Department of
Primary Industries and Regional Development

GOVERNMENT OF WESTERN AUSTRALIA

Fisheries Research Report No. 294

Resource Assessment Report Temperate Demersal Elasmobranch Resource of Western Australia

Matias Braccini, Nick Blay, Alex Hesp & Brett Molony

November 2018

Correct citation:
Braccini, M., Blay, N., Hesp, A. & Molony, B. 2018. Resource Assessment Report Temperate Demersal Elasmobranch Resource of Western Australia. Fisheries Research Report No. 294 Department of Primary Industries and Regional Development, Western Australia. 149 pp.

Enquiries:

WA Fisheries and Marine Research Laboratories, PO Box 20, North Beach, WA 6920
Tel: +61 8 9203 0111
Email: library@fish.wa.gov.au
Website: www.fish.wa.gov.au

A complete list of Fisheries Research Reports is available online at **www.fish.wa.gov.au**

Department of Primary Industries and Regional Development
Gordon Stephenson House
140 William Street
PERTH WA 6000
Telephone: (08) 6551 4444
Website: dpird.wa.gov.au
ABN: 18 951 343 745

ISSN: 1035-4549 (Print) ISBN: 978-1-921258-18-3 (Print)
ISSN: 2202-5758 (Online) ISBN: 978-1-921258-19-0 (Online)

Table of Contents

Executive Summary

Whiskery (*Furgaleus macki*), gummy (*Mustelus antarcticus*), dusky (*Carcharhinus obscurus*) and sandbar (*C. plumbeus*) sharks are the main (~80% of the shark catch) shark species of the Temperate Demersal Elasmobranch Resource (TDER). These species are targeted in the Temperate Demersal Gillnet and Demersal Longline Fisheries (TDGDLF), which operate in the West Coast and South Coast Bioregions and comprise the West Coast Demersal Gillnet and Demersal Longline (Interim) Managed Fishery (WCDGDLF), which operates between 26° and 33° S, and the Joint Authority Southern Demersal Gillnet and Demersal Longline Managed Fishery (JASDGDLF[1]), which operates from 33° S to the WA/SA border. Most fishers employ demersal gillnets to target mainly sharks. Scalefish, dominated by blue morwong (*Nemadactylus valenciennesi*), blue groper (*Achoerodus gouldii*) and snapper (*Chrysophrys auratus*), are also landed as a byproduct and typically account for ~10% of catches. Demersal longline is also permitted but is not widely used.

Based on their inherent vulnerability and risk to the sustainability, whiskery, gummy, dusky and sandbar sharks have been selected as indicators for the status of the temperate elasmobranch (sharks and rays) 'suite' as they represent the range of life history strategies of other elasmobranch species caught by these fisheries. The catch of sharks and rays in other Western Australia (WA) commercial fisheries is negligible (< 10 t per annum) and recreational fishers retain very small numbers of sharks in WA. Indigenous catches of these species have always been negligible.

For whiskery and gummy sharks, an integrated size-based model was implemented in 2017 to extend previous assessment models. The integrated model incorporated life history, gear selectivity, size composition, growth, catch and standardised fishery-dependent catch rate data up to and including the 2015-16 financial year. In addition, life history and catch information were used in a combined demographic and stock-reduction model (SR) to assess stock sustainability. Standardised fishery-dependent catch rate of gummy sharks was concluded to be a poor index of population abundance. For dusky and sandbar sharks, the time series of catch and effort data were considered to be insufficient for estimating biomass trends from fitting population dynamics models. Hence, a SR modelling approach was implemented to determine catch sustainability using life history and catch information up to and including the 2015-16 financial year.

Currently, there is a single biological Reference Point (RP) for whiskery, gummy and dusky sharks. The biological RP is 40% of the unfished biomass and was considered a target level as an overall management objective: '*to maintain the biomass of the fisheries' for the three traditional target stocks at or above 40% of their unfished levels by 2010 for gummy and whiskery sharks and by 2040 for dusky shark*'. Currently, there is no specific biological RP for sandbar sharks and no economic or social RPs for the fisheries. As a result, and similar to assessments for other WA finfish resources, the current assessment sets the target, threshold and limit RPs at 40%, 30% and 20% of the unfished biomass, respectively.

For the whiskery shark stock, the current (2015-16) risk level was estimated to be Medium. Biomass projections indicate continued stock rebuilding under current fishing and management settings for the projection period (to 2020-21). Hence, the current status of the

[1] The JASDGDLF transitioned to solely WA authority on 1 December 2018

whiskery shark stock is acceptable with current risk control measures in place (i.e. no new management required).

For the gummy shark stock, the current (2015-16) risk level was estimated to be Medium. Biomass projections indicate only minor declines in biomass under current fishing and management settings for the projection period (to 2020-21). Hence, the current status of the gummy shark stock is acceptable with current risk control measures in place (i.e. no new management required).

For the dusky shark stock, the current (2015-16) risk level was estimated to be Medium. Biomass projections indicate only minor declines in biomass under current fishing and management settings for the projection period (to 2020-21). Hence, the current status of the dusky shark stock is acceptable with current risk control measures in place (i.e. no new management required).

For the sandbar shark stock, the current (2015-16) risk level was estimated to be Medium. Biomass projections indicate continued stock rebuilding under current fishing and management settings for the projection period (to 2020-21). Hence, the current status of the sandbar shark stock is acceptable with current risk control measures in place (i.e. no new management required).

A formal harvest strategy that considers and defines RPs and harvest control rules for managing the resource (which also considers economic and social objectives) is required and will be developed as part of the JASDGDLF transition to WA. Currently, there is only a single reference point for assessing all temperate shark species (i.e. 40% unfished biomass) which is not explicitly defined as a target, threshold or limit in the current management settings, but has been interpreted as a target to determine stock status and risks.

Additional data (e.g. providing information on mortality for a certain period, as could be generated from representative age composition data), would assist in reducing assessment uncertainties, and an investigation of an index of abundance on large juvenile and adult dusky and sandbar sharks based on existing fishery-independent longline survey data should be undertaken for use in future integrated assessment models for these two species.

The TDGDLF key target species span multiple regional boundaries but risks to the stocks from other fisheries are currently low due to the negligible catches levels from other fisheries. Environmental drivers pose low risk to shark stocks due to their life history strategies. The main external risk to the viability of the TDGDLF is the introduction of Commonwealth Marine Reserves and Australian Seal Lion, *Neophoca cinerea*, (ASL) closures.

1. Scope

This document provides a cumulative description and assessment of the TDER and all of the fishing activities (i.e. fisheries / fishing sectors) affecting this resource in WA. Future Resource Assessment Reports will assess the Statewide Sharks and Rays Resource.

The report is focused on the temperate indicator species (whiskery, gummy, dusky and sandbar sharks) used to assess the suites of demersal sharks and rays that comprise this resource. These species are primarily captured by demersal gillnets used in the TDGDLF that operate in the West Coast and South Coast Bioregions. For the North Coast bioregion, no commercial fishing for sharks has been reported since 2008-09 by the Northern Shark Fisheries (NSF).

The report contains information relevant to assist the assessment of the resource against Environment Protection and Biodiversity Conservation (EPBC) Act export approval requirements (i.e. Wildlife Trade Operations, WTO), the Marine Stewardship Council (MSC) Principles and Criteria for Sustainable Fishing and for other reporting requirements (e.g. Status of Australian Fish Stocks, SAFS).

2. How the Department Operates

Fisheries management in WA has evolved over the last 40-50 years from a focus on managing catch of target species by commercial fishers to a fully integrated Ecosystem-Based Fisheries Management (EBFM) approach, which ensures that fishing impacts on the overall ecosystems are appropriately assessed and managed (Fletcher et al. 2010). In line with the principles of Ecologically Sustainable Development (ESD) (Fletcher 2002), the EBFM approach also recognises that the economic and social benefits of fishing to all users must be considered.

Implementation of EBFM involves a risk-based approach to monitoring and assessing the cumulative impacts on WA's aquatic resources from all fishing activities (commercial, recreational, customary), operating at a bioregional or ecosystem level. The level of risk to each resource is used as a key input to the Department Risk Register, which is an integral component of the annual planning cycle for assigning activity priorities (research, management, compliance, education etc.) across each bioregion. A summary of the Department's risk-based planning annual cycle that is delivering EBFM in the long-term is provided in Figure 2.1.

To ensure that management is effective in achieving the relevant ecological, economic and social objectives, formal harvest strategies are being developed for each resource. These harvest strategies outline the performance indicators used to measure how well objectives are being met and set out control rules that specify the management actions to be taken in situations when objectives are not being met. The WA harvest strategy policy (DoF 2015) has been designed to ensure that the harvest strategies cover the broader scope EBFM and thus considers not only fishing impacts of target species but also other retained species, bycatch, endangered, threatened and protected (ETP) species, habitats and other ecological components (Fletcher et al. 2016).

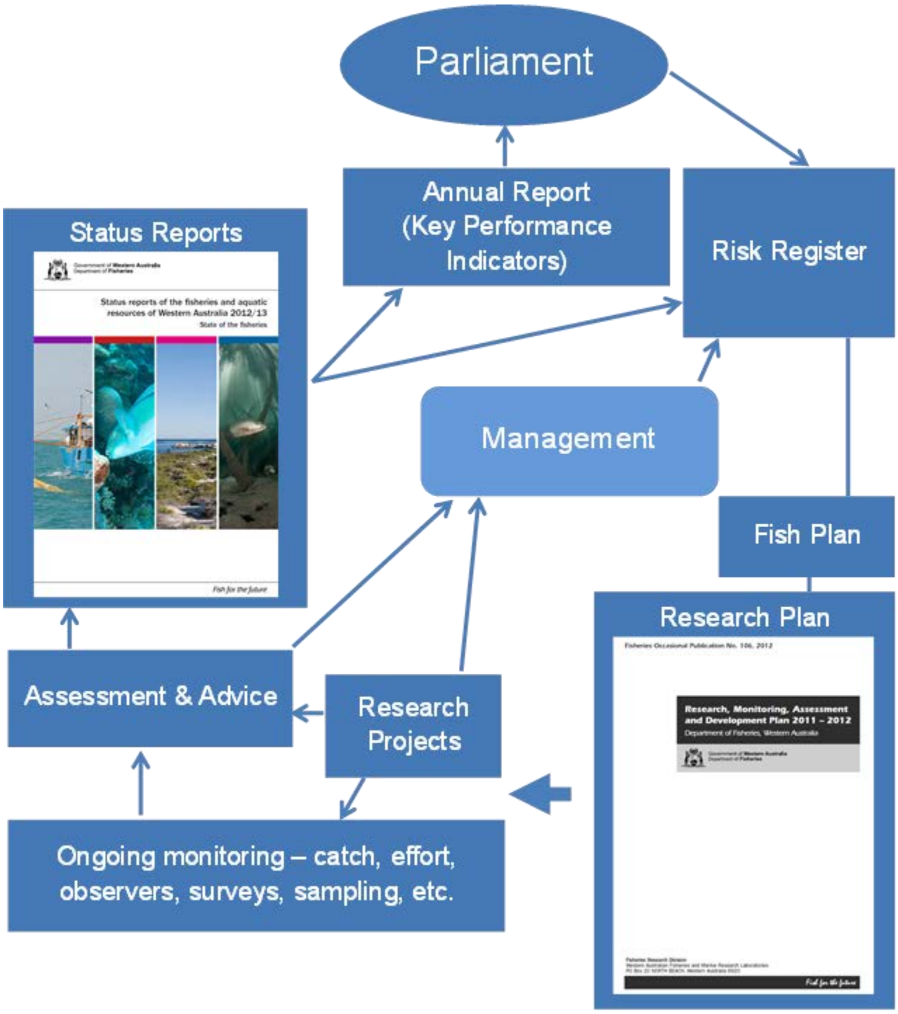


Figure 2.1. An outline of the risk-based planning cycle used for determining Departmental priorities and activities.

3. Aquatic Environment

The marine ecosystems of WA have moderate to low productivity (Molony et al. 2011). The assessed species are currently captured in fisheries operating in continental shelf waters along the West Coast Bioregion (WCB) and South Coast Bioregion (SCB).

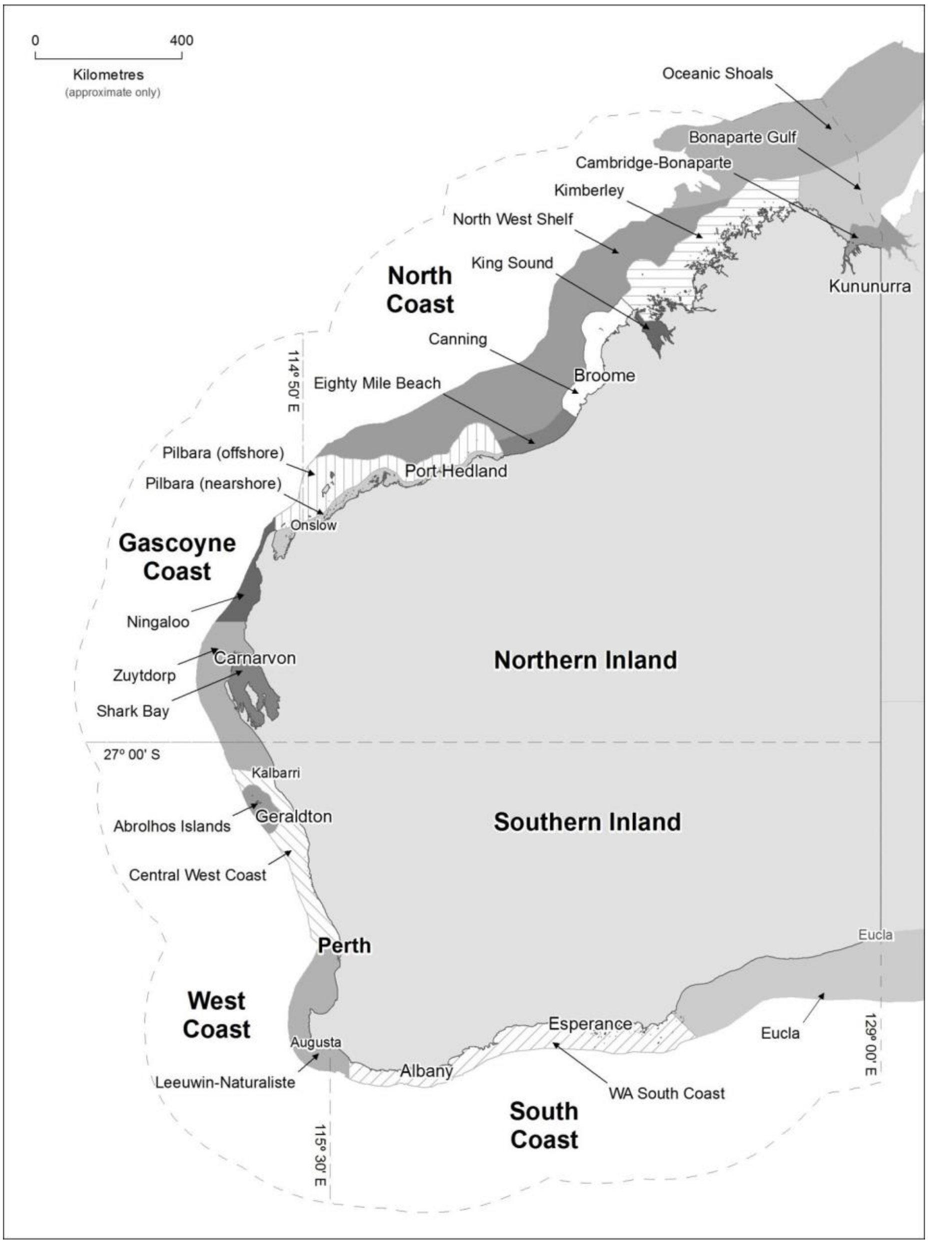


Figure 3.1. The Bioregions of Western Australia.

3.1 West Coast Bioregion

The marine environment of the WCB (see Figure 3.1) between Kalbarri (27.7° S 114.16° E) and Augusta (34.310° S and 115.16° E) is predominantly a temperate oceanic zone, but it is heavily influenced by the Leeuwin Current, which transports warm tropical water southward along the edge of the continental shelf (Gaughan & Santoro 2018). Most of the fish stocks of the region are temperate, in keeping with the coastal water temperatures that range from 18° C to about 24° C. The Leeuwin Current is also responsible for the existence of the unusual Abrolhos Islands coral reefs at latitude 29° S and the extended southward distribution of many tropical species along the West Coast and even into the South Coast.

The Leeuwin Current system, which can be up to several hundred kilometres wide along the West Coast, flows most strongly in autumn / winter (April to August) and has its origins in ocean flows from the Pacific through the Indonesian archipelago. The current is variable in strength from year-to-year, flowing at speeds typically around 1 knot, but has been recorded at 3 knots on occasions. The annual variability in current strength is reflected in variations in Fremantle sea levels, and is related to El Niño Southern Oscillation (ENSO) events in the Pacific Ocean. Weaker counter-currents on the continental shelf (shoreward of the Leeuwin Current), such as the Capes Current that flows northward from Cape Leeuwin as far as Shark Bay, occur during summer and influence the distribution of many of the coastal finfish species.

The most significant impact of the clear, warm, low-nutrient waters of the Leeuwin Current is on the growth and distribution of the temperate seagrasses. These form extensive meadows in protected coastal waters of the WCB, generally in depths of 20 m (but up to 30 m), and act as major nursery areas for many fish species and particularly for the western rock lobster stock.

The West Coast is characterised by exposed sandy beaches and a limestone reef system that creates surface reef lines, often about 5 kilometres off the coast. Further offshore, the continental shelf habitats are typically composed of coarse sand interspersed with low limestone reef associated with old shorelines. There are few areas of protected water along the West Coast, the exceptions being within the Abrolhos Islands, the leeward sides of some small islands off the Midwest Coast, plus behind Rottnest and Garden Islands in the Perth metropolitan area.

The two significant marine embayments in the West Coast are Cockburn Sound and Geographe Bay. Along the West Coast, there are four significant estuarine systems – the Swan-Canning, Peel-Harvey and Leschenault estuaries and Hardy Inlet (Blackwood estuary). All of these are permanently open to the sea and form an extension of the marine environment except when freshwater run-off displaces the oceanic water for a short period in winter and spring. Southward of Cape Naturaliste, the coastline changes from limestone to predominantly granite and becomes more exposed to the influences of the Southern Ocean.

3.2 South Coast Bioregion

The SCB (Figure 3.1) extends east from Augusta (34.310° S, 115.16° E) to the South Australian (SA) border. The continental shelf waters of the SCB are generally temperate but low in nutrients, due to the seasonal winter presence of the tail of the tropical Leeuwin Current and limited terrestrial run-off from an infertile landscape (Gaughan & Santoro 2018). Sea surface temperatures typically range from approximately 15°C to 21°C, which is warmer than would normally be expected in these latitudes due to the influence of the Leeuwin Current. The effect of the Leeuwin Current, particularly west of Albany, limits winter minimum temperatures (away from terrestrial effects along the beaches) to about 16 to 17°C. Fish stocks in this region are predominantly temperate, with many species' distributions extending right across southern Australia. Tropical species are occasionally found, which are thought to be brought into the area as larvae as they are unlikely to form breeding populations.

The SCB is a high-energy environment, heavily influenced by large swells generated in the Southern Ocean. The coastline from Cape Leeuwin to Israelite Bay is characterised by white sand beaches separated by high granite headlands. East of Israelite Bay, there are long sandy beaches backed by large sand dunes, until replaced by high limestone cliffs at the South

Australian border. There are few large areas of protected water along the South Coast, the exceptions being around Albany and in the Recherche Archipelago off Esperance.

Along the western section of the coastline that receives significant winter rainfall, there are numerous estuaries fed by winter-flowing rivers. Several of these, such as Walpole/Nornalup Inlet and Oyster Harbour, are permanently open, but most are closed by sandbars and open only seasonally after heavy winter rains. The number of rivers and estuaries decreases to the east as the coastline becomes more arid. While these estuaries, influenced by terrestrial run-off, have higher nutrient levels (and some, such as Oyster Harbour and Wilson Inlet, are suffering eutrophication), their outflow to the ocean does not significantly influence the low nutrient status of coastal waters.

The marine habitats of the SCB are similar to the coastline, having fine, clear sand sea floors interspersed with occasional granite outcrops and limestone shoreline platforms and sub-surface reefs. A mixture of seagrass and kelp habitats occurs along the South Coast, with seagrass more abundant in protected waters and some of the more marine estuaries. The kelp habitats are diverse but dominated by the relatively small *Ecklonia radiata*, rather than the larger kelps expected in these latitudes where waters are typically colder and have higher nutrient levels.

