) and limits (representing an unacceptable boundary which, if breached, triggers immediate significant management actions) (Anonymous, 1995). Threshold BRPs (an intermediate level between target and limit BRP) have also been adopted as 'early warnings' so an appropriate management response is generated before limit levels are breached (e.g. Hart et al., 2009).

Typically, optimal depletion (i.e. maximum sustainable yield, MSY), estimated from quantitative assessments, is used to define BRP. Due to data requirements, MSY estimation is only possible for data-rich fisheries. As an alternative, MSY proxies, which are commonly derived from per-recruit type analyses, can be used (Restrepo and Powers, 1999). These per-recruit proxies may be based on yield per-recruit (YPR) such as F_{max}, the fishing mortality that maximizes YPR, or $F_{0.1}$, the fishing mortality where the slope of the YPR curve is only one-tenth the slope at the origin. Alternatively, proxies can be based on a ratio of spawners per recruit with fishing mortality relative to spawners per-recruit without fishing mortality, referred to as spawning potential ratio (SPR). Based on work by Clark (1991, 1993), SPR ratios of 30%–40% are often proposed as defaults.

MSY proxies have been used for defining BRP for sharks as most species are data-limited (e.g. Chang and Liu, 2009; Tsai et al., 2011). Early BRP for sharks were general values across all species expressed as some proportion of the unfished biomass (B_U) (Bensley et al., 2010). To avoid arbitrary levels that may be too

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REVIEWS

Incorporating movement in the modelling of shark and ray population dynamics: approaches and management implications

Matias Braccini · Alexandre Aires-da-Silva · Ian Taylor

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Abstract The explicit incorporation of movement in the modelling of population dynamics can allow improved management of highly mobile species. Large-scale movements are increasingly being reported for sharks and rays. Hence, in this review we summarise the current understanding of long-scale movement patterns of sharks and rays and then present the different methods used in fisheries science for modelling population movement with an emphasis on sharks and rays. The use of movement data for informing population modelling and deriving management advice remains rare for sharks and rays. In the few cases where population movement was modelled explicitly, movement information has been solely derived from conventional tagging. Though shark and ray movement has been increasingly studied through a range of approaches these different sources of information have not been used in population models. Integrating these multiple sources of movement information could advance our understanding of shark and ray dynamics. This, in turn, would allow the use of more adequate models for assessing stocks and advising management and conservation effort.

Keywords Elasmobranchs · Integrated assessment · Tagging · Conservation

Introduction

Incorporating movement in the modelling of population dynamics may not be required when a population of a species is closed and fishing is distributed uniformly over the population range (Beverton and Holt 1957). However, migrations and large-scale movements are increasingly being reported for many marine taxa. These widely evolved traits are driven by ecological and biogeographic factors such as seasonality, spatiotemporal distribution of resources, habitats, predation and competition (Alerstam et al. 2003). Understanding these movements can allow a better representation of their population dynamics (Hilborn 1990; Xiao 1996). Furthermore, the explicit consideration of space in fisheries science and governance may address management failures caused by the inappropriate set of boundaries and the disregard of spatial dynamics (Lorenzen et al. 2010).

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Masters Thesis – Spatial and temporal movement dynamics of four commercially Important shark species in Western Australia

Spatial and Temporal Movement Dynamics of Four Commercially Important Shark Species in Western Australia

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Supervisors:

Research Scientist Dr. Matias Braccini, Department of Fisheries

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Braccini, J.M. & R. McAuley. 2014. Going spatial: movement information and population dynamics of commercially-fished Western Australian sharks. Sharks International, Durban, South Africa.

Braccini, J.M. & R. McAuley. 2012. Movimiento y dinámica poblacional de tiburones de Australia Occidental. VIII Jornadas Nacionales de Ciencias del Mar 2012, Comodoro Rivadavia, Argentina (in Spanish).

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Appendices

Appendix 1: Intellectual property.

No intellectual property has arisen from the research that is likely to lead to significant commercial benefits, patents or licences.

Appendix 2: Staff.

The following DoF staff were engaged on the project:

Matias Braccini: fieldwork, data management, analysis and reporting (85%, 4 y).