4. Resource Description

4.1 Resource

Whiskery, gummy, dusky and sandbar sharks are the main shark species targeted (~80% of the fisheries' shark catch) in the TDGDLF, which comprised the JASDGDLF and the WCDGDLF. These fisheries 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 (mainly blue morwong, blue groper and snapper) also being a legitimate byproduct of these fisheries. Demersal longline is also a permitted method of fishing, but is not widely used. Whiskery, gummy, dusky and sandbar sharks have been identified as indicators for the status of the temperate shark 'suite' as they represent the range of life history strategies of other shark species caught by these fisheries (DoF 2011).

4.2 Selection of Indicator Species for Resource

Following the adoption of the ESD policy (Fletcher 2002) by the Department in 2002, the process for monitoring and assessment of marine fishery resources in WA has involved identifying species within Bioregions and allocating each species into one of five suites – Estuarine, Nearshore, Inshore Demersal, Offshore Demersal and Pelagic (DoF 2011). A risk-based approach is then employed to quantify the risks to the sustainability of the stocks based on biological and other criteria to develop a matrix of risk. From the list of species within a suite for a given Bioregion, indicator species are identified based on their vulnerability to fishing and other considerations, such as whether they are target species in the major fisheries, the value to the community, economic value, recreational value and cultural value (Newman et al. 2018). It is these indicator species that are monitored and the status of these indicators is assumed to represent the status of the suite and therefore the resource.

Based on the inherent vulnerability and risk to the sustainability of major species within the different suites of inshore and offshore demersal sharks and rays in the West and South Coast Bioregions (see DoF 2011), the indicator species selected for assessing the status of Statewide sharks and rays include:

- Whiskery shark
- Gummy shark
- Dusky shark
- Sandbar shark

5. Species Descriptions

5.1 Whiskery shark

Figure 5.1 Whiskery shark, *Furgaleus macki*. Source: Last and Stevens (2009) **- Illustration © R.Swainston/www.anima.net.au**.

5.1.1 Taxonomy and Distribution

The whiskery shark, *Furgaleus macki* (Whitley, 1943) (Figure 5.1), is a small to moderate sized (up to 1.6 m TL) species of houndshark (Family Triakidae) endemic to Australia (Last & Stevens 2009). Whiskery sharks occur in temperate continental shelf waters from the North West Cape in WA to Wynyard in Tasmania (Figure 5.2).

Figure 5.2 Distribution of whiskery shark (Last & Stevens 2009).

5.1.2 Stock Structure

Relatively little is known about the stock structure of whiskery sharks. The length and sex composition of the commercial catch differs markedly between regions; adult males are more common in southeast regions of WA while females dominate the catch numerically around the lower south-west coast (McAuley & Simpfendorfer 2003). Tagging studies indicate that this species moves relatively little although large-scale displacements have been recorded (Simpfendorfer et al. 1999; Braccini et al. 2017a).

5.1.3 Life History

5.1.3.1 Movements and Important Habitats

Tagging 618 whiskery sharks in the 1990s showed that the species moves relatively little (Simpfendorfer et al. 1999). The majority of recaptures were made less than 50 km from where individuals were tagged, although a small number of sharks moved distances of up to 550 km between the west and south coast of WA. Recent acoustic tagging has confirmed this overall movement pattern (Braccini et al. 2017a, 2017b).

Whiskery sharks occur on or near the seafloor to a depth of 220 m (Last & Stevens 2009). Investigation into potential nursery habitats of this species have proved inconclusive; however, the smallest individuals captured were taken in depths 29–51 m in outer Geographe Bay and south of Augusta (Simpfendorfer et al. 1999).

5.1.3.2 Age and Growth

Whiskery sharks are relatively fast-growing and short to moderately long-lived; males have been aged to 10.5 years and females to 11.5 years (Simpfendorfer & Chidlow 2000) although the periodicity of band formation has not been validated. Growth rates and maximum sizes are similar between the sexes with males growing slightly faster than females.

5.1.3.3 Natural Mortality

No empirical estimates of natural mortality (M) are available for whiskery sharks. Simpfendorfer et al. (2000b) estimated M as 0.27 yr^{-1} using Hoenig's (1983) method, assuming the maximum age of the population was 15 under unexploited conditions.

5.1.3.4 Reproduction

Whiskery sharks are viviparous giving birth to between 4 and 28 pups, with an average of 19 pups (Simpfendorfer & Unsworth 1998b). The reproductive cycle is synchronous with mating thought to occur from August to September and females storing sperm until ovulation occurs in late January to early April. Parturition occurs in August to October after a gestation period of approximately 7–9 months. Although adult males reproduce each year females only reproduce every second year. Length at birth is between 22–27 cm Fork length (FL) and FL at maturity is 107 cm for males and 112 cm for females. This corresponds to an age at maturity of approximately 4.5 years for males and 6.5 years for females (Simpfendorfer & Chidlow 2000). Fecundity, *F,* increases in proportion to FL (in cm) following the relationship $F = 0.314\ FL - 17.8$ (Simpfendorfer & Unsworth 1998b).

5.1.3.5 Conceptual Stock Recruitment Relationship

The recruitment dynamics of sharks differ markedly in comparison to those of most broadcast spawning teleosts and invertebrates. Although little is known about juvenile and neonate whiskery sharks since they are rarely encountered due to gear selectivity (Simpfendorfer et al. 1999), as whiskery sharks are viviparous, recruitment is likely to be proportional to the number of adults across most adult biomass levels and not affected by environmental conditions to the same extent as in some broadcast spawning teleosts.

5.1.3.6 Diet and Predators

The whiskery shark has a highly specialised diet feeding almost exclusively on cephalopods (95.7%), largely octopus. The remainder of their diet is composed of small amounts of crustaceans (0.8%) and teleosts (4.8%) (Simpfendorfer et al. 2001).

5.1.3.7 Parasites and Diseases

The whiskery shark does not have any known parasites that have a major impact on its commercial exploitation.

5.1.3.8 Inherit Vulnerability

Whiskery sharks are moderately long-lived. Females mature at ~6.5 years of age and reproduce every two years. Being a viviparous species with relatively low fecundity, annual recruitment is likely to be relatively consistent among years and proportional to stock size. Given these biological traits, whiskery sharks have moderate vulnerability to fishing with a relative productivity score of 2.43 (Table 9.5).

Whiskery sharks are mostly taken by gillnets (the dominant fishing method in the TDGDLF). Individuals are fully selected by gillnets at ~5 years of age. The highly-selective nature of gillnets can introduce hyper-stability in catch rates.

5.2 Gummy shark

Figure 5.3 Gummy shark, *Mustelus antarcticus*. Source: Last and Stevens (2009) **- Illustration © R.Swainston/www.anima.net.au**.

5.2.1 Taxonomy and Distribution

The gummy shark, *Mustelus antarcticus*, Günther 1870 (Figure 5.3), is a small to moderate sized (up to 1.85 m TL) houndshark (Family Triakidae) that is likely to be endemic to southern Australia. Gummy sharks occur in temperate waters from Geraldton in WA to Port Stephens in NSW (Last and Stevens 2009) (Figure 5.4). Three other species of *Mustelus* occur in Australian waters, all of which are difficult to distinguish from each other (Last & Stevens 2009). However, all occur in more northerly waters and *M. antarcticus* is the only species taken in large commercial quantities.

Figure 5.4 Distribution of gummy shark (Last & Stevens 2009).

5.2.2 Stock Structure

The gummy shark population is composed of a single genetic stock across southern Australia (MacDonald, 1988; Gardner and Ward 1998). Nonetheless, differing environmental conditions mean that individuals from the east and west regions differ substantially in life history characteristics. Kangaroos Island in SA provides an approximate east-west boundary that separates individuals with differing life history characteristics (Walker 2007). Given the relatively low mixing between regions, the population is divided into a number of sub-stocks for assessment purposes (Walker et al. 2000). Structuring by size and sex also occurs within the gummy shark population, with sharks forming small schools composed mainly of one sex or size group (Last & Stevens 2009). WA catches contain a much higher proportion of females than males, indicative of broader scale sex segregation within the population (Lenanton et al. 1990).

5.2.3 Life History

5.2.3.1 Movements and Important Habitats

Extensive tagging of gummy sharks indicates that there is a relatively low rate of movement between major fisheries regions (Walker et al. 2000). Overall, inter-regional movement is greater for females than males, although movement rates between SA and WA are among the highest. There is a 6% annual rate of movement of adult males into WA and a 15% return rate. In comparison, there is a 9% annual rate of movement of females into WA and a 3% return. There is a weak trend for females in the population to move westwards and males to move eastwards or not at all. Acoustic tagging showed that gummy sharks are less mobile than dusky and sandbar sharks but can still move over long distances (>900 km) and attain considerable maximum speeds (65 km/day) (Braccini et al. 2017a, 2017b).

Gummy sharks are mainly demersal occurring on the continental shelf from nearshore to about 80 m, although occasionally on the continental slope to 350 m (Last & Stevens 2009). Unlike some species of shark, gummy sharks do not appear to give birth in discrete inshore nurseries and pupping is thought to take places over scattered locations in inshore waters (Stevens & West 1997).

5.2.3.2 Age and Growth

Gummy sharks are relatively fast growing and moderately long lived with males reaching at least 17 years and females 20 years (Moulton et al. 1992) with growth bands being formed annually (Walker, et al. 2001). Like most sharks, growth is sexually dimorphic and females grow larger and live longer than males.

5.2.3.3 Natural Mortality

Based on tagging studies the estimated rate of M is 0.283 yr^{-1} (Walker et al. 2000), which is comparable to estimates derived from Hoenig's (1983) method (0.22 yr^{-1}).

5.2.3.4 Reproduction

The gummy shark has a reproductive mode of aplacental viviparity with minimal histotrophy. Developing embryos are initially nourished by a yolk sac during the early part of gestation, and uterine secretions once the yolk is absorbed (Walker 2007). The gestation period of the gummy shark is ~1 year throughout southern Australia with parturition, mating and ovulation occurring between November and early February (Lenanton et al. 1990; Walker 2007). Neonate gummy sharks are born at a length of 30-36 cm in inshore areas. Parturition is synchronous across the population but the frequency of reproduction varies between different geographic regions. West of Kangaroo Island (KI) and in WA waters, gummy sharks reproduce annually, while east of KI reproduction is biennial (Lenanton et al. 1990; Walker 2007). Length at maturity also differs spatially; west of KI 50% of males and females are mature by 978 mm (~4 years) and 1,129 (~5 years) mm TL, respectively, and 50% of females are in maternal condition by 1,263 mm TL (~6 years) (Walker 2007). Fecundity increases exponentially with increasing size in gummy sharks. The relationship between fecundity, *F,* and maternal total length, *TL,* is given by $F = \exp(-4.13398 + 0.049171\ TL)$ (Lenanton et al. 1990).

5.2.3.5 Conceptual Stock Recruitment Relationship

As gummy sharks are viviparous, recruitment is likely to be proportional to adult biomass across most adult biomass levels and not affected by environmental conditions to the same extent as in some broadcast spawning teleosts (Walker 1998). This feature of their life history makes them vulnerable to fisheries that directly target the adult biomass. A corollary to this is that the dome-shaped selectivity of gillnets, which are frequently used to target gummy sharks, effectively leads to the adult component of the stock remaining unfished (Prince 2005). In other parts of Australia this has resulted in long-term stability of gummy shark recruitment and catches over a highly variably range of fishing effort (Prince 2011). Little is known about potential density dependent mechanisms and how they may affect recruitment in sharks.

5.2.3.6 Diet and Predators

The diet of the gummy shark in WA waters consists largely of teleost fish (50%), crustaceans (37.3%), and cephalopods (27.8%) (Simpfendorfer et al. 2001). Broadnose sevengill sharks (*Notorynchus cepedianus*) are a major predator of gummy sharks (Barnett et al. 2010).

5.2.3.7 Parasites and Diseases

The gummy shark does not have any known parasites that have a major impact on its commercial exploitation.

5.2.3.8 Inherit Vulnerability

Gummy sharks are moderately long-lived. Females mature at ~5 years of age (west of KI) and reproduce every year. Being a viviparous species with relatively low fecundity, annual recruitment is likely to be relatively consistent among years and proportional to stock size. Given these biological traits, gummy sharks have moderate vulnerability to fishing with a relative productivity score of 2.43 (Table 9.5).

Gummy sharks are mostly taken by gillnets (the dominant fishing method in the TDGDLF). Females and males are fully selected by gillnets at ~6 and 10 years of age, respectively. The highly-selective nature of gillnets can introduce hyper-stability in catch rates.

5.3 Dusky shark

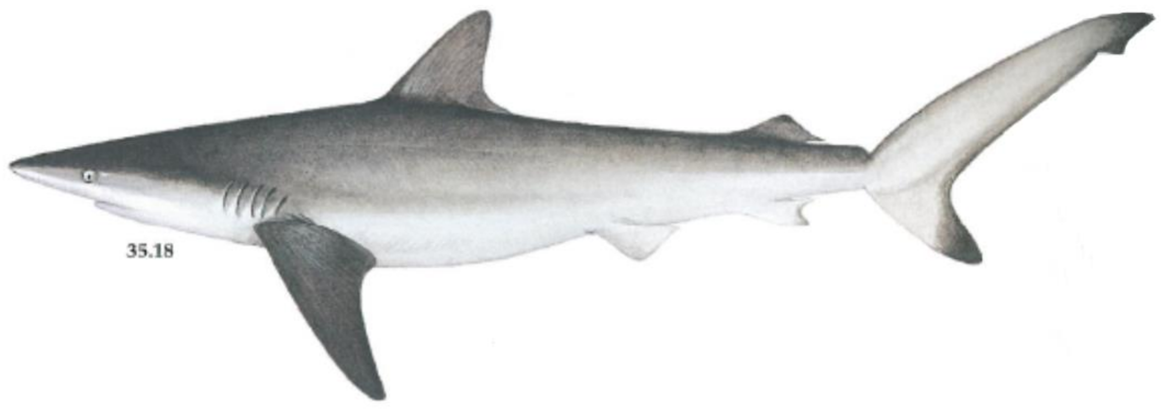


Figure 5.5 Dusky shark, *Carcharhinus obscurus*. Source: Last and Stevens (2009) **- Illustration © R.Swainston/www.anima.net.au**.

5.3.1 Taxonomy and Distribution

The dusky shark, *Carcharhinus obscurus* (Lesueur, 1818) (Figure 5.5), is a large (~3.5 m) species of coastal whaler shark (Family Carcharhinidae) found in tropical and temperate seas circumglobally and throughout Australian waters (Last and Stevens, 2009) (Figure 5.6).

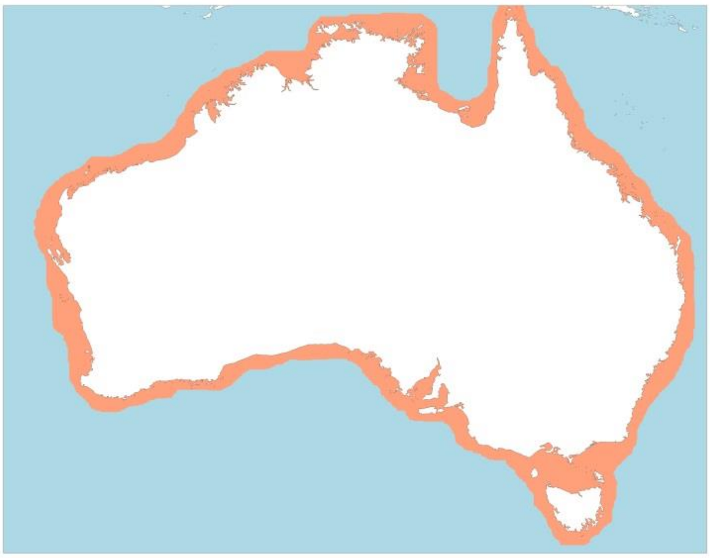


Figure 5.6 Distribution of the dusky shark in Australian waters (Last & Stevens 2009).

5.3.2 Stock Structure

Dusky sharks in WA constitute a single stock, although different life stages occur in different geographical regions. Newborn and juvenile sharks occur in the south-west of WA, while adults mainly occur in north-western waters between the Abrolhos Islands and the North West Cape. Adults migrate seasonally between the two regions for parturition. Genetic analyses suggest there is restricted gene flow between eastern and western Australia (Geraghty et al.,

2014) and dusky sharks from northern Australia and Indonesia are genetically distinct (Ovenden et al., 2009).

5.3.3 Life History

5.3.3.1 Movements and Important Habitats

Like many species of sharks, the dusky shark population is highly spatially structured. Electronic (Rogers et al., 2013) and conventional (Simpfendorfer et al., 1999) tagging studies have shown dusky sharks move between SA and WA. For WA, the adult component of the stock occurs mainly in north-western waters between the Abrolhos Island and the North West Cape. Adults make regular seasonal migrations to shallow waters off the southwest for pupping (Braccini et al. 2018). Conventional tagging of neonate and juvenile dusky sharks during the mid-1990s showed that they generally remained within 100 km of their point of release (Simpfendorfer et al., 1996). Acoustic tagging showed that dusky sharks have very high mobility across WA, showing high interconnectivity among management zones and being capable of very large displacements (>2,000 km) and maximum speeds of 107 km/day (Braccini et al. 2017a, 2017b).

Dusky sharks occur on continental and insular shelves from the surf zone to adjacent oceanic waters to 400 m depth (Last and Stevens, 2009). Pups are born in discrete coastal nurseries where they spend the early part of their lives, and where they are also targeted by commercial fisheries. In WA, dusky shark nurseries are between Geraldton and Bremer Bay, with the highest abundance of newborn sharks occurring between Lancelin and Albany (Simpfendorfer et al., 1996; Simpfendorfer et al., 1999a). On the east coast of Australia, Moreton Bay is known to be a nursery area for dusky sharks (Taylor and Bennett 2013).

5.3.3.2 Age and Growth

The dusky shark is long-lived and slow-growing. Empirical estimates of longevity are 32 years for females and 25 years for males based on vertebrae, validated up to 4 years of age (Simpfendorfer et al., 2002). Maximum longevity is likely substantially higher and has been assumed to be 55 years (McAuley et al., 2007a). Females attain a larger size and grow more slowly than males.

5.3.3.3 Natural Mortality

The dusky shark has a low rate of M. McAuley et al. (2007a) used life history invariants and Monte Carlo methods to derive the M of dusky sharks from a number of different mortality estimators. Mean estimates of M range from 0.056 to 0.103 yr^{-1}.

5.3.3.4 Reproduction

Dusky sharks have a reproductive mode of placental viviparity; developing embryos are initially nourished by the yolk sac which subsequently attaches to the uterine wall forming a placental connection to the mother. Details on the duration of the gestation period are scant, but it is estimated that the gestation period is up to two years and that the frequency of reproduction is every 2-3 years (McAuley et al., 2005). Females give birth to between six and 13 embryos with a mean size at birth of 921 mm TL (Simpfendorfer 2000). Young are born year-round with pupping rates highest during autumn (Simpfendorfer et al., 1996). Length at 50% maturity of female dusky sharks is estimated at 3012 mm TL (McAuley et al., 2005). Size-fecundity relationships are not known for this species, although it is likely that fecundity increases in proportion to length.

5.3.3.5 Conceptual Stock Recruitment Relationship

Dusky sharks are born at close to 1 m in length, and likely to have a high survival rate in the absence of fishing. As such recruitment is likely to be proportional to the number of adults across most adult biomass levels. This life history feature means that dusky sharks are highly sensitive to any fishing of adult biomass (McAuley et al., 2007a).

5.3.3.6 Diet and Predators

The diet of the dusky shark is composed primarily of teleosts and cephalopods, with minor components of elasmobranchs and crustaceans (Simpfendorfer et al., 2001).

5.3.3.7 Parasites and Diseases

The dusky shark does not have any known parasites that have a major impact on its commercial exploitation.

5.3.3.8 Inherit Vulnerability

Dusky sharks are long-lived. Females mature at ~27–35 years of age and reproduce every two to three years. Being a viviparous species with low fecundity, annual recruitment is likely to be relatively consistent among years and proportional to stock size. Given these biological traits, dusky sharks have high vulnerability to fishing with a relative productivity score of 3.00 (Table 9.5).

Dusky sharks are mostly taken by gillnets (the dominant fishing method in the TDGDLF). Individuals are fully selected by gillnets at around 0–3 years with relative selectivity rapidly decreasing with age and by ~6 years of age it is negligible. The highly-selective nature of gillnets can introduce hyper-stability in catch rates.

5.4 Sandbar shark

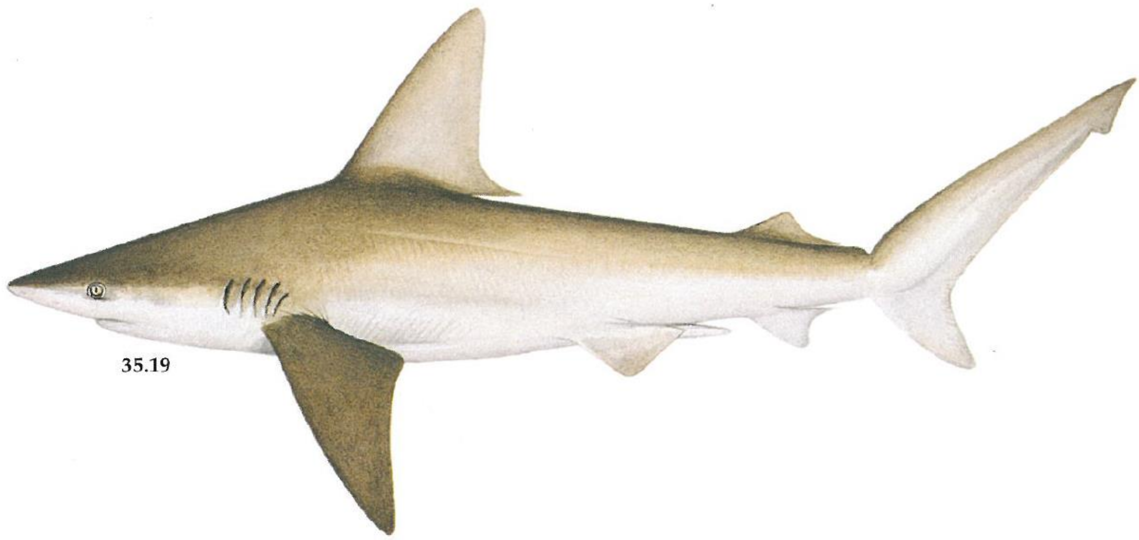


Figure 5.7 Sandbar shark, *Carcharhinus plumbeus*. Source: Last and Stevens (2009) - **Illustration © R.Swainston/www.anima.net.au**.

5.4.1 Taxonomy and Distribution

The sandbar shark, *Carcharhinus plumbeus* (Nardo, 1827) (Figure 5.7), is a medium sized whaler shark (up to 2.5 m) with a cosmopolitan but patchy distribution in tropical and warm temperate seas (Last and Stevens, 2009). Within Australian waters populations exist on both the east and west coast. In WA waters, the sandbar shark ranges from at least Cape Leveque and Point D'Entrecasteaux (McAuley et al., 2005) (Figure 5.8).

Figure 5.8 Distribution of the sandbar shark in Australian waters (Last & Stevens 2009).

5.4.2 Stock Structure

The WA sandbar shark stock exhibits considerable segregation between juveniles, which occur mainly in deeper continental-shelf waters south of 26°S, and adults, which occur in more northerly waters (McAuley et al., 2005). The limited gene flow between eastern and western Australia (Portnoy et al., 2010) and limited reported catches in northern WA, the Gulf of Carpentaria and southern Australia suggest sandbar sharks are largely separate from populations on the east coast of Australia.

5.4.3 Life History

5.4.3.1 Movements and Important Habitats

Adult sandbar sharks migrate seasonally from the waters in the north-west of WA into temperate waters to give birth (McAuley et al., 2005). Dispersal rates from tagged sharks indicate that sandbar sharks are probably capable of migrating distances of more than 1,000 km in less than a year.

Juvenile sandbar sharks occur in deeper waters of the continental shelf with highest catch rates between 120-130 m depth (McAuley et al., 2005). Neonate sandbar sharks primarily occur south of the Houtman Abrolhos Islands in depths 28-119 m, although they have been observed as far north as Broome. This indicates that parturition may occur throughout the species' range (McAuley et al., 2007b).

Acoustic tagging showed that large sandbar sharks can move over large distances (>1,400 km) and attain maximum speeds of 63 km/day (Braccini et al. 2017a, 2017b).

5.4.3.2 Age and Growth

Sandbar sharks are slow-growing and long-lived; males have been empirically aged to 19 years and females to 25 years based on vertebral ageing and growth bands are formed annually (McAuley et al. 2006). However, maximum longevity is thought to be at least 30–40 years (McAuley et al., 2007a). Growth is sexually dimorphic with females attaining a larger size and growing at a slower rate than males.

5.4.3.3 Natural Mortality

The sandbar shark has a low rate of M. McAuley et al. (2007a) used life history invariants and Monte Carlo methods to derive the M of sandbar sharks from a number of different mortality estimators. Mean estimates of M range from 0.098 to 0.137 yr^{-1}.

5.4.3.4 Reproduction

Sandbar sharks have a reproductive mode of placental viviparity. Mating occurs during summer and autumn, and females ovulate during March (McAuley et al, 2007b). The gestation period is 12 months, with females giving birth to between 4 and 10 pups (mean 6.5) of length 509–565 mm TL. Females reproduce biennially and have a resting year between pregnancies. Male sandbar sharks reach sexual maturity at a smaller size than females; 50% maturity occurs at 1484 mm TL for males and 1585 mm TL for females. These lengths correspond to age at maturity of around 14 years for males and 16 years for females. There is a weak but statistically significant increase in fecundity with increasing female length (McAuley et al., 2007b).

5.4.3.5 Conceptual Stock Recruitment Relationship

Parturition of sandbar sharks in WA waters occurs on the continental shelf in water depths 28–119 m. This contrasts with the ecology of the species elsewhere within its range, where it is well-documented using shallow coastal areas as nursery habitats (Merson et al., 2001). The reasons for this are likely to be complex but may include the presence of the larger and more abundant young of the dusky shark in these areas (McAuley et al., 2007b). Nonetheless, it is likely that survival of neonate sandbar sharks is relatively high, and recruitment proportional to the number of adults in the population across most adult biomass levels. As such, recruitment of sandbar sharks is likely highly sensitive to direct removal of adults from the population (McAuley et al., 2007a).

5.4.3.6 Diet and Predators

The sandbar shark has a relatively broad diet. McAuley et al. (2005) found that teleosts were the most common dietary item, present in 34.2% of examined stomachs, followed by cephalopods (20.5%) and other elasmobranchs (3.2%).

5.4.3.7 Parasites and Diseases

The sandbar shark does not have any known parasites that have a major impact on its commercial exploitation.

5.4.3.8 Inherit Vulnerability

Sandbar sharks are long-lived. Females mature at ~16 years of age and reproduce every two years. Being a viviparous species with low fecundity, annual recruitment is likely to be relatively consistent among years and proportional to stock size. Given these biological traits, sandbar sharks have high vulnerability to fishing with a relative productivity score of 2.71 (Table 9.5).

Sandbar sharks are mostly taken by gillnets (the dominant fishing method in the TDGDLF). Individuals are fully selected by gillnets at ~6 years of age with relative selectivity gradually decreasing with age and by ~30 years of age it is negligible. The highly-selective nature of gillnets can introduce hyper-stability in catch rates.

6. Fishery Information

6.1 Temperate Demersal Gillnet and Demersal Longline Fisheries

The TDGDLF comprise the JASDGDLF and the WCDGDLF. These fisheries 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 also being a legitimate component of the catch. Demersal longline is also a permitted method of fishing, but is not widely used.

The main shark species targeted in the TDGDLF are gummy, dusky, whiskery and sandbar sharks. 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 both fisheries catch. The main scalefish species captured in the TDGDLF are blue morwong, which is principally taken on the south coast, and blue groper and snapper, caught on both the south and west coast.

The JASDGDLF spans the waters from 33° S latitude to the WA/SA border and comprises three discrete zones (Figure 6.1) although for assessment purposes Zone 3 is combined with Zone 2. The WCDGDLF extends northwards from 33° S latitude to 26° S longitude; however, fishing is prohibited or restricted in some areas (see areas shaded in dark grey in Figure 6.1).

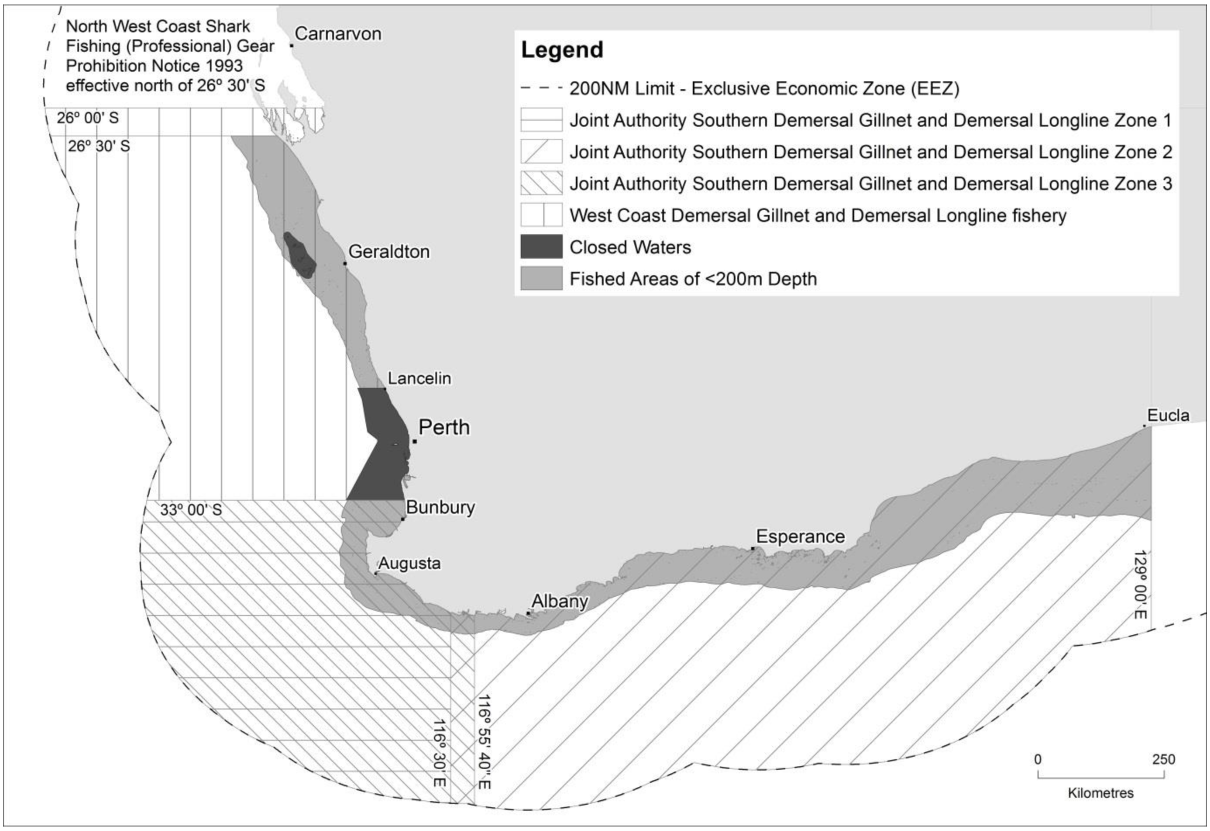


Figure 6.1 Management boundaries of the Temperate Demersal Gillnet and Longline Fisheries. Shaded areas represent fished areas <200 m depth.

6.1.1 History of Development

Sharks have been commercially harvested in WA waters since the 1940s, thus the harvest process has a relatively long evolutionary history. A single boat began targeting gummy sharks with demersal longlines in the Leschenault Inlet in the south west of the State as early as 1941 (Whitley 1943). Later that year other vessels began fishing for sharks in the inlet and adjacent offshore waters and by 1942 there were 6 shark-fishing boats operating around the south-western port of Bunbury. During the late 1940s and early 1950s the shark fishery expanded to other ports including Albany, Fremantle and Geraldton. Despite remaining a largely part-time occupation for most fishers, shark-fishing effort steadily increased as more operators entered the fishery. Throughout the 1960s, the shark fishery gradually moved further offshore and demersally-set multifilament gillnets began to replace longlines as the preferred fishing method. By 1965 commercial shark catches had exceeded 300 tonnes per year (Figure 6.2). Catches continued to rise steadily throughout the late 1960s until, in the early 1970s, public concern over the level of mercury in shark flesh contributed to a dramatic decline in demand for shark and catches decreased sharply (Heald 1987; Simpfendorfer & Donohue 1998). For dusky (146 samples), whiskery (165 samples) and gummy (110 samples) sharks average mercury concentrations were ~0.75 parts per million (p.p.m., Hancock et al. 1977), based on samples collected mostly at Perth Metropolitan Markets during the early 1970s, whereas most areas and seasons were inadequately sampled. On the basis of these results, in 1974 the Health Department prohibited the sale of shark flesh with average mercury concentrations in excess of 0.5 p.p.m. (Hancock et al. 1977) which corresponds to shark carcasses heavier than 18 kg (Simpfendorfer 1999). Between 1989 and 1990, further studies showed a reduction of average mercury concentrations to 0.48 p.p.m. for whiskery and 0.5 p.p.m. for dusky sharks due to a reduction in the average size of individuals landed (Western Australian Food Monitoring Program 1993). Consumer confidence gradually returned in subsequent years and the local market for shark flesh began to recover.[2]

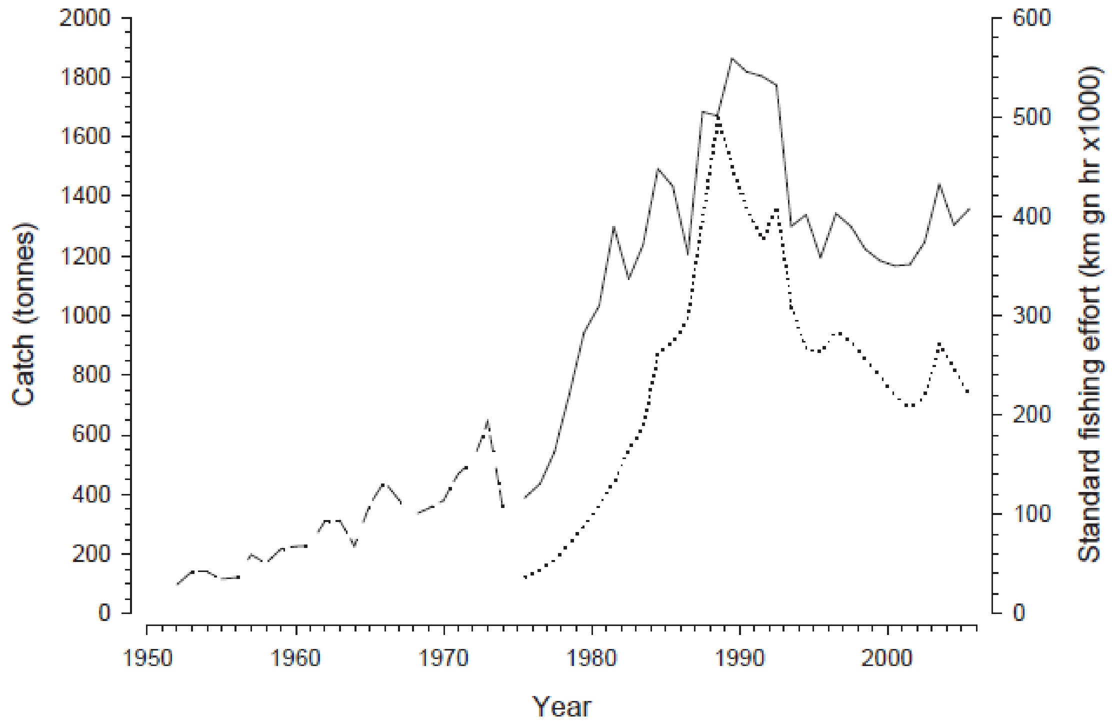


Figure 6.2 Catch and effort history of the temperate Western Australian commercial shark fishery, 1952-2006. Dashed line is estimated annual shark catches plotted by calendar year for 1952-1974 (from McAuley and Simpfendorfer, 2003) and solid line is validated shark catches for financial years 1975-76 to 2005-06. Dotted line shows annual fishing effort in terms of equivalent demersal gillnet effort units of km gillnet hours^{-1} (km gn hr; from McAuley, 2007).

As new management regulations restricted access to other fisheries, shark fishing became an increasingly full time occupation during the late 1970s and early 1980s and targeted shark fishing effort increased rapidly (Figure 6.2). Operators also began using larger and faster vessels equipped with satellite navigation systems and colour echo sounders, which enabled them to operate further offshore and in areas that had previously been out of range of the shark fishing fleet. Additionally, new fishing gear technology, such as monofilament gillnets and powered net-reels, significantly increased the amount of net that vessels were able to operate. By the mid-1980s, the use of monofilament gillnet was widespread, with longlines only being used by a handful of smaller operators. Fishing effort peaked in 1988-89 at half a million gillnet hours, 5 times the level of effort in 1980-81 (McAuley 2007).

Unregulated shark fishing effort, together with declining catch rates of key shark species, prompted the introduction of the first Western Australian commercial shark fishery management plan in 1988. Under a Joint Authority agreement between the State and

[2] Department of Fisheries, Western Australia (2009) Appendix E. Western Australian shark catch. In Bensley et al. (2009) Shark Assessment Report for the Australian National Plan of Action for the Conservation and Management of Sharks. Final Report to the Department of Agriculture, Fisheries and Forestry. Bureau of Rural Sciences, Canberra.

Commonwealth Governments[3] the area south of latitude 33°S on the lower west coast (Figure 6.1) up to the SA border (129°E) was declared a limited entry fishery, with access restricted to fishers who could demonstrate a historical use of the stocks (i.e. a catch history). Fishing effort in the JASDGDLF was limited by the allocation of time/gear units that initially allowed the use of 600 metres of demersal gillnet or 200 longline hooks for one month. However, in response to subsequent stock assessment advice, the amount of net (or number of hooks) allowed by each unit was gradually reduced to 40% of the initial entitlement (McAuley 2007). Mesh sizes, net length and net depth were also restricted.[2]

To limit targeted exploitation of shark stocks outside the managed fishery, the number of vessels authorised to use powered net-reels north of 33°S was also restricted in 1988. However, despite this restriction, demersal gillnet effort continued to increase off the west coast (north of 33° S) throughout the late 1980s and early 1990s. In 1993, the use of shark fishing gear (specifically large mesh gillnets and droplines or longlines with metal snoods) was prohibited north of 26° 30' S latitude and west of 114° 06' E longitude to protect the breeding stock of the shark fishery's largest key target species, the dusky shark. An interim management plan for demersal gillnet and demersal longline fishing in the area between 33° S and 26° S latitude was introduced in 1997 to provide more robust controls on targeted shark fishing effort north of the JASDGDLF. This plan, which imposed similar unitised effort controls as the JASDGDLF, established the WCDGDLF.[2]

6.1.2 Current Fishing Activities

There are currently 57 licences in the JASDGDLF (24 in Zone 1 and 33 in Zone 2) and 20 WCDGDLF permits, which can be used collectively in conjunction with a fishing boat licence.

Only 7 Zone 1, 15 Zone 2 and 5 WCDGDLF vessels reported active fishing returns during 2016-17, similar to the levels of participation in the fisheries over the last years. Fishing returns showed that between 53 and 65 crew were employed in the JASDGDLF and between 18 and 21 crew were employed in the WCDGDLF during 2016-17. Gillnet fishing continues to be by far the most dominant method employed in the fishery.

For 2016-17, a summary of the total catch of elasmobranchs and scalefish is provided in Table 6.1 and Table 6.2, respectively.

Table 6.1 Summary of the 2016-17 shark and ray catch (t live wt.) by the TDGDLF. Data are given by management zone and also by Bioregion.

Common name	Scientific name	Zone			Bioregion		Total
		Zone1 JASDGLF	Zone2 JASDGLF	WCDGDLF	South Coast	West Coast	
Gummy shark	*Mustelus antarcticus*	12.9	402.3	2	405.5	11.7	417.3
Dusky shark	*Carcharhinus obscurus*	89.2	101.7	13	119.1	84.9	203.9
Whiskery shark	*Furgaleus macki*	36.4	101.1	4.8	114.9	27.4	142.3
Sandbar shark	*Carcharhinus plumbeus*	5.8	2.9	8.6	3.9	13.4	17.3
Hammerheads	F. Sphyrnidae	13.2	27.4	1.9	29.5	13	42.5
Spinner shark	*Carcharhinus brevipinna*	17	3.5	4.5	5.7	19.3	25.0

[3] Joint Authority Southern Demersal Gillnet and Demersal Longline Management Plan 1992: http://www.slp.wa.gov.au/statutes/subsiduary.nsf/0/57BFAEA1A259765F48257B7C0031218C/$file/17+southern+demersal+gillnet+&+longline+31.05.13.pdf

Common name	Scientific name	Zone			Bioregion		Total
		Zone1 JASDGLF	Zone2 JASDGLF	WCDGDLF	South Coast	West Coast	
Wobbegongs	F. Orectolobidae	19	12.6	3.4	18.0	16.9	34.9
Rays	Batoidea	2.5	2.3	1.8	2.9	3.7	6.6
Common saw shark	*Pristiophorus cirratus*	1.1	5.2	<0.1	5.2	1.1	6.3
School shark	*Galeorhinus galeus*	<0.1	26.7		26.7	<0.1	26.7
Other elasmobranchs		5.6	6.2	1.6	7.0	6.4	13.4
Total Elasmobranchs		202.8	691.8	41.6	738.4	197.8	936.2

Table 6.2 Summary of the 2016-17 scalefish catch (t live wt.) by the TDGDLF. Data are given by management zone and also by Bioregion.