Rory McAuley: Principal Investigator, development and management of tagging, acoustic receiver installation, collection and maintenance, staff and data systems (50%, 4 y).

Alastair Harry: data analysis and reporting (5%, 2 y).

Silas Mountford, Ian Keay, DoF (25%, 4y).

Mark Davidson (15%, 2y).

Nick Jarvis (10%, 2y).

Skipper and crews of the Research Vessel '*Naturaliste'* and Patrol Vessels, '*Hamelin'*, '*Houtman*' and '*Walcott*': equipment data collection (5%, 3 y).

Adrian Thomson, Peter Stephenson, Norm Hall, Alex Hesp, Ross Marriot, Ainslie Denham, Simon de Lestang, DoF, provide statistical support (2.5%, 3 y).

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Appendix 4: Spatial detection patterns for bronze whaler sharks.

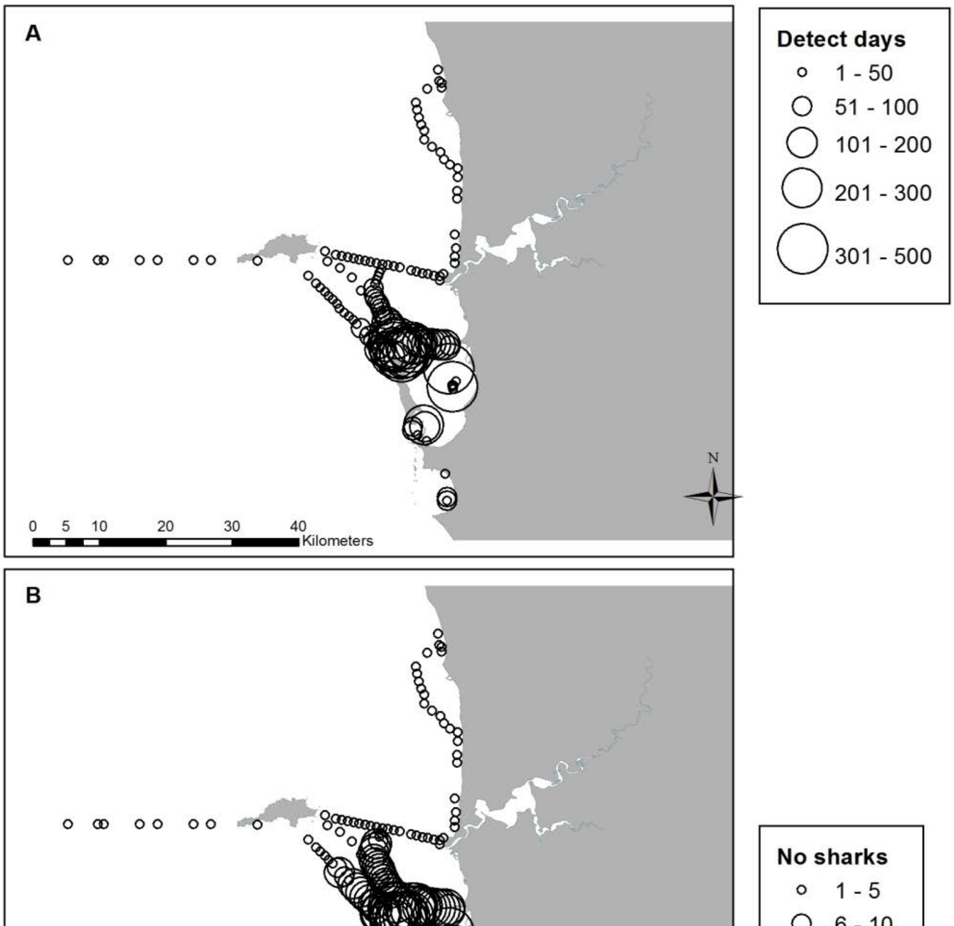

Figure 69. Spatial detection patterns of bronze whaler sharks in the Perth arrays