Common name	Scientific name	Zone			Bioregion		Total
		Zone1 JASDGLF	Zone2 JASDGLF	WCDGDLF	South Coast	West Coast	
Blue morwong	*Nemadactylus valenciennesi*	7.1	27.2	0.1	30.8	3.5	34.3
Blue groper	*Achoerodus gouldii*	18.9	21	0.2	30.4	9.7	40.1
West Australian dhufish	*Glaucosoma hebraicum*	7	1	2.6	3.1	7.4	10.6
Pink snapper	*Chrysophrys auratus*	11.7	8	1.9	11.6	10	21.6
Boarfishes	F. Pentacerotidae	1.3	2.5	<0.1	2.8	1	3.9
Samsonfish	*Seriola hippos*	2.4	3.1	1.3	3.6	3.3	6.9
Redfishes	*Centroberyx* spp.	0.4	3.2	<0.1	3.6	<0.1	3.7
Mulloway	*Argyrosomus japonicus*	0.8	3.1	1.3	3.1	2	5.1
Sweetlips	F. Haemulidae			0.5		0.5	0.5
Baldchin groper	*Choerodon rubescens*	0.1		0.7	0.1	0.7	0.8
Other scalefish		3.3	1.6	0.9	2.9	3	5.9
Total Scalefish		53	70.8	9.5	92	41.3	133.3
Demersal scalefish suite component		46.6	63.4	6.2	83	33.3	116.3

For 2016-17, fishers reported catching and releasing 0 ASL, 2 dead muttonbirds, 14 dead and 16 alive grey nurse sharks, 2 alive turtles, and 2 dead and 9 alive white sharks.

The estimated economic value to fishers in 2016-17 was $3.9 and $0.2 million for JASDGDLF and WCDGDLF, respectively.

As sharks are generally not targeted by recreational fishers in WA, their direct social importance to this group is negligible.

6.2 Northern Shark Fisheries

The NSF comprise 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 (Figure 6.3). Historically, the majority of operators employ demersal longlines and to lesser extent pelagic gillnets. The main shark species targeted in the NSF have been sandbar, blacktip (*Carcharhinus* spp.), tiger (*Galeocerdo cuvier*) and lemon (*Negaprion acutidens*) sharks, and hammerheads (*Sphyrna* spp).

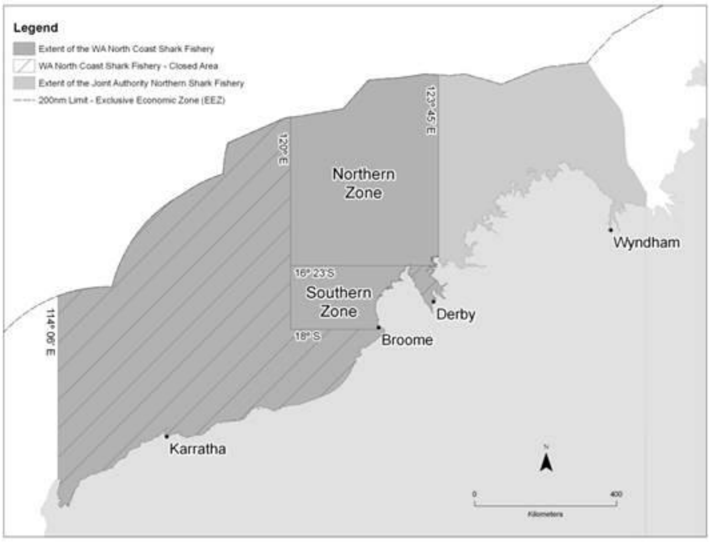


Figure 6.3 Management boundaries of the Northern Shark Fisheries. Shaded areas represent fished areas <200 m depth.

6.2.1 History of Development

A Taiwanese pelagic gillnet fishery operated to within 12 nautical miles of the WA north-west coast between 1974 and 1986 though in 1983 this fleet was restricted to waters north of 18° S (Stevens 1999). Declining catch rates of shark and concerns about the fishery's high incidental catch rates of dolphins prompted the introduction of net length restrictions in 1986, effectively rendering the fishery economically unviable. Despite some limited attempts to redevelop the fishery using longlines, Taiwanese shark fishing vessels ceased operating in Australian waters by mid-1986 (Stevens 1999).

After the cessation of the Taiwanese fishery, a few domestic vessels (both State and Commonwealth-managed) continued to report small shark catches from northern WA waters. The first initiative to manage these vessels' activities occurred in May 1993, when the use of shark longlines and droplines (defined as those having metal snoods) and large-mesh (> 114 mm) gillnets in waters east of North West Cape (114° 06' E) was restricted to 14 licences. Total annual catches of remained below 80 t until 1997-98 when a single dedicated demersal longline vessel entered the fishery and the fisheries' shark catch more than doubled to 210 t. Apart from a brief resurgence of pelagic gillnet effort in the JANSF during 2001-02 and 2002-03, additional longline vessels entered the fishery between 1999 and 2003 and demersal longlining became the fisheries' preferred fishing method. As a result of the continued escalation in demersal shark longlining in the WANCSF, the fisheries' combined shark catch increased nearly twelve-fold between 1999-2000 and 2004-05 (Figure 6.4).

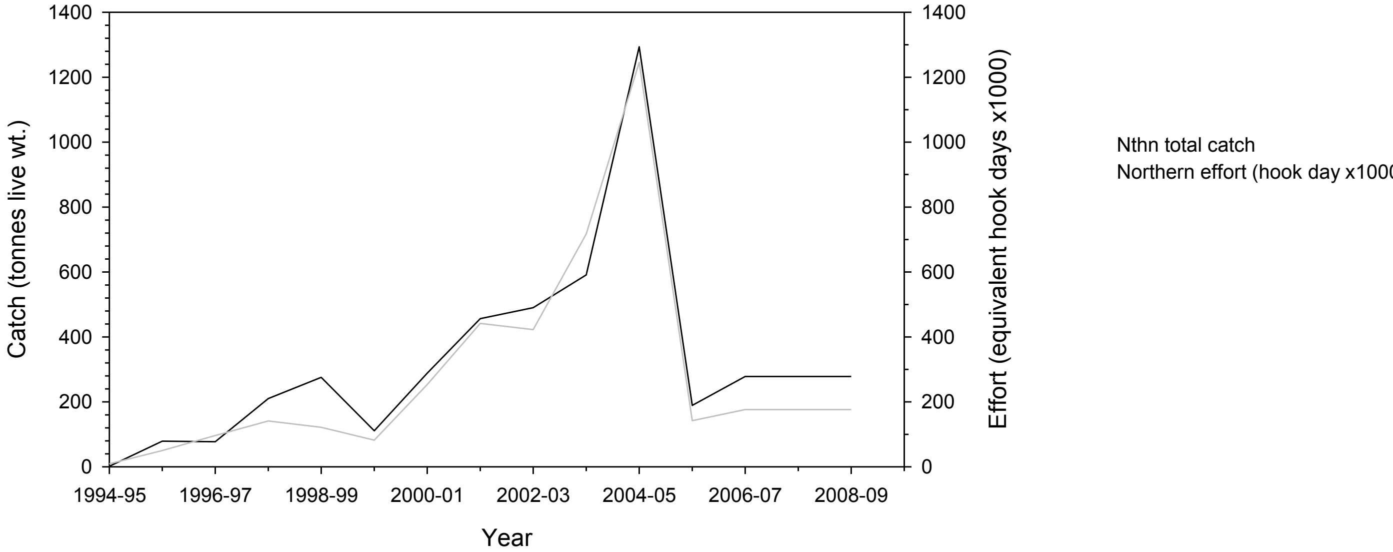


Figure 6.4 Total annual elasmobranch landings and fishing effort (WANCSF and JANSF).

Prior to 2005, the WANCSF and JANSF were managed solely through limited entry provisions. However, recommendations from stock (McAuley et al. 2007a) and risk (Salini et al. 2007) assessments led to closure of the solely WA managed sector of these fisheries in 2005 (Molony et al. 2013). Holders of an Exemption to continue fishing in the WANCSF were restricted to approximately 40% of the fishery's previous area. Operators are only allowed to fish in the area between 16° 23' S and 18° S (Southern Zone) between 1 October and 31 January (Figure 6.3) and in the remaining area (north of 16° 23' S and between 120° E and 123° 45' E), throughout the year. In April 2008, the JANSF's export approval under the EPBC Act was revoked due to the lack of formal management arrangements and concerns about the Fishery's ecological sustainability. In February 2009, the WTO approval that allowed the export of products from the WANCSF expired and therefore, no product from either fishery can be legally exported.

6.2.2 Current Fishing Activities

The NSF have not operated since February 2009 and thus catches of sandbar shark (and other species) by the NSF have been zero since this date.

6.3 Fishing Methods

6.3.1 Commercial Fishery

The majority of vessels in the TDGDLF use demersally set monofilament gillnets to catch a wide variety of sharks and scalefish (teleosts). While JASDGDLF and WCDGDLF (demersal gillnet and demersal longline fisheries) endorsements also permit the use of demersal longlines, these are generally only used by a few small and mainly part-time operators (since 2007-08, longlines have accounted for less than 1% of total effort expended). The specifications for construction and use of demersal gillnets and longlines are outlined in the *Joint Authority Southern Demersal Gillnet and Demersal Longline Managed Fishery*

Management Plan Amendment 2013[4] and the *West Coast Demersal Gillnet and Longline Interim Managed Fishery Management Plan 1997*[5].

6.3.1.1 Demersal gillnet

Nets are constructed of nylon monofilament with a diameter of between 1 mm and 1.3 mm (line 35 - line 70). The mesh is hung between a negatively buoyant ‘ground line’, which sinks the net to the seabed and a positively buoyant ‘head line’, which floats the net vertically off the bottom (Figure 6.5). As fish do not easily ‘gill’ in taut mesh, the net is attached to the head and ground lines using a hanging ratio of 1.5 to 2 metres of net for every metre of line to ensure some slack. Additional ballast is usually attached to each end of the net and often intermittently along its length to prevent dragging. Floats are attached at each end to assist with relocation and recovery. It is common practice for intermediate surface float lines to be attached to nets to reduce the amount of net that is susceptible to two or more double ‘bite-offs’ (where both the head line and ground line are severed between the float lines) and the fragments of net would otherwise be difficult to retrieve.

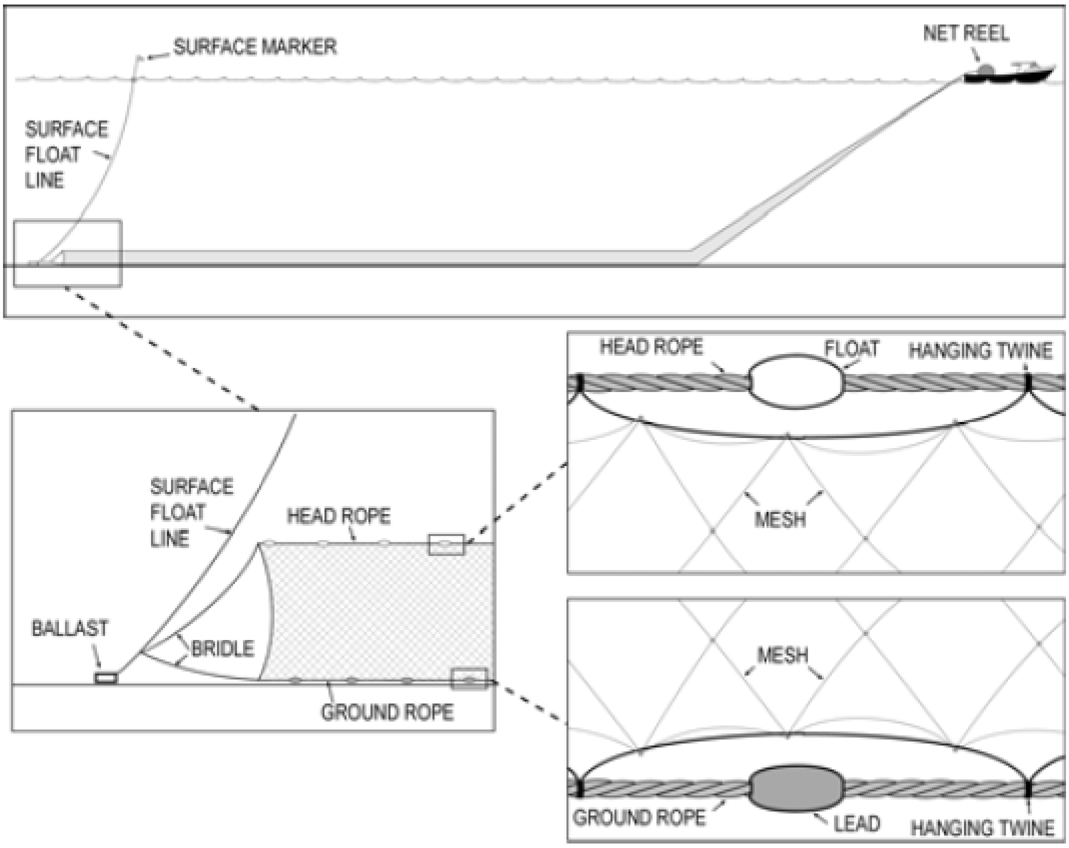


Figure 6.5 Typical demersal gillnet configuration (source: www.environment.gov.au/system/files/pages/1d02c301-cfff-4557-9ab9-a288f34a5627/files/wa-temperate-shark-submission.pdf).

[4] Joint Authority Southern Demersal Gillnet and Demersal Longline Managed Fishery Management Plan Amendment 2013 https://www.slp.wa.gov.au/gazette/gg.nsf/5c8e4a50495aaeb248256b4c0028d27d/0f6ec5965137cef948257b7b0013f7b1?OpenDocument

[5] West Coast Demersal Gillnet and Longline Interim Managed Fishery Management Plan 1997 https://www.slp.wa.gov.au/gazette/gazette.nsf/gazlist/C9CC6F7AFD9F3D5A48256F6A000DAAEA/$file/gg079.pdf

Fishers generally set between 1 and 4 nets at any one time, depending on their unit allocation, vessel size, area of operation and expected catch rates. Nets are typically between 1,000 m and 2,500 m long and may be set in close proximity to each other or separated by distances of several kilometres. Most vessels deploy their gear overnight but some deploy and recover their gear several times each day, making catch rate estimation complex.

6.3.1.2 Demersal longline

Demersal longlines (see Figure 6.6) are currently only used by a handful of vessels in these fisheries. Longlines consist of a mainline (rope or monofilament), which is weighted in such a way that it lies roughly parallel to the seabed. Baited hooks are attached to the mainline via ‘snoods’, which, for the purpose of catching sharks, are most likely to have a length of wire at the hook end to prevent the shark from biting through. Demersal longlines in the TDGDLF may consist of up to 2,745 circle/ezi-baiter hooks (ranging between 7/O and 14/O), but without automatic baiting machines (which are not used in these fisheries) it is unlikely that more than 1,500 hooks could be set at a time.

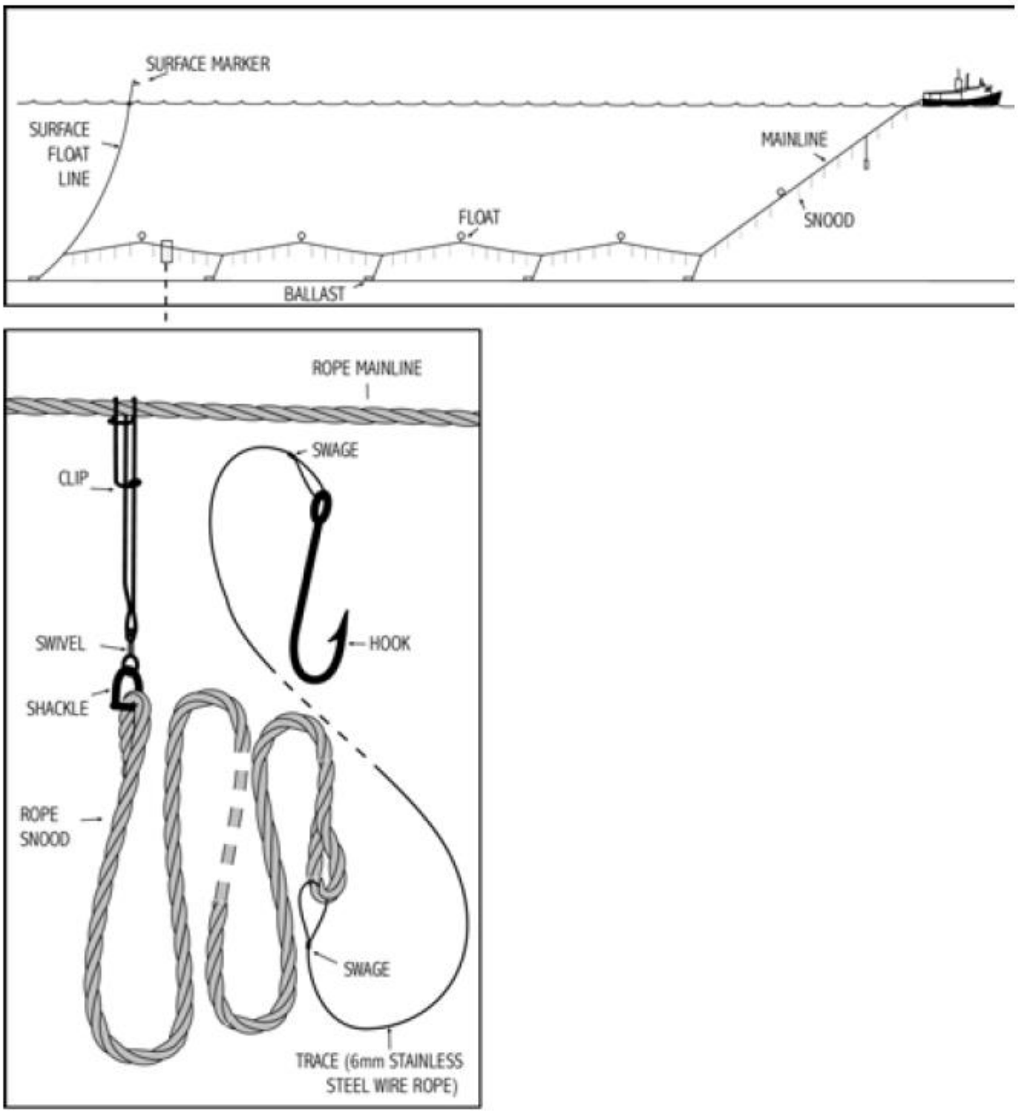


Figure 6.6 Typical demersal longline configuration (source: www.environment.gov.au/system/files/pages/1d02c301-cfff-4557-9ab9-a288f34a5627/files/wa-temperate-shark-submission.pdf).

6.3.2 Recreational Fishery

Recreational fishing is a popular pastime in WA although sharks are generally not targeted specifically. Integrated surveys of boat-based recreational fishing in WA during 2011-12, 2013-14 and 2015-16 provide estimates of the total annual catch, indicating that Statewide retention rates of sharks are less than 20% (Ryan et al. 2017). Although most species of sharks are generally released, gummy and whiskery sharks are exceptions; 76% and 75% of these species, respectively, are retained. For 2015-16, a summary of the total annual boat-based recreational catch of elasmobranchs is provided in Table 6.3.

Table 6.3 Estimated annual recreational catch (kept, released and total numbers) with standard error (se) during 2015-16 (Ryan et al. 2017).

Common name	Scientific name	Bioregion	Kept		Released		Total	
			Estimate	se	Estimate	se	Estimate	se
Blacktip Reef Shark	*Carcharhinus melanopterus*	North Coast	0	0	464	110	464	110
Blacktip Reef Shark	*Carcharhinus melanopterus*	Gascoyne	102	59	414	154	516	177
Blacktip Reef Shark	*Carcharhinus melanopterus*	West Coast	105	49	333	165	438	176
Bronze Whaler	*Carcharhinus brachyurus*	West Coast	309	84	843	229	1,151	248
Bronze Whaler	*Carcharhinus brachyurus*	South Coast	45	21	39	37	84	43
Dusky Whaler	*Carcharhinus obscurus*	North Coast	7	6	853	536	859	537
Dusky Whaler	*Carcharhinus obscurus*	Gascoyne	177	86	384	142	561	194
Dusky Whaler	*Carcharhinus obscurus*	South Coast	47	38	0	0	47	38
Greynurse Shark	*Carcharias taurus*	Gascoyne	0	0	8	8	8	8
Greynurse Shark	*Carcharias taurus*	West Coast	0	0	19	19	19	19
Hammerhead Sharks	Sphyrnidae	North Coast	0	0	42	18	42	18
Hammerhead Sharks	Sphyrnidae	Gascoyne	0	0	16	13	16	13
Hammerhead Sharks	Sphyrnidae	West Coast	40	32	71	34	111	47
Hammerhead Sharks	Sphyrnidae	South Coast	12	8	32	22	45	24
Lemon Shark	*Negaprion acutidens*	North Coast	0	0	84	53	84	53
Lemon Shark	*Negaprion acutidens*	Gascoyne	0	0	50	27	50	27
Lemon Shark	*Negaprion acutidens*	West Coast	0	0	13	12	13	12
Port Jackson Shark	*Heterodontus portusjacksoni*	West Coast	37	36	886	200	923	203
Port Jackson Shark	*Heterodontus portusjacksoni*	South Coast	0	0	124	55	124	55
Rays & Skates	Rajiformes	North Coast	0	0	42	21	42	21
Rays & Skates	Rajiformes	Gascoyne	0	0	77	59	77	59
Rays & Skates	Rajiformes	West Coast	38	37	2024	354	2,063	356
Rays & Skates	Rajiformes	South Coast	0	0	59	40	59	40
Sandbar Shark	*Carcharhinus plumbeus*	North Coast	0	0	40	38	40	38
Sandbar Shark	*Carcharhinus plumbeus*	Gascoyne	0	0	18	18	18	18
Sandbar Shark	*Carcharhinus plumbeus*	West Coast	0	0	49	34	49	34
Sharks	Sharks - undifferentiated	North Coast	0	0	605	204	605	204
Sharks	Sharks - undifferentiated	Gascoyne	169	94	1009	369	1,178	401
Sharks	Sharks - undifferentiated	West Coast	220	120	599	178	819	215
Sharks	Sharks - undifferentiated	South Coast	0	0	137	97	137	97
Tiger Shark	*Galeocerdo cuvier*	North Coast	0	0	32	26	32	26
Tiger Shark	*Galeocerdo cuvier*	Gascoyne	0	0	98	56	98	56
Tiger Shark	*Galeocerdo cuvier*	West Coast	0	0	70	43	70	43
Western Shovelnose Ray	*Aptychotrema vincentiana*	North Coast	0	0	25	18	25	18
Western Shovelnose Ray	*Aptychotrema vincentiana*	West Coast	0	0	231	71	231	71
Western Shovelnose Ray	*Aptychotrema vincentiana*	South Coast	0	0	32	22	32	22
Whaler & Weasel Sharks	Carcharhinidae, Hemigaleidae	Gascoyne	65	34	242	177	308	184
Whaler & Weasel Sharks	Carcharhinidae, Hemigaleidae	West Coast	0	0	58	55	58	55
Whiskery Shark	*Furgaleus macki*	West Coast	168	61	199	100	367	143
Whiskery Shark	*Furgaleus macki*	South Coast	12	11	0	0	12	11
Whitetip Reef Shark	*Triaenodon obesus*	North Coast	13	12	189	71	202	80
Whitetip Reef Shark	*Triaenodon obesus*	Gascoyne	30	22	307	224	337	226
Wobbegong	Orectolobidae	Gascoyne	0	0	80	42	80	42
Wobbegong	Orectolobidae	West Coast	87	35	462	156	548	160
Wobbegong	Orectolobidae	South Coast	12	11	19	18	32	22

The recreational catch of sharks in WA is managed using a range of input and output controls (e.g. size and possession limits, closed seasons). Additionally, a Recreational Fishing from Boat Licence is required for any fishing activity from a powered boat.

6.3.3 Customary Fishing

Indigenous catches of these species have always been negligible.

6.4 Susceptibility

Whiskery sharks are distributed across the temperate waters of Australia, from Bass Strait to North West Cape, WA, in depths of up to 220 m. Gummy sharks are distributed across the temperate waters of Australia, from at least Port Stevens, NSW, to Geraldton, WA, from nearshore to depths of at least 80 m. Dusky and sandbar sharks are distributed throughout large extents of WA coastal waters form the surface down to 400 and 280 m, respectively, and have a complex life cycle that includes large-scale spatial separation of different life stages. The majority of the geographic distribution of whiskery and gummy sharks is commercially fished. For dusky and sandbar sharks, a large part of the adult distribution is not commercially fished but adults are exposed to fishing mortality during their natal migrations to the south. The distribution of juveniles of both species is commercially fished. For these four species, therefore, the availability (i.e. areal overlap between species and fisheries distribution) is high (>30%). Encounterability is also high as these are the target species of the TDGDLF. For whiskery and gummy sharks, selectivity is medium as individuals smaller than the size at maturity are regularly caught. For dusky and sandbar sharks, selectivity is high as individuals smaller than the size at maturity are frequently caught. Finally, for these four species, post-capture mortality is high as they are mostly retained. In combination, all these factors yield a high susceptibility for the four species.

7. Fishery Management

This section provides an overview of the fishery-specific governance and management relating to the TDGDLF.

7.1 Management System

The JASDGDLF and WCDGDLF fisheries are regulated through two complementary management plans, the Joint Authority Southern Demersal Gillnet and Demersal Longline Management Plan 1992[6] and the West Coast Demersal Gillnet and Demersal Longline (Interim) Management Plan 1997[7]. The JASDGDLF (Joint Authority jurisdiction fishery) became managed under WA state law in 1988 and since then the fishery has been managed by the Western Australian Government on behalf of a Joint Authority comprising the Western Australian and Commonwealth Governments (NB the JASDGDLF transitioned to WA jurisdiction in December 2018). Both plans operate with a set of management arrangements, each of which have been refined through time. These arrangements include:

- Limited entry;

[6] Joint Authority Southern Demersal Gillnet and Demersal Longline Management Plan 1992: http://www.slp.wa.gov.au/statutes/subsiduary.nsf/0/57BFAEA1A259765F48257B7C0031218C/$file/17+southern+demersal+gillnet+&+longline+31.05.13.pdf

[7] West Coast Demersal Gillnet and Demersal Longline (Interim) Management Plan 1997: http://www.slp.wa.gov.au/statutes/subsiduary.nsf/0/EC401A926EDE8D2A48257BF3002FC730/$file/23+west+coast+demersal+gillnet++&+longline+27.09.13[1].pdf

- An explicit hourly effort management system;
- Gear specifications;
- Species restrictions and species specific size restriction;
- Spatial closures;
- Seasonal closure; and
- Real-time monitoring of fleet dynamics and operations using the Vessel Monitoring System (VMS)

The TDGDLF was first declared as an approved Wildlife Trade Operations (WTO) in February 2006. The fishery has been reassessed several times, and most recently re-accredited in 2018, under the Commonwealth Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act). The accreditation allows continued export of product from these fisheries for a period of three years[8].

In addition to the renewal of the WTO, the TDGDLF were reaccredited in August 2012 for the purposes of Part 13 of the EPBC Act which provides protection for operators who may interact with threatened, endangered and protected species (TEPs). The Part 13 accreditation requires that the TDGDLF address the potential interaction between fishers and ASLs.

The TDGDLF also has the following specific management objectives:

- To keep effort in the TDGDLF at or below levels recorded during 2001-02.
- To maintain catches of demersal scalefish below 50% of those recorded in the WCB during 2005-06 (to reduce fishing mortality to a level that will enable recovery of all of these stocks) and to adhere to the recent allocation regarding the demersal scalefish resource (64% commercial and 36% recreational) which applies to Zone 1 and part of Zone 3 of the JASDGDLF and the all of the WCDGDLF[9].

The TDGDLF are limited entry fisheries; the JASDGDLF has 57 licenses and the WCDGDLF has 17 permits. Both fisheries are managed mainly via input controls, primarily in the form of transferable time/gear effort units. Historically, each unit has permitted the use of a specified length of net or an equivalent number of hooks for one month. However, in 2009, the Department transitioned the fishery to a more explicit hourly effort management system, with the objectives of removing excessive latent effort capacity and restricting effort within each management zone to 2001-02 levels. All units now permit the use of 27 m of gillnet or the use of 1 hook on a demersal longline for 1 hour in the WCDGDLF, 264 hours in Zones 1 and 3 of the JASDGDLF or 380 hours in Zone 2 of the JASDGDLF. Entitlement usage is calculated and monitored by the Department through the VMS system. Both management plans require all boats operating in the TDGDLF to have automatic location communicators (ALC) and to nominate to fish via VMS. In 2006-07 statutory daily/trip catch and effort logbooks were introduced. In addition to these effort controls there are additional restrictions on mesh and net height (‘drop’), maximum net length, longline materials and hook sizes:

WCDGDLF Gillnet mesh not less than 175 millimetres and a depth not exceeding

[8] Western Australian Temperate Shark WTO: http://www.environment.gov.au/topics/marine/fisheries/wa/temperate-shark
[9] West Coast Demersal Scalefish (Interim) Management Plan 2007: https://www.slp.wa.gov.au/statutes/subsiduary.nsf/0/07265AB5EDE0B3E4482580720034131B/$file/39.16+west+coast+demersal+scalefish+(interim)+-+18.11.16.pdf

	20 meshes; Longlines traces and snoods must be made of unsheathed monofilament nylon or fluorocarbon and have a maximum width at any point of 1.8 millimetres; and Longline hooks must not be made of material that exceeds 3 millimetres in width at any point and that when measured externally does not exceed 8 centimetres in length or width.
JASDGDLF	Gillnet mesh not less than 162.5 millimetres and a depth not exceeding 20 meshes; A maximum of 8,235 metres of gillnet or 2,745 hooks; Longlines traces and snoods must be made of unsheathed monofilament nylon or fluorocarbon and have a maximum width at any point of 1.8 millimetres; and Longline hooks must not be made of material that exceeds 3 millimetres in width at any point and that when measured externally does not exceed 8 centimetres in length or width.

The principal management tool employed in the TDGDLF to assist in the protection of medium-high risk dusky stocks is a 70 cm maximum (inter-dorsal fin, IDF) length limit for whaler sharks. There are also a number of other shark species that are totally protected as per Schedule 2, Part 2 of the *Fish Resources Management Regulations 1995* (FRMR) and the EPBC Act, including grey nurse (*Carcharias taurus*), white (*Carcharodon carcharias*), speartooth (*Glyphis glyphis*) and whale (*Rhincodon typus*) sharks. The retention of sharks and rays was prohibited in most other non-target fisheries throughout the State by commercially protecting all sharks and rays (elasmobranchs) in November 2006.

There are a number of spatial closures for the TDGDLF. The metropolitan zone of the WCDGDLF between latitudes 31° S and 33° S (inshore of 250 metres depth) was closed to all commercial fishing in November 2007. To offset the Metropolitan Area Closure and mitigate potential impacts of effort displacement to northern grounds of the fishery the Government established a Voluntary Fisheries Adjustment Scheme (VFAS) that bought back 36% of WCDGDLF entitlements. Other closures in the WCDGDLF include the area of WA waters adjacent to the Abrolhos Islands from the high water mark to the seaward limit of the coastal waters of the State (3 nautical miles) and the area north of 26° 30’ S (Steep Point).

A seasonal closure of inshore waters to 200 m depth throughout all of the WCDGDLF and the waters of the South Coast west of 118° E (in the JASDGDLF) was in placed during the main whiskery shark pupping season (16 August-15 October between 2006-07 and 2011-12 inclusive and a one-month closure in September between 2012-13 and 2013-14) to assist in the recovery of the then over-exploited whiskery shark stock. In 2018, a total of 17,300 square kilometres around ASL colonies were closed to gillnet fishing along the WA coast.

Significant effort is put into ensuring adequate compliance with these regulations and other relevant legislation. Licence and permit holders in the JASDGDLF and WCDGDLF, respectively, must adhere to the management arrangements specified in the respective management plans and enforcement is undertaken by the Department’s Fisheries and Marine Officers. Compliance is monitored via both at-sea and on-land inspections, with the majority of checks being carried out on land at the point of landing (port areas specified in the respective management plans).

Recreational fishing for sharks in WA is managed through a series of input and output controls.[10] As with commercial fishing, the principal management tool employed to further assist in the protection of medium-high risk dusky stocks is a 70 cm maximum IDF length limit for all whaler sharks taken by recreational fishers within the waters of the South Coast and West Coast Bioregions. This was introduced in February 2009. In addition, there is a total mixed species daily bag limit of 3 sharks per fisher. Restrictions also govern gear types that can be used to take sharks, including a Statewide prohibition of metal trace wire and large hooks (introduced in 2008).

7.2 Harvest Strategy

7.2.1 Current framework

7.2.1.1 Sharks

The current harvest strategy and controls focus on maintaining current stocks above specified biomass levels and/or the recovery of over exploited stocks to specified biomass levels. Given the relatively low productivity of sharks compared to many teleosts, the time period for recovery of dusky and sandbar sharks is expected to take up to several decades (e.g. dusky shark, recovery target to be reached by 2040). The most critical element of the current harvest strategy is the control rule which sets a cap on effort throughout the fishery to 2001-02 levels.

For whiskery, gummy, dusky and sandbar sharks, the current harvest strategy focuses on maintaining (or rebuilding) biomass levels of each species at above B_{MSY}. Post-recovery harvest strategies, while being developed, will not be in place for all species until recovery. Thus, there is a long-term monitoring and assessment schedule for these stocks.

The current Harvest Strategy is a MSY-based approached. Since 1995, the main operational objective of the TDGDLF has been "to maintain the biomass of the fisheries' for the three traditional target stocks at or above 40% of their unfished levels (B_U) by 2010 for gummy and whiskery sharks and by 2040 for dusky shark". This reference level has been maintained post 2010 for whiskery and gummy sharks. These biomass targets were set by the WA Demersal Net and Hook Fisheries Management Advisory Committee (WADNHFMAC; previously the WA Demersal Gillnet and Demersal Longline Fishery Management Advisory Committee) as these levels were considered to represent the level at which long-term sustainable catches (i.e. MSY) could be achieved in these shark populations (Donohue et al. 1993). In November 2004, maximum acceptable catch (whole of fishery) and effort levels (by management zone) were also set by the WADNHFMAC equal to the fisheries' 2001-02 levels (McAuley 2005).

Maximum acceptable effort levels for each management zone have been based on their respective 2001-02 (daily) levels. These levels were set to both deliver sustainable harvests of target shark species while allowing for ongoing stock recovery and rebuilding, as well as allow sustainable harvests of by-product teleost species. Further, capping effort at 2001-02 levels also minimised bycatch and protected species interactions. A summary of the current harvest strategy is provided in Table 7.1.

[10] Recreational fishing guide: http://www.fish.wa.gov.au/Documents/recreational_fishing/rec_fishing_guide/recreational_fishing_guide.pdf

Table 7.1 Summary of current performance indicator, performance measures, control rules and justification for the shark target species of the TDGDLF.

Performance Indicators	Performance Measures	Control Rules	Justification
Biomass			
Target (Recovery)	Median value of total biomass is 0.4 B_U (whiskery, gummy and dusky sharks).	Effort levels are capped so as not to exceed 2001-02 levels.	This level was estimated to constrain catches of all species below which recovery would be jeopardised. This conservative measure accounts for all effort in the fishery (i.e. all used and latent effort), such that if all effort was used, total effort in the fishery would not exceed 2001-02 levels. The corresponding catches of target shark stocks at this level of effort would allow recovery of all stocks. The biomass targets were based on internationally accepted targets (Mace 1994; Caddy & Mahon 1995). This also effectively caps the effort and exploitation rate of the more productive teleost species below levels that would result in recruitment limitation.
Threshold	Catch rates (as an index of relative biomass) are stable or increasing	Review species specific effort levels with a view to species specific effort controls (e.g. whiskery pupping closure)	The capping of effort levels of 2001-02 levels ensures that exploitation rates are below those which would allow recovery of all target shark species. Annual review of species specific catch rates allows trends in recovery to be monitored and allows review of external factors (e.g. impacts of other fisheries beyond WA's jurisdiction). This effort cap effectively caps the effort and exploitation rate of the more productive teleost species below levels that would result in recruitment limitation.
Limit	Catch rates (as an index of relative biomass) are declining	Review species specific effort levels with a view to further species specific effort controls (e.g. whiskery pupping closure)	The capping of effort levels of 2001-02 levels ensures that exploitation rates are below those which would allow recovery of all target shark species. Annual review of species specific catch rates allows trends in recovery to be monitored and allows review of external factors (e.g. impacts of other fisheries beyond WA's jurisdiction). This effort cap effectively caps the effort and exploitation rate of the more productive teleost species below levels that would result in recruitment limitation.

7.2.1.2 Teleosts

The teleost harvest strategy is driven by the shark harvest strategy around effort levels (with the exception of the WCB). That is, while demersal teleosts are a legitimate and important part of the catches of TDGDLF, catches of teleosts will vary as effort is altered in response to the biomass levels of the targeted shark species, as well as changes in teleost biomass.

The component of the TDGDLF operating within the WCB is also managed in relation to the WDCSF resource and management. That is, the components of the TDGDLF in the WCB (i.e. the WCDGDLF and part of the JASDGDLF Zone 1, west of 115°30') are managed to 50% of the 2005-06 catches of demersal scalefish (see Fairclough et al. 2013; blue groper and blue morwong are a part of the demersal scalefish suite). Total catches of demersal scalefish by the component of the TDGDLF which operates in the WCB are to be maintained below 40 t.

7.2.2 Proposed framework

7.2.2.1 Sharks

The current harvest strategy is based on setting effort levels and hence maximum exploitation rates that will allow recovery of even less productive target shark stocks. Given the generally low productivity of sharks stocks as compared to many teleost species, the recovery period for some species (dusky) is multi-decadal. The key components of the proposed harvest strategy will include relative biomass levels as well as monitoring trends in species-specific effective effort (i.e. the effort exerted in the area where the species commonly occur in the catch) to better monitor effort and targeting. It is likely that a harvest strategy will be developed as a result of the transitioning of the JADGDLF to WA. However, the likely components of the harvest strategy are presented in Table 7.2.

Table 7.2 Summary of potential components of performance indicators, performance measures, control rules and justification for each target shark species (whiskery, gummy, dusky, and sandbar) to be considered in the development of a harvest strategy for the TDGDLF after the completion of two recent stock assessment projects. These will be in addition to the effort cap at 2001-02 levels. Additional performance indicators may also be considered (e.g. catch based, see Martell & Froese 2013).

Proposed Performance Indicators	Proposed Performance Measures	Proposed Control Rules	Justification
Biomass / biomass proxy			
Target	Median value of breeding biomass is above revised estimates of species specific MSY. Biomass target set at a proportion 1/p of B_{MSY}. Species specific biomass targets are likely to be higher for all species of target shark than that generally accepted for teleosts, a	If breeding biomass is below Target but higher than Threshold, fishing effort will remain unchanged. If breeding biomass is above Target, Department may discuss the potential for effort increases with industry and WAFIC.	Reference levels will be based on upon revised internationally accepted biomass benchmarks (Mace 1994; Caddy & Mahon 1995; Brooks et al. 2010), taking into consideration species specific productivity and new understanding of the reproductive biomass required to support MSY for shark stocks.

	reflection of the lower productivity.		
Threshold	Species-specific median B_{MSY} for the target shark species.	If breeding biomass of one or more stocks is/are below the threshold, a review of the fishery data and consultation with industry and WAFIC will be undertaken to determine causes and management options. Effort may be reduced by between 0–50% in some or all zones, in order to reduce exploitation rates and therefore catches.	As above. In addition, a review of the fishery is required as the distribution of target species and catches is not uniform throughout the TDGDLF. There may be species specific management actions that could be implemented (e.g. whiskery pupping closure) that will benefit a specific stock in a specific area.
Limit	Some proportion p of species-specific median B_{MSY} for the target shark species.	If breeding biomass of one or more stocks is/are below the limit, a review of the fishery data and consultation with stakeholders will be undertaken to determine causes and management options. Effort may be reduced by between 50–100%, in order to reduce exploitation rates and therefore catches.	Justification as for Target. In addition, a review of the fishery is required as the distribution of target species and catches is not uniform throughout the TDGDLF. There may be species specific management actions that could be implemented (e.g. whiskery pupping closure) that will benefit a specific stock in a specific area.
Effective effort			
Target	Annual estimate of effective effort for the target shark species remains below 2001-02 level.	If effective effort in zones that include a shark specie's primary distribution remains below the 2001-02 estimates, then effort settings will remain unchanged.	Effective effort provides an index of targeting among shark species (within or among zones). Shifts in effective effort will likely to be driven by shifts in targeting and spatial closures (e.g. marine parks, ASL) and not necessarily changes in biomass.
Threshold	Multi-year average of effective effort is less than specified level above 2001-02 level for the target shark species.	If multi-year average of effective effort increases considerably above 2001-02 levels a review of the fishery data and consultation with stakeholders will be undertaken to determine causes and management	Effective effort provides an index of targeting among shark species. Multi-year average shifts in effective effort will likely to be driven by shifts in targeting. The review will focus on if there has been evidence of significant increases in biomass to support the

		options. Species specific management (e.g. spatially based) may be considered to limit effective effort for any species. Effort changes are likely to be in the order of 0-50%.	increase in effective effort and likely increase in catches, and the magnitude of any changes. This information will be considered in parallel with standardised catch rate data.
Limit	Multi-year average of effective effort is more than specified level above 2001-02 level for the target shark species.	If multi-year average of effective effort for a target shark species remains above 2001-02 levels (for example, more than 50%) a review of the fishery data and consultation with stakeholders will be undertaken to determine causes and management options. Species specific management (e.g. spatially based) may be considered to limit effective effort for a given species. Effort changes are likely to be greater than 50%.	Effective effort provides an index of targeting among shark species. Multi-year average shifts in effective effort will likely to be driven by shifts in targeting. The review will focus on if there has been evidence of significant increases in biomass to support the increase in effective effort and likely increase in catches, and the magnitude of any changes. This information will be considered in parallel with standardised catch rate data.