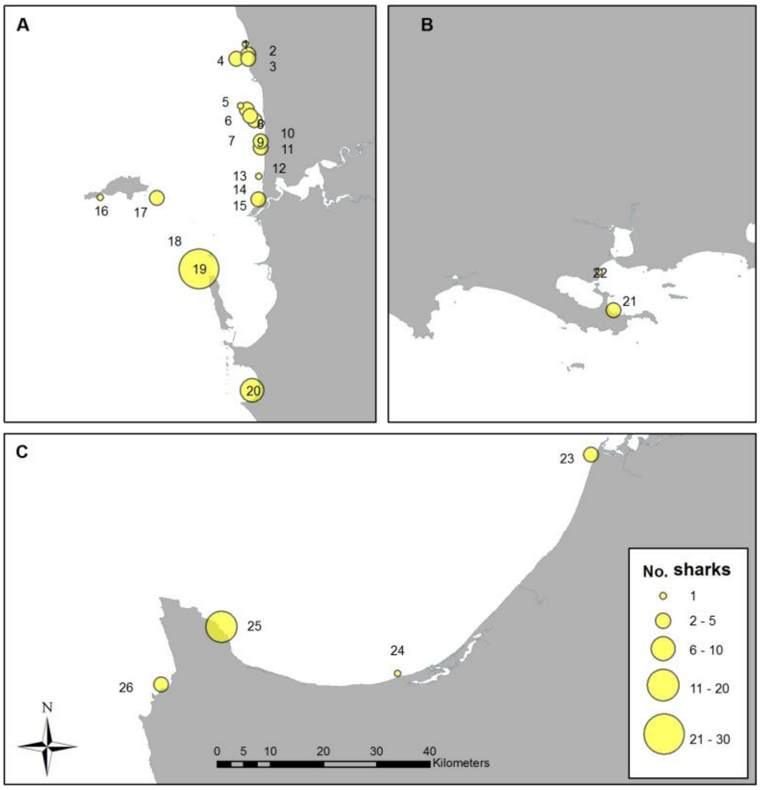

Figure 70. Spatial detection patterns of bronze whaler sharks in the VR4G receivers

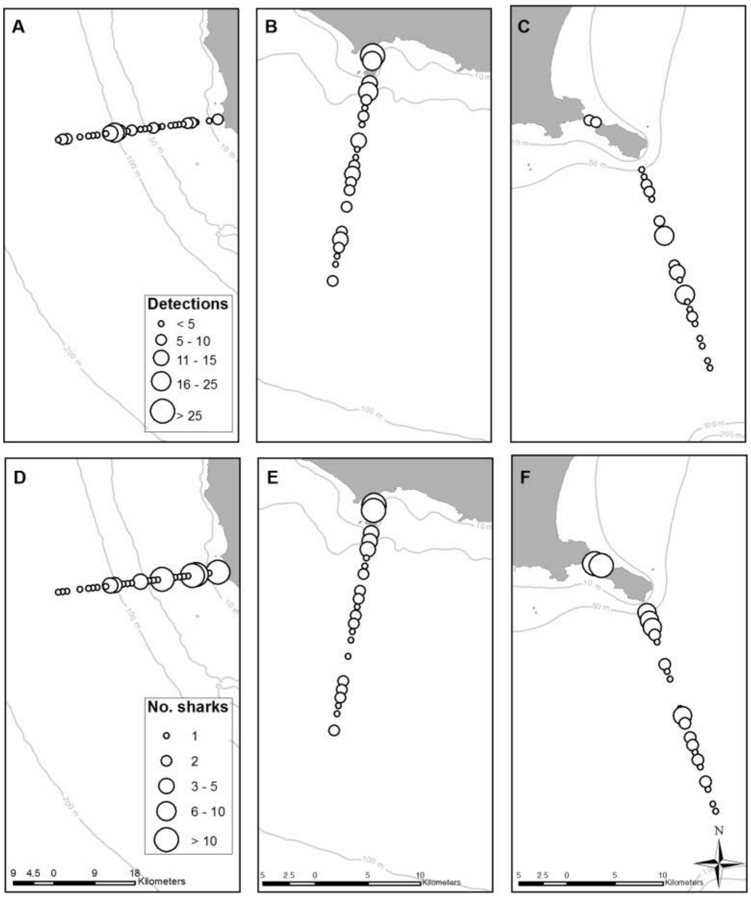

Figure 71. Spatial detection patterns of bronze whaler sharks in south-western Western Australia