7.2.2.2 Teleosts

The proposed harvest strategy for the target shark stocks will also effectively manage demersal teleost exploitation rates. This is a result of the productivities of the target shark stocks (especially, sandbar and dusky) being much lower than the productivities of the main teleost species captured by the TDGDLF. Thus, management settings that permit recovery and sustainable harvest of target shark stocks would result in the sustainable harvest of teleost species. Nonetheless, the harvest strategy to be developed will specifically consider blue morwong and blue groper and any other significant teleost species.

While specific species actions were not applied to the TDGDLF as a result of the stock status of the suite of West Coast demersal scalefish, the TDGDLF was given a nominal maximum catch level of 40 t of all demersal scalefish for that component of the TDGDLF that operates in the WCB. This setting will also be reviewed as the harvest strategy for the TDGDLF is reviewed after the completion of the two externally funded projects.

7.2.3 Design

The proposed harvest strategy will be responsive to the state of the stock and the elements of the harvest strategy work together towards achieving management objectives reflected in the target and limit reference points.

The key components include biomass reference points estimates of effective effort and trends in catch rates in an adaptive management framework. The proposed design builds upon the adaptive management approach in the TDGDLF that has been effective in reducing and capping effort levels to those which are allowing key target species to recover to agreed-to targets, accounting for the biological characteristics (e.g. longevity, age at maturity, fecundity) of the key target species.

7.2.4 Evaluation

The principal measures of the harvest strategy success are the biological sustainability indicators and the broader ecological sustainability of the TDGDLF. Evidence suggests that the current rebuilding (harvest) strategy has been successful in maintaining sustainability of the whiskery, gummy, dusky and sandbar shark catches in WA while allowing stocks to rebuild. Although the harvest strategy has not been fully tested, evidence exists that it is achieving its objectives.

The proposed harvest strategy will build on the existing harvest strategy with updated assessment and monitoring. The proposed strategy will continue stock rebuilding, confirm that some stocks have already met their biomass recovery targets, and allow adaptive management of the TDGDLF.

7.2.5 Monitoring

Information on effort, catch and catch rates is reported annually in Status Reports on the Fisheries and Aquatic Resources Report (Fletcher & Santoro 2012). Catch includes the total extractions from all other WA fisheries affecting the stocks. Hence, monitoring of these metrics on an annual basis is considered to be adequate in terms of monitoring the stock and determines the effectiveness of the harvest strategy.

Commercial catch and effort in the TDGDLF is monitored using data obtained from statutory daily logbook returns since 2006 (statutory monthly returns were used prior to 2006).

Recreational catch and effort for boat-based fishing in State waters is currently monitored using the integrated Statewide phone-diary survey (Ryan et al. 2017).

7.2.6 Review

The Harvest Strategy is periodically reviewed and modified as necessary.

In addition, due to the straddling nature of the target shark stocks (dusky and sandbar sharks), the Department is also a member of the Northern Australian Fisheries Management (NAFM) forum. NAFM reviews total annual removals of northern sharks across all jurisdictions, as well as reviewing and planning monitoring, assessment and research of this and other fisheries that target straddling stocks.

The Department regularly meets with licensees of the TDGDLF and NSF at specific AMMs, which are part of the industry consultation process coordinated by the Western Australian Fishing Industry Council (WAFIC).

In addition, biennial reporting of the dusky, sandbar and gummy shark stocks and catches (and several other species of shark) are reported and reviewed at a national level in the *Status of Key Australian Fish Stocks Reports*, providing another level of oversight (see Flood et al. 2012).

7.2.7 Shark Finning

It is highly likely that illegal shark finning is not taking place in the fishery.

There are anti-finning and anti-filleting regulations in place in all WA shark fisheries and there are significant penalties for contravention of these regulations. In 2000, there was growing concern about dusky and sandbar shark mortality in non-shark fisheries, particularly in the Western Tuna and Billfish fishery due, in part, to escalating shark fin prices (McAuley et al. 2000). In addition, the high fin prices triggered the drastic effort increases of the late 1990s in the NSF. As a result, in October 2000, regulations were passed to prohibit the landing of shark fins only (Fish Resources Management Act, FRMA, regs. 38E and 38F).

The fin component of the TDGDLF is small, primarily because the main target species are small and therefore have relatively small fins. The fins removed from landed sharks are mostly exported. To maintain export approval of fins, the shark fisheries are subject to assessment under the EPBC Act. The TDGDLF is accredited under the EPBC Act as approved Wildlife Trade Operations until August 2021.The compliance section of the Department also makes contact with commercial fishers, including those in the TDGDLF. This includes checking catches for compliance with compliance finning regulations.

7.2.8 Reference Points

7.2.8.1 Appropriateness of Reference Points

7.2.8.1.1 Current

The current reference point is appropriate for the stocks during their rebuilding phases and can be easily estimated. The level of effort is capped to that of 2001-02, which from empirical information (e.g. tagging studies to estimate fishing mortality, F) is below the level to allow recovery.

7.2.8.1.2 Proposed

The proposed reference points will also be appropriate for the stocks and will provide additional streams of information for adaptive management of these stocks. The proposed biomass points are based on new information from international studies. Braccini et al. (2017a) refined the assessment models and developed a time series of standardised catch rates. The refined data streams will be used to define appropriate reference points which can be estimated from the ongoing data streams from the TDGDLF.

7.2.8.2 Level of Limit Reference Point

7.2.8.2.1 Current

The reference point focuses on capping effort below 2001-02 levels. This level of effort was estimated to be below the level that would impair reproductive capacity of any target shark species. Thus, maintaining effort below 2001-02 levels results in stable or increasing biomass as monitored through the index of effective CPUE for each species. The additional adaptive management in place (e.g. metropolitan closure) further reduces risks to reproductive capacity of the stocks. The adaptive management approach also takes into account precautionary issues (e.g. the whiskery pupping closure).

7.2.8.2.2 Proposed

The limit reference points will be built around more precautionary biomass reference levels, estimating and monitoring effective effort and standardised catch rates (Braccini et al. 2017a). Thus, the proposed limit reference points will likely be set above the level at which there is an appreciable risk of impairing reproductive capacity, following consideration of relevant precautionary issues.

7.2.8.3 Level of Threshold Reference Point

7.2.8.3.1 Current

The reference point focuses on capping effort below 2001-02 levels. This level of effort was estimated to be below the level that would impair reductive capacity of any target shark species. Thus, maintaining effort below 2001-02 levels results in stable or increasing biomass as monitored through the index of effective CPUE for each species. The additional adaptive management in place (e.g. metropolitan closure) further reduces risks to reproductive capacity of the stocks. The adaptive management approach also takes into account precautionary issues.

7.2.8.3.2 Proposed

The proposed biomass threshold reference point will likely to be set at a level about B_{MSY} that will impose a low risk of impairing reproductive capacity, but allows effort to be restricted to allow rapid recovery.

In addition, the proposed threshold reference points around effective effort for each species and standardised catch rates will provide more rapid information on fishery and stock performance. The proposed framework for these reference points will involve a multi-year average that triggers a review to determine causes for changes in effective effort and/or catch rate trajectories to understand the causes. The proposed threshold reference points will be set above the level at which there is an appreciable risk of impairing reproductive capacity, following consideration of relevant precautionary issues. Management actions (e.g. effort settings) for a specific species are likely to be used to address stock issues.

7.2.8.4 Level of Target Reference Point

7.2.8.4.1 Current

The current target reference point is focussed on allowing all target shark stocks to recover to agreed-to levels of biomass. Thus, the target reference point is such that the stocks will recover to a level consistent with B_{MSY}.

The reference point focuses on capping effort below 2001-02 levels. This level of effort was estimated (via tagging studies to estimate fishing mortality and modelling approaches) to be below the level that would impair reductive capacity of any target shark stock. Thus, maintaining effort below 2001-02 levels results in stable or increasing biomass as monitored through the index of effective CPUE for each species. The adaptive management approach also takes into account precautionary issues specific to individual shark stocks, further reducing risks to the reproductive capacity of the stocks.

7.2.8.4.2 Proposed

The proposed target reference points also aim to ensure that the stocks are maintained at levels consistent with B_{MSY} or above. Precautionary issues, including differences in productivity among stocks, will be explicitly taken into account via setting species-specific target biomass levels (Braccini et al. 2015).

7.2.9 Control Rules and Tools

If a performance measure is outside acceptable limits a review will be conducted to determine the likely cause (e.g. market forces, other non-biological factors, stock status). If there is reasonable evidence to suggest that the breach of the trigger was not due to a decline in breeding biomass, then no action will be taken. Alternatively, if evidence indicates that the stock is at risk then the Department can instigate additional management actions, i.e. reduce effort thereby reducing catches. The Department has a strong record in doing so when required. Throughout the history of the TDGDLF, substantial adaptive management actions and management changes have been undertaken by the Department to allow species-specific outcomes in this multi-species fishery.

The ability to implement these actions is provided through the Aquatic Resources Management Act (ARMA) 2016 and previously the FRMA 1994. The authority to adjust effort is held by the Minister of Fisheries. Management action in the TDGDLF is accompanied by management action in the recreational sector, as appropriate.

7.2.9.1 Design and Application

7.2.9.1.1 Current

The current design and application of the control rules are consistent with the Harvest Strategy for the stocks during their rebuilding phases. The application of the effort cap at 2001-02 levels ensured that the exploitation rate was reduced to allow stock rebuilding. It is thus well designed, implemented and defined.

7.2.9.1.2 Proposed

The proposed control rules will be consistent with the Harvest Strategy and ensure that the exploitation rate is reduced as limit reference points are approached.

7.2.9.2 Accounting for Uncertainty

The design of the harvest control rules takes into account a wide range of uncertainties. The largest of these being the uncertainties around key life history parameters of the long-lived shark species (e.g. sandbar shark). The current management settings have used a precautionary approach, setting effort levels (that equate to catches) that will allow recovery of target shark stocks (dusky, sandbar and gummy).

There is a high level of certainty in the data for commercial catches as the TDGDLF is currently the only fishery permitted to land sharks. Further, the target shark stocks (dusky, gummy, whiskery and sandbar) are completely within WA’s jurisdictional boundaries.

Recreational catches of sharks have been estimated intermittently in the past and are now estimated biennially; however, recreational catches of sharks are relatively small. There is also specific protection for whaler sharks applied to the recreational sector; it is illegal for recreational fishers to retain whaler sharks with an inter-dorsal fin length greater than 700 mm. Recreational size, bag and boat limits also apply for blue groper and blue morwong.

All available data, including uncertainties, are presented to managers and stakeholders for consideration.

7.2.9.3 Evaluation

The available evidence clearly shows that the tools in use are effective in achieving the exploitation levels required under the harvest control rules. The biomass targets and effort levels and monitoring are appropriate and effective in achieving the exploitation levels required under the harvest control rules.

Multiple lines of evidence indicate that the fishery is currently operating at sustainable levels. There is good evidence that the monitoring, assessment and management regime for these fisheries have been successful in regulating effort to maintain fishing at sustainable levels. Further, the management actions undertaken have ensured that stock rebuilding and recovery of the gummy and dusky shark stocks is likely to have occurred and that recovery of the sandbar shark stock is well underway.

7.3 External Influences

Overall, environmental drivers pose low risk to shark stocks although climate-change related shifts in species distributions, depth ranges and abundances have been observed (Fuentes et al. 2016). For WA, the potential impacts of climate change on gummy, dusky, whiskery and sandbar sharks are poorly understood. However, as climate change is known to be causing an increase in water temperature (particularly in autumn and winter) and affecting the Leeuwin Current, it can be reasonably assumed that these changes maybe impacting these species off the WA coast, particularly dusky and sandbar sharks which undertake north-south seasonal movements; with juveniles moving north as they grow and adults moving south to give birth. The extent of these impacts on stock recruitment is not understood.

The main external risk to the viability of the TDGDLF is the introduction of Commonwealth Marine Reserves and ASL closures in 2018. The economic impact of these closures on the profitability of the fisheries is currently not known.

Finally, as the TDGDLF key target species span multiple regional boundaries there are a number of factors outside of the control of the fishery which can negatively impact the performance of key temperate shark stocks. In particular, the potential for catches of breeding stock of sandbar sharks in WA's NSF remains cause for concern. Other potential factors affecting key temperate shark stocks include targeted fishing for gummy shark by Commonwealth managed vessels in the Southern and Eastern Scalefish and Shark Fishery (SESSF) that occurs to the east of Zone 2 of the JASDGDLF (although the fishery is tightly managed via quota controls) and incidental catches of dusky and gummy sharks in other State and Commonwealth Government-managed fisheries. While the risks associated with these outside influences are largely unqualified they must be acknowledged to ensure appropriate management strategies are implemented that address the long-term sustainability of the shark stocks.

8. Information and Monitoring

8.1 Range of Information

A comprehensive range of information exists (Table 8.1). This includes information on stock structure, stock productivity, fleet composition, stock abundance, fishery removals and other information (e.g. shark movements), including some that may not be directly relevant to the current harvest strategy.

There is considerable relevant information to support the Harvest Strategy. There is more than 40 years of catch and effort data available for the TDGDLF in WA as statutory monthly returns provided by fishers. In 2006, the monthly statutory returns were replaced with daily logbooks, collecting catch and effort data on finer temporal and spatial scales.

Catch and effort information has been used to compile annual statistics and to provide data for stock assessments. These data are corrected and validated for missing/incorrect information and the non-identification of species. Current research monitoring involves analysis of fishing returns data and periodic biological sampling of commercial and fishery-independent catches (Braccini et al. 2013). To support the fishery management arrangements introduced, improve assessments of key stocks, and facilitate the more detailed reporting requirements of the fisheries' export accreditation under the Commonwealths Environment Protection and Biodiversity Conservation (EPBC) Act, statutory daily/trip catch and effort logbooks were introduced in 2006-07. After rectifying some initial problems this exercise generally improved reporting standards and has provided the basis for development and implementation of new catch and effort data validation protocols.

The introduction of VMS (2006) allowed to accurately monitor fishery compliance with spatial and temporal closures and provides a robust and efficient tool for monitoring the consumption of effort entitlements.

The first stock assessment of the fishery was based on the best available information (Donohue et al. 1993). One of the main points raised by this study was the considerable uncertainty in biological and fishery information. Hence, the Department has carried out fisheries research to continually improve the monitoring of the status of WA's main commercial shark species.

Major FRDC-funded studies of the shark fishery on the south and west coasts of WA, undertaken over the period 1993–2004, have provided a detailed basis for monitoring and assessing the fisheries. The extensive biological and fishery information gained from these studies have been reported in three FRDC final reports (Simpfendorfer et al. 1996b, 1999; McAuley et al. 2005), numerous international journal publications (Simpfendorfer & Unsworth 1998a, 1998b; Simpfendorfer & Chidlow 2000; Simpfendorfer et al. 2002; McAuley et al. 2007b, 2007c, 2007a) and have been used to develop stock assessment models for the fisheries' key target stocks to determine their likely responses to current levels of exploitation and to test alternative harvest regimes.

A conventional tagging program between 1994 and 1996 initially tagged 2,199 juvenile dusky, 343 sandbar (mostly juveniles) and 282 whiskery sharks (Simpfendorfer et al. 1996b). A second major tagging program was conducted between 2000 and 2004 when 1,759 sandbar sharks were tagged (McAuley et al. 2005). The two tagging programs were undertaken to generate information on movement, growth, age validation, stock structure, tag shedding and reporting, and exploitation rate level (Simpfendorfer et al. 1996b, 1999). The tagging studies were part of two major studies that also investigated the reproductive biology, diet, nursery areas, stock structure, recruitment, growth and gillnet mesh selectivity for these species (Simpfendorfer et al. 1996b, 1999). The fisheries catch composition was reported by McAuley & Simpfendorfer (2003). This information has since been used in the simulation models used for improving the stock assessment advice given to management and has formed the basis for several scientific and popular publications on the biology and fishery of shark populations.

Annual fishery-independent longline surveys in the Gascoyne Coast and North Coast Bioregions provide ongoing information and assessment of the recovery of the dusky and sandbar shark breeding stocks.

A four year FRDC-funded study of movements of whiskery, gummy, dusky and sandbar sharks using acoustic tagging technologies was completed in 2017 (Braccini et al. 2017a). Results from this study are being used to help in the reassessment of the status of these stocks enabling greater reference to their spatial and temporal dynamics.

Tactical research is also completed on bycatch issues with Threatened, Endangered and Protected (TEP) species. Two WA Marine Science Institution (WAMSI)-funded projects developed a method to rapidly assess the cumulative risk to sustainability of bycatch species (Evans & Molony 2010) and undertook a pilot study to test the efficacy of using electronic monitoring to determine the catch composition of demersal gillnets (Evans & Molony 2011). Two National Heritage Trust-funded projects investigated movements and aggregation locations of grey nurse sharks (Chidlow et al. 2006). Two FRDC-funded projects developed a risk-based assessment of the impact of incidental capture of TEP species in demersal gillnets (Campbell 2011) and examined the relative spatial risks of ASL interactions with demersal gillnets (Hesp et al. 2012). WA Government funded research into white shark movements around the south-west of WA provided information on the ecology and population structure of this protected species (McAuley et al. 2016). Recently, a FRDC-funded project was initiated to develop novel approaches to assess and monitor the population status of ASLs in WA using remote cameras.

The fishing industry is involved in research and the management decision-making process (Simpfendorfer & Donohue 1998; Borg & McAuley 2004).

Table 8.1 Summary of information available to support the harvest strategy for the TDGDLF Fishery.

Data type	Fishery dependent or independent	Analyses used in stock assessment	Additional analyses and purpose	Areas of data collection	Frequency of data collection	History of data collection
Catch and effort statistics (CAES)	Dependent	Catch and effort trends	Statutory requirement	Extent of TDGDLF	Monthly	1975–2006
Daily logbook	Dependent	Annual catches and catch rates as indicators of abundance	Statutory requirement Finer spatial scale analysis of catch and effort	Extent of TDGDLF; Detailed latitude and longitude	Daily - by fishing session	Compulsory since 2006
VMS	Dependent	Determine and verify fishing	Statutory requirement	Extent of TDGDLF	Daily -by fishing session	Since 2006

		activity within areas	Verify vessel location and speed			
Biological	Dependent and independent	Age, growth, reprod. biology		Extent of TDGDLF	Opportunistically and as part of several FRDC research projects	1990s–2010s
Annual longline survey	Independent	Catch rate and catch data and trends of breeding stock		Shark Bay (Gascoyne Coast Bioregion) to 80 Mile Beach (North Coast Bioregion)	Annual	2001 onwards
Recreational catch and effort	Dependent	Catch and effort trends	Examining catch shares	West Coast Bioregion only	Opportunistically	1996-97 (Sumner & Williamson 1999) 2005-06 (Sumner et al. 2008)
iSurvey (Recreational catch and effort data)	Dependent	Catch and effort trends	Examining catch shares	Extent of TDGDLF	Biennial	Since 2011-12 (Ryan et al. 2017)
Conventional tagging	Dependent	Estimation of exploitation rate		Extent of TDGDLF and beyond	As part of two FRDC research projects. Currently, opportunistically	1994–1996 2001–2004 Ongoing since 2012

8.2 Monitoring

Effort, catch and catch rate levels are regularly monitored to support the harvest strategy.

8.2.1 Commercial Catch and Effort

Catch and effort data for the TDGDLF are derived from monthly (1975-2005) and daily (2006 onwards) fishing returns submitted to the Department by commercial fishers as a condition of their licences. Monthly returns were reported by 60 nm spatial blocks whereas daily returns are reported by 10 nm spatial blocks. These data are routinely validated and corrected if necessary.

Traditionally, catch and effort were reported on a monthly basis. To support the harvest strategy, a new daily/trip catch and effort reporting system was introduced in June 2006. The transition from monthly to daily reporting resulted in data inconsistencies/problems. To resolve this, an extensive data recovery exercise was undertaken during 2009. By early 2010, catch and effort data had been fully recovered, validated and standardised (DoF 2012). As well as rectifying previously problematic fishing returns, the data recovery exercise provided a platform for generally improved reporting standards across the TDGDLF and has provided the basis for the development and implementation of new catch and effort data validation protocols (DoF 2012).

As the key target species of the TDGDLF span multiple regional boundaries there are a number of factors outside of the control of the fishery which can negatively impact the performance of these shark stocks. In particular, the potential for ongoing catches of breeding stock of sandbar sharks across the NSF remains a potential cause for concern; however, the NSF have not operated since February 2009 and thus catches of sandbar shark (and other species) by the NSF have been zero since this date.

Other potential catches include targeted fishing for gummy shark by Commonwealth managed vessels that occurs to the east of Zone 2 of the JASDGDLF (although the fishery is tightly managed via quota controls) and incidental catches of dusky and gummy sharks in other State and Commonwealth Government-managed fisheries. In addition, tag recapture data and micro-chemical analyses showed that for gummy shark there is limited mixing between WA and SA (Simpfendorfer et al. 1999).

Sharks were also historically caught off the south and west coasts in a variety of other commercial fisheries. However, due to the very poor standard of reported species identification of non-targeted shark catches and those catches' contribution to identified sustainability risks to some stocks (e.g. dusky shark), the retention of sharks and rays was prohibited in most non-target fisheries throughout the State by commercially protecting all sharks and rays (elasmobranchs) in November 2006. Reported elasmobranch catches by vessels operating in other managed fisheries between North West Cape and the SA border subsequently declined to less than 5 t per year (Braccini et al. 2013).

8.2.2 Recreational Fishing

The current recreational catch of sharks in the West Coast and South Coast Bioregions represents less than 5% of total shark catch. All whaler sharks with an inter-dorsal length of greater than 700 mm are protected State-wide.

The recreational catch of sharks by fishers operating from trailer-boats between Augusta and Kalbarri was estimated from surveys conducted in 1996-97 (Sumner & Williamson 1999) and 2005-06 (Sumner et al. 2008). The total recreational shark catch was estimated to have declined from ca. 7,000 sharks per year in 1996-97 to ca. 5,500 sharks per year in 2005-06, although only about half of these were reported to have been retained. The reported species composition of the retained catch in 2005-06 was similar to that of the TDGDLF. Whaler shark species were the most commonly retained group (31%), followed by hound sharks (gummy, whiskery, etc.; 28%), wobbegongs (14%) and hammerheads (10%). However, identification by recreational fishers of sharks to species levels is not robust. Assuming an average weight of 5 kg per shark, the recreational take of sharks in the WCB in 2005-06 is point-estimated at approximately 13.5 t (Braccini et al. 2013).

State-wide integrated system used to survey boat-based recreational fishers throughout WA (Ryan et al. 2012) estimated the 2011-12 recreational capture of sharks at 21,319 (± 6,199, standard error, se) individuals, of which 4,466 (± 1,834) were retained. Thus, most sharks hooked by the recreational sector are released (more than 70% overall). The total estimated recreational retained catch of all sharks was estimated at 22.4 t (based on 5 kg per shark). Similar figures were estimated for subsequent years (Ryan et al. 2015; Ryan et al. 2017).

For the West Coast and South Coast Bioregions (in which the TDGDLF operate), a total of 10,697 (± 3,135) individuals were captured with 3,026 (± 973) retained, equating to approximately 15.1 t of recreationally captured shark. Most sharks landed by the recreational fishery were reported from the WCB (10,081 ± 2,874), of which 2,634 (± 823) were retained (13.1 t). These estimates for the WCB are similar to the numbers of recreationally retained sharks estimated for this Bioregion in 2005-06 (Braccini et al. 2013). The similarity is likely due to the total protection of sharks with an inter-dorsal length of greater than 700 mm and a high (self) compliance.

Based on the estimate of 909 t of commercial captured shark from the TDGDLF estimated for the 2011-12 commercial season (Braccini et al. 2013), the recreational catch in the West Coast and South Coast Bioregions represents less than 2% of the total catch of sharks. Recreational catches of shark by the charter industry is likely to be significantly less than that of the recreational boat based sector.

While species identification of sharks by recreational fishers is unreliable, recreational fishers reported that the most commonly retained species were hound sharks (43%), whalers (28%), other sharks (14%), wobbegongs (9%) and hammerheads (5%). For the WCB, the most commonly retained species were also hound sharks (38%), whalers (31%), other sharks (16%), wobbegongs (10%) and hammerheads (5%).

8.2.3 Fishery-Independent Monitoring

An extensive range of data sources support the monitoring, assessment and management of this fishery. In addition, annual fishery independent longline surveys have been undertaken in the Gascoyne Coast and North Coast Bioregions since 2001. This survey aims to provide ongoing information and assessment of the recovery of the dusky and sandbar shark breeding stocks. These annual surveys also provide a platform for ongoing tagging of these and other species of sharks.

8.3 Data Governance

8.3.1 Data Storage (non-public)

CAES, commercial monitoring and research logbook data are entered into departmental data bases with original paper copies being stored on site within the WAFMRL (Western Australia Fisheries & Marine Research Laboratories), Hillarys WA.

8.3.2 Data Treatment (non-public)

The business rules applied for amending commercial catch and effort records are summarised in Figure 8.1 and are detailed in (McAuley et al. 2005) and previous stock assessment reports.

The code developed for applying the business rules is stored in https://github.com/JuanMatiasBraccini/Git_catch.and.effort

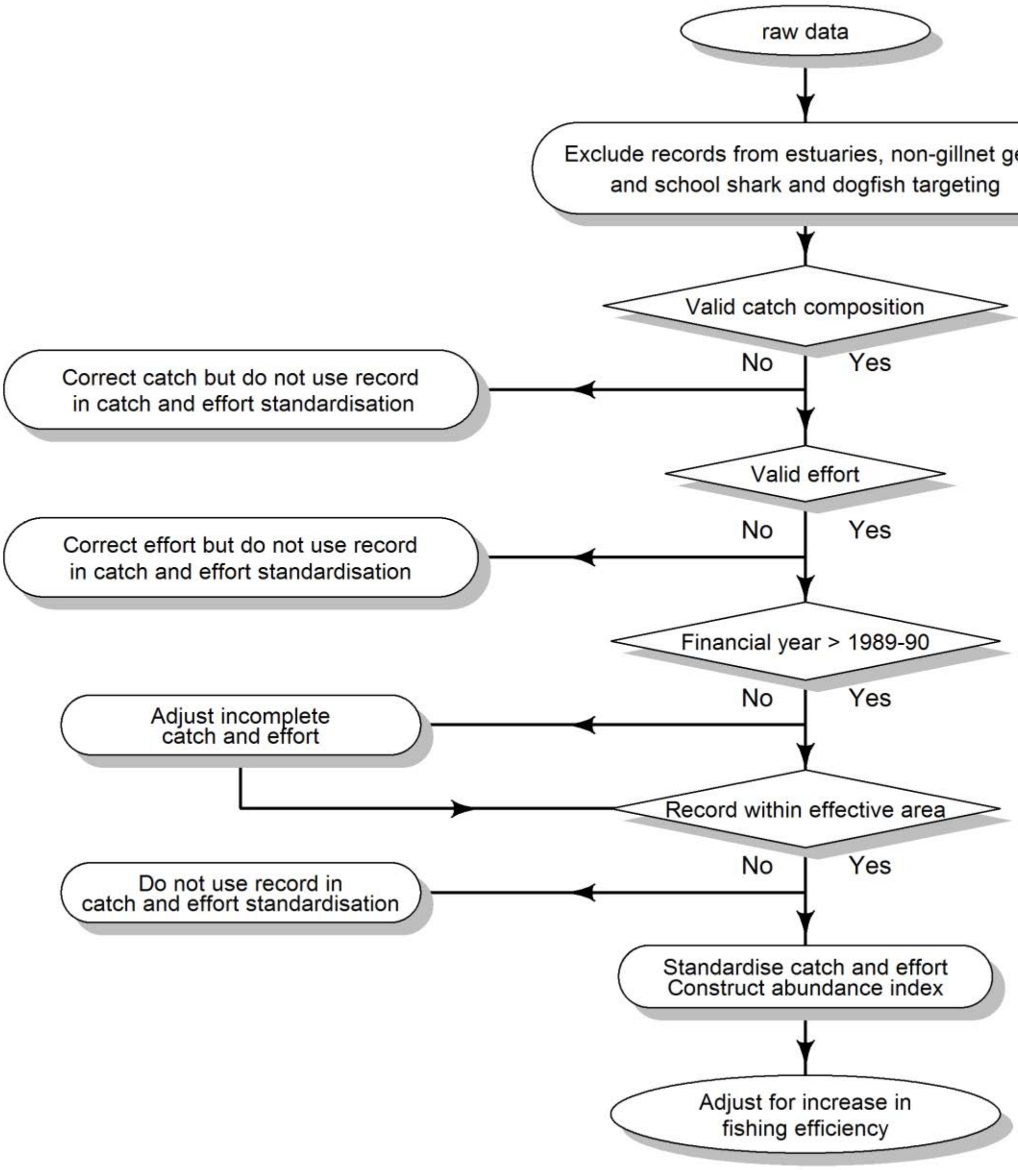


Figure 8.1 Flowchart of analysis steps for verifying and correcting the catch and effort data.

9. Stock Assessment

9.1 Principles

The different methods used by the Department to assess the status of aquatic resources in WA have been categorised into five broad levels, ranging from relatively simple analysis of catch levels and standardised catch rates, through to the application of more sophisticated analyses and models that involve estimation of fishing mortality and biomass (Fletcher & Santoro 2012). The level of assessment varies among resources and is determined based on the level of ecological risk, the biology and population dynamics of the relevant species, the characteristics of the fisheries exploiting the species, data availability and historical level of monitoring.

Irrespective of the types of assessment methodologies used, all stock assessments undertaken by the Department take a weight-of-evidence, risk-based approach (Fletcher 2015). This requires specifically the consideration of each available line of evidence, both individually and collectively, to generate the most appropriate overall assessment conclusion. The lines of evidence include the outputs that are generated from each available quantitative method, plus any qualitative lines of evidence such as biological and fishery information that describe the productivity and vulnerability of the species/stock, and information from fishers, stakeholders and other sources. The strength of this approach is that it explicitly assigns a specific consequence level to each line of evidence and highlight areas of uncertainty and inconsistencies, which assist in determining the overall risk level.

9.2 Assessment Overview

For whiskery and gummy sharks, an integrated size-based model was implemented to extend previous assessment models. The integrated model incorporated life history, gear selectivity, size composition, growth, catch and standardised fishery-dependent catch rate data up to and including the 2015-16 financial year. In addition, life history and catch information was used in a combined demographic and stock-reduction model (SR) to assess stock sustainability because the standardised fishery-dependent catch rate of gummy sharks was concluded to be a poor index of population abundance, limiting the ability of the integrated model to represent population dynamics.

For dusky and sandbar sharks, the time series of catch and effort data were insufficient for estimating biomass trends from fitting population dynamics models to abundance indicators, such as catch rates, due to the size-selective nature of the fishing gear used in the TDGDLF (selecting mostly neonates and young juveniles) and longevity of these species. Hence, a SR modelling approach was implemented to determine catch sustainability using life history and catch information up to and including the 2015-16 financial year.

9.2.1 Peer Review of Assessment

Stock assessments of key indicator species are internally reviewed as part of the Department's process for providing scientific advice to management and the Minister on the status of fish stocks. Assessment summaries are signed off by the relevant Supervising Scientists and the Director of Research before being provided to the fishery managers to inform decision-making. Assessments and annual catch information are also presented by the Department and discussed with commercial licence holders at Management Meetings (MMs).

9.3 Analyses and Assessments

9.3.1 Data Used in Assessment

The information used in the assessment includes CAES data, Logbook data, Fishery-dependent data, Fishery-independent survey data, and Tagging data.

9.3.2 Catch and Effort Trends

9.3.2.1 Catch of Resource and Indicator Species by Sector

For whiskery sharks, almost all of the reported catch in WA is taken by the TDGDLF (Figure 9.1). For these fisheries, annual catches increased from over 100 t in 1975-76 to over 500 t in 1981-82. Between the mid-1980s and early-1990s annual catches fluctuated at ~400 t. Following management intervention, catches subsequently decreased to between ~150 and

200 t since the early 1990s and have fluctuated around these levels ever since. Reported catches from other commercial fisheries and the estimated recreational catches are negligible. For the TDGDLF, the spatial distribution of reported catches of whiskery shark changed over the period of the fishery's earliest development, corresponding to an expansion phase of the fisheries (Figure 9.2). However, it has remained relatively stable since the 1990s, with catches being reported throughout most of the species' range.

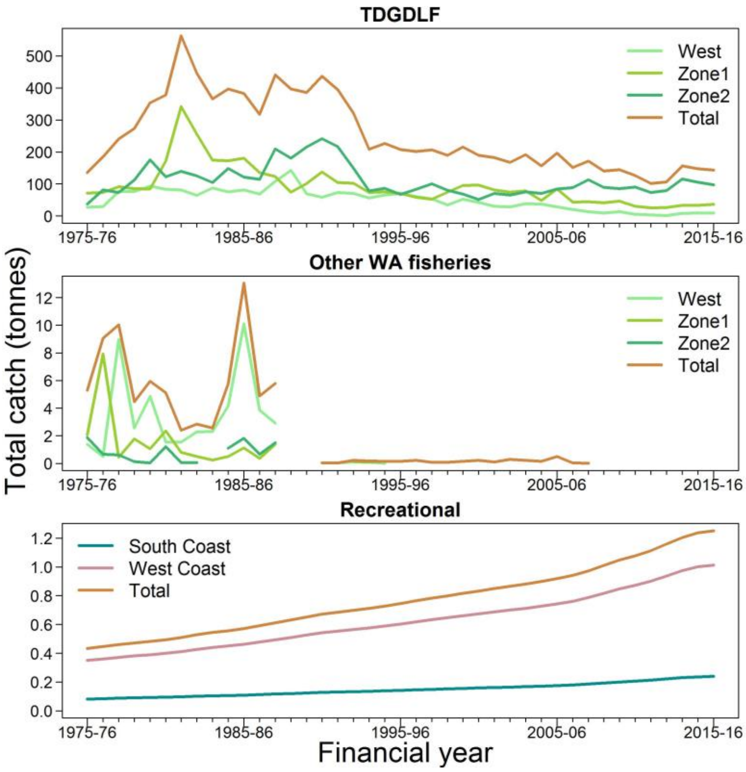


Figure 9.1 Reported catches of whiskery shark in WA. TDGDLF, Temperate Demersal Gillnet and Demersal Longline Fisheries (West, West Coast Demersal Gillnet and Demersal Longline (Interim) Fishery; Zone1 and Zone2, Zones 1 and 2 of the Joint Authority Southern Demersal Gillnet and Demersal Longline Fishery). Note that the y-axes are different for each panel.

For gummy sharks, almost all of the reported catch in WA is taken by the TDGDLF, specifically Zone 2 of the JASDGDLF (Figure 9.3). For these fisheries, annual catches gradually increased from just over 50 t in 1975-76 to over 750 t in 2007-08. The historic peak observed in 2007-08 was perceived to be due to an increase in abundance/availability as effort since the early 2000s has remained relatively constant at ~ 25–30% of the historic effort peak observed in the late 1980s (Figure 9.9). Since 2010-11, catches have been maintained within or just above the recommended target catch ranges (350–450 t). Reported catches from other commercial fisheries and the estimated recreational catches are negligible. For the TDGDLF, the spatial distribution of reported catches of gummy shark changed over the period of the fishery's earliest development, corresponding to an expansion phase of the fisheries (Figure 9.4). However, it has remained relatively stable since the 1990s, with catches being reported throughout most of the species' range.

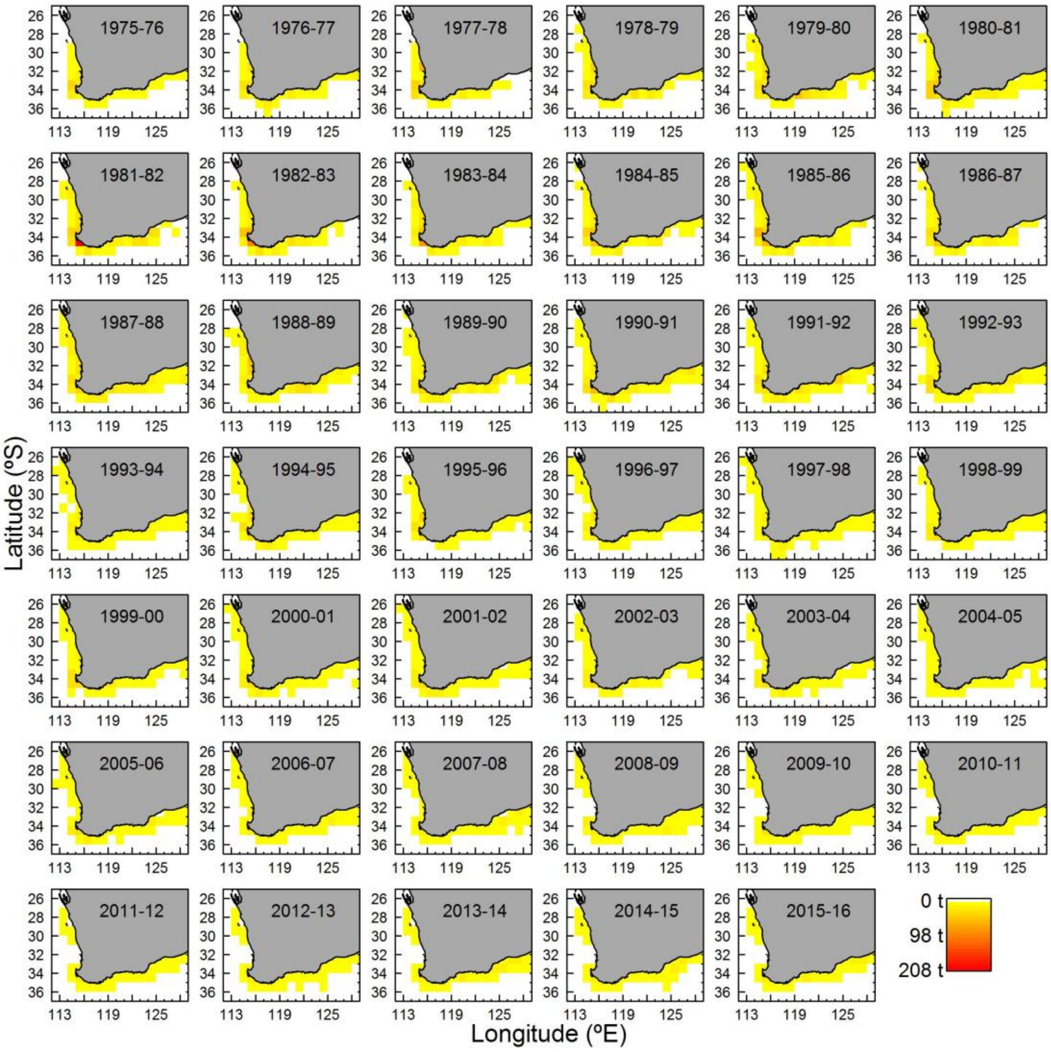


Figure 9.2. Distribution of whiskery shark reported catches by financial year and 60 nm block in the TDGDLF.

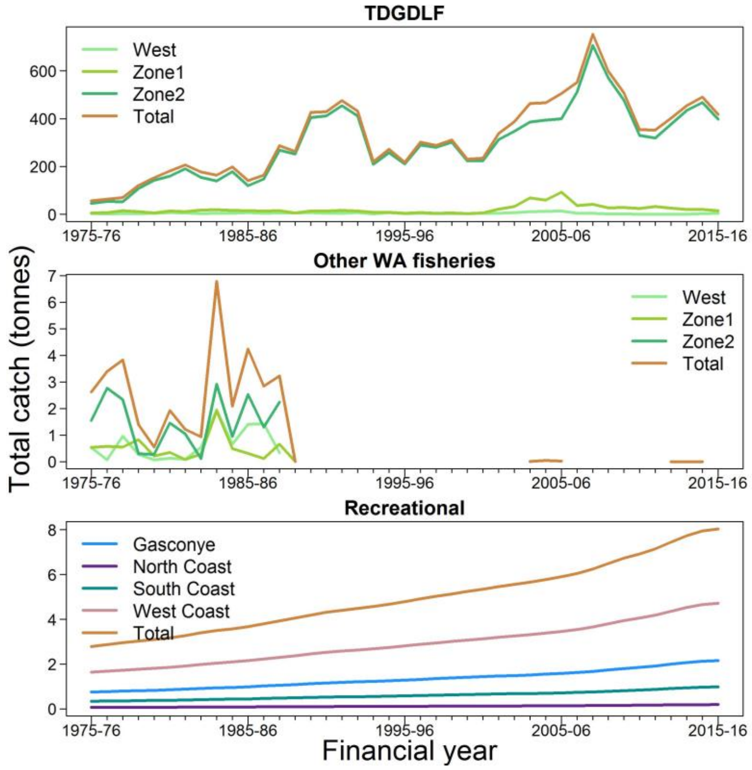


Figure 9.3. Reported catches of gummy shark in WA. TDGDLF, Temperate Demersal Gillnet and Demersal Longline Fisheries (West, West Coast Demersal Gillnet and Demersal Longline (Interim) Fishery; Zone1 and Zone2, Zones 1 and 2 of the Joint Authority Southern Demersal Gillnet and Demersal Longline Fishery). Note that the y-axes are different for each panel.

For dusky sharks, almost all of the reported catch in WA is taken by the TDGDLF although up to almost 40 t were taken in the NSF in the early 2000s (NB dusky shark catches include catches of bronze whaler, *C. brachyurus*, which cannot be accurately separated in catch returns data prior to 2006-07, Figure 9.5). For the TDGDLF, annual catches gradually increased from ~110 t in 1975-76 to over 670 t in 1988-89. Following management intervention, catches subsequently decreased, and have fluctuated at ~200 t since the late 2000s remaining within the recommended target catch ranges (200–300 t). Reported catches from other commercial fisheries and the estimated recreational catches are negligible. For the TDGDLF, the spatial distribution of reported catches of dusky shark changed over the period of the fishery's earliest development, corresponding to an expansion phase of the fisheries (Figure 9.6). However, it has remained relatively stable since the early 2000s, with catches being reported throughout most of the species' range. In the South Coast and West Coast Bioregions of WA, whaler sharks with an inter-dorsal fin length greater than 700 mm (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 post-capture mortality (PCM), however, is uncertain. The only records of oversized dusky shark captures are TEP 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 3 m dusky shark (166 kg) was multiplied by the number reported dead plus the number reported to be released alive times an assumed PCM of 0.3. The calculated annual catches are shown in Figure 9.5 (TEPS panel). It must be noted that the calculations were made assuming a 100% reporting rate and are likely to be underestimates of the true levels of catch.

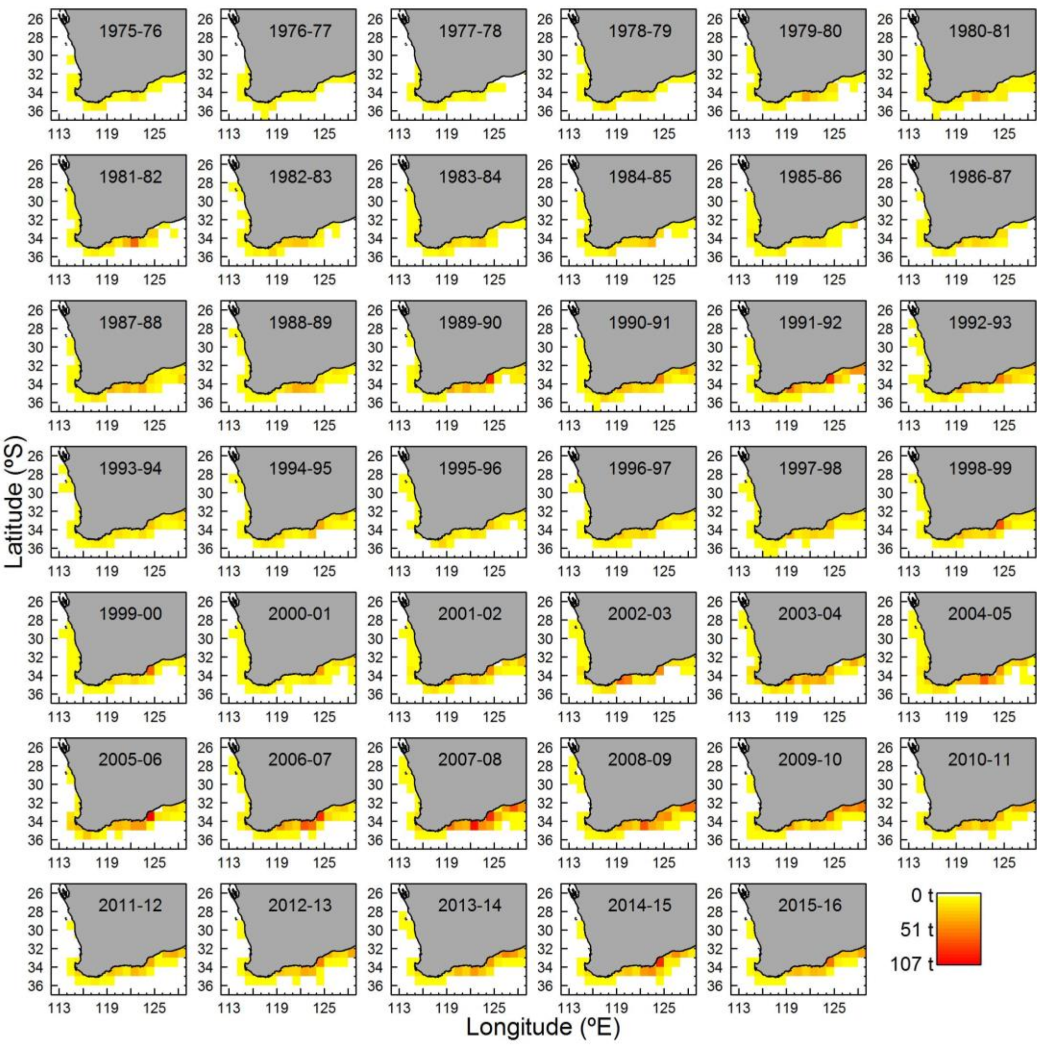


Figure 9.4. Distribution of gummy shark reported catches by financial year and 60 nm block in the TDGDLF.

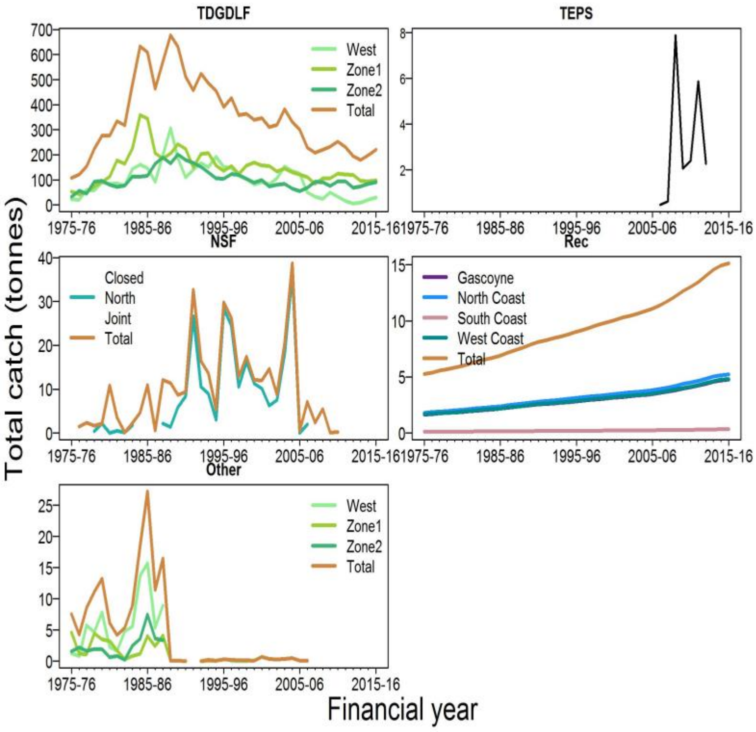


Figure 9.5. Reported catches of dusky shark in WA. TDGDLF, Temperate Demersal Gillnet and Demersal Longline Fisheries (West, West Coast Demersal Gillnet and Demersal Longline (Interim) Fishery; Zone1 and Zone2, Zones 1 and 2 of the Joint Authority Southern Demersal Gillnet and Demersal Longline Fishery); NSF, Northern Shark Fisheries (Closed, Ningaloo closure; North, Western Australia North Coast Shark Fishery; Joint, Joint Authority Northern Shark Fishery); Other, Other commercial fisheries of WA; TEPS, Threatened, Endangered, or Protected Species; Rec, Recreational fisheries of Western Australia. Note that the y-axes are different for each panel.

For sandbar sharks, significant catches were reported from the NSF (Figure 9.7). Catches in these fisheries increased rapidly from negligible levels in the 1980s and early 1990s to more than 750 t in 2004-05 (Figure 9.7). Catches then rapidly declined (as a result of management intervention) and no catches have been reported since 2008-09. Currently, almost all of the reported catch in WA is taken by the TDGDLF, specifically the WCDGDLF (Figure 9.7). For these fisheries, annual catches fluctuated between ~100 t and more than 200 t between 1989-90 and 2009-10. Following management intervention, catches subsequently decreased, fluctuating at ~40 t since 2011-12 and remaining below the recommended target catch limit (<120 t). For the TDGDLF, the spatial distribution of reported catches of sandbar shark changed over the period of the fishery's earliest development, corresponding to an expansion phase of the fisheries (Figure 9.8). However, it has remained relatively stable since the late 1980s, with catches reported throughout most of the species' range.

(NB recreational catches for all species were calculated by multiplying the annual point estimate for 2015-16 of Ryan et al. (2017) by the trends in population growth in WA and the proportion of the population participating in recreational fishing).

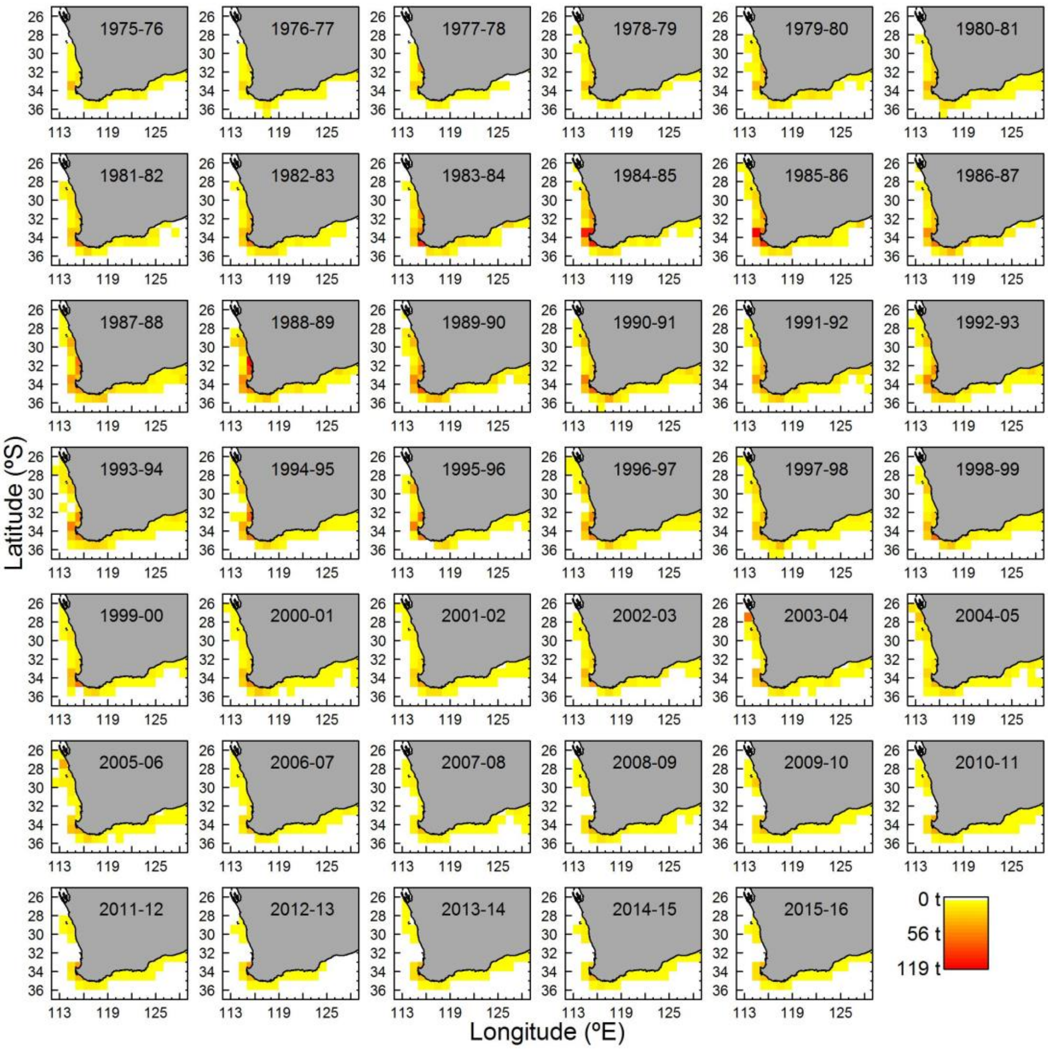


Figure 9.6.Distribution of dusky shark reported catches by financial year and 60 nm block in the TDGDLF.

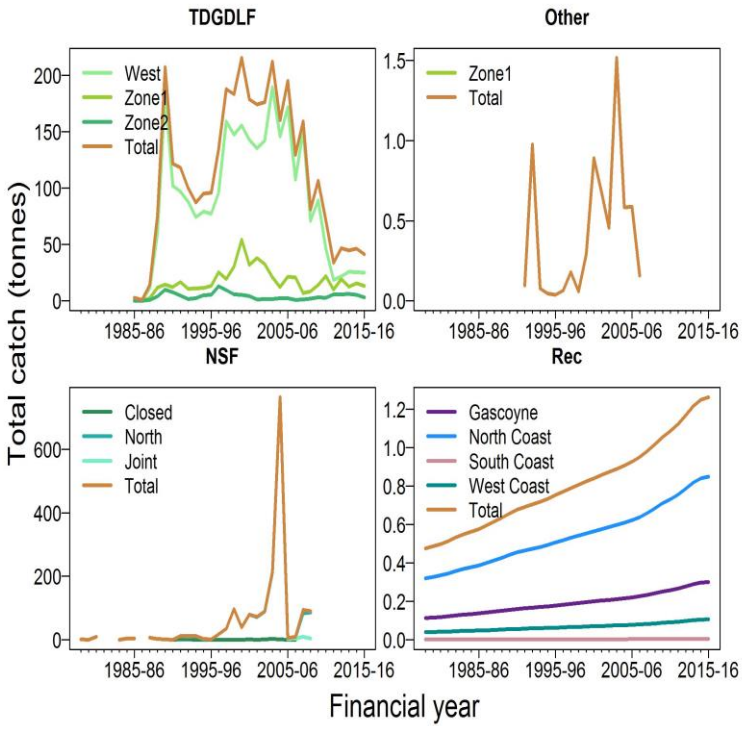


Figure 9.7. Reported catches of sandbar shark in WA. TDGDLF, Temperate Demersal Gillnet and Demersal Longline Fisheries (West, West Coast Demersal Gillnet and Demersal Longline (Interim) Fishery; Zone1 and Zone2, Zones 1 and 2 of the Joint Authority Southern Demersal Gillnet and Demersal Longline Fishery); NSF, Northern Shark Fisheries (Closed, Ningaloo closure; North, Western Australia North Coast Shark Fishery; Joint, Joint Authority Northern Shark Fishery); Other, Other commercial fisheries of WA; Rec, Recreational fisheries of Western Australia. Note that the y-axes are different for each panel.

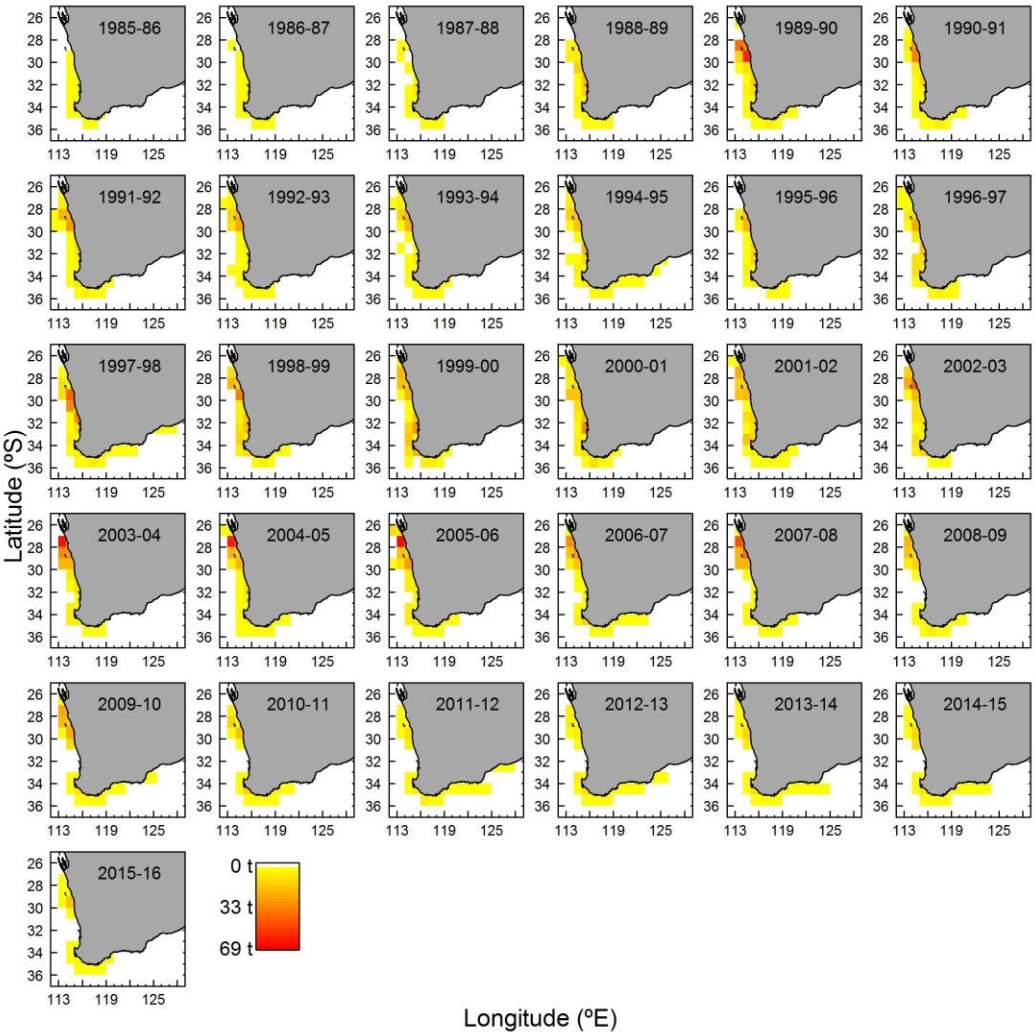


Figure 9.8. Distribution of sandbar shark reported catches by financial year and 60 nm block in the TDGDLF.

9.3.2.2 Effort by Sector

TDGDLF fishing effort rapidly increased between 1975-76 and the late 1980s (Figure 9.9). Between the early 1990s and late 2000s management measures were introduced to reduce effort due to sustainability concerns. Specifically, effort limits (equivalent to 2001-02 levels, considered likely to deliver sustainable catches) were introduced in 2006-07. Subsequently, effort showed a substantial decline, remaining relatively constant since the mid-2000s (at ~25–30% of the historic effort peak) and within effort limits.

For the TDGDLF, the spatial distribution of fishing effort changed over the period of the fishery's earliest development, corresponding to the expansion phase of the fisheries. However, it has remained stable and widely distributed since the 1990s (Figure 9.10). It must be noted that the Metropolitan Area (31°–33° S inshore of 250 m depth) was closed to commercial fishing in November 2007.

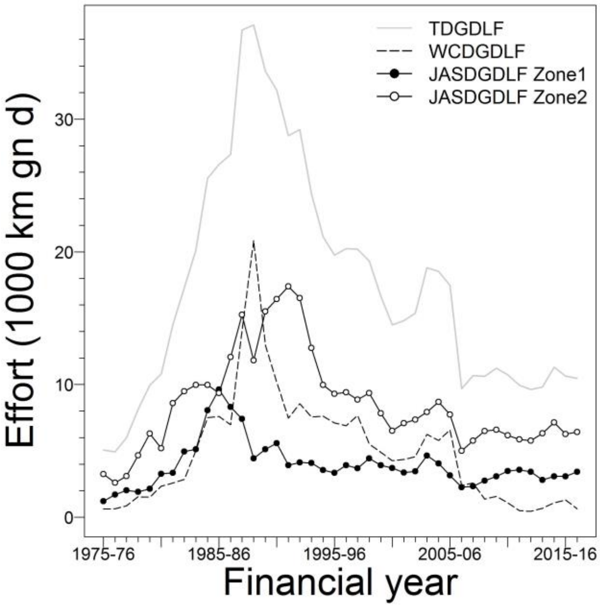


Figure 9.9. Standardised demersal gillnet and demersal longline effort for the TDGDLF. Black circles = JASDGDLF Zone 1; white circles = JASDGDLF Zone 2; dashed black line = WCDGDLF; plain grey line = total from the three management zones.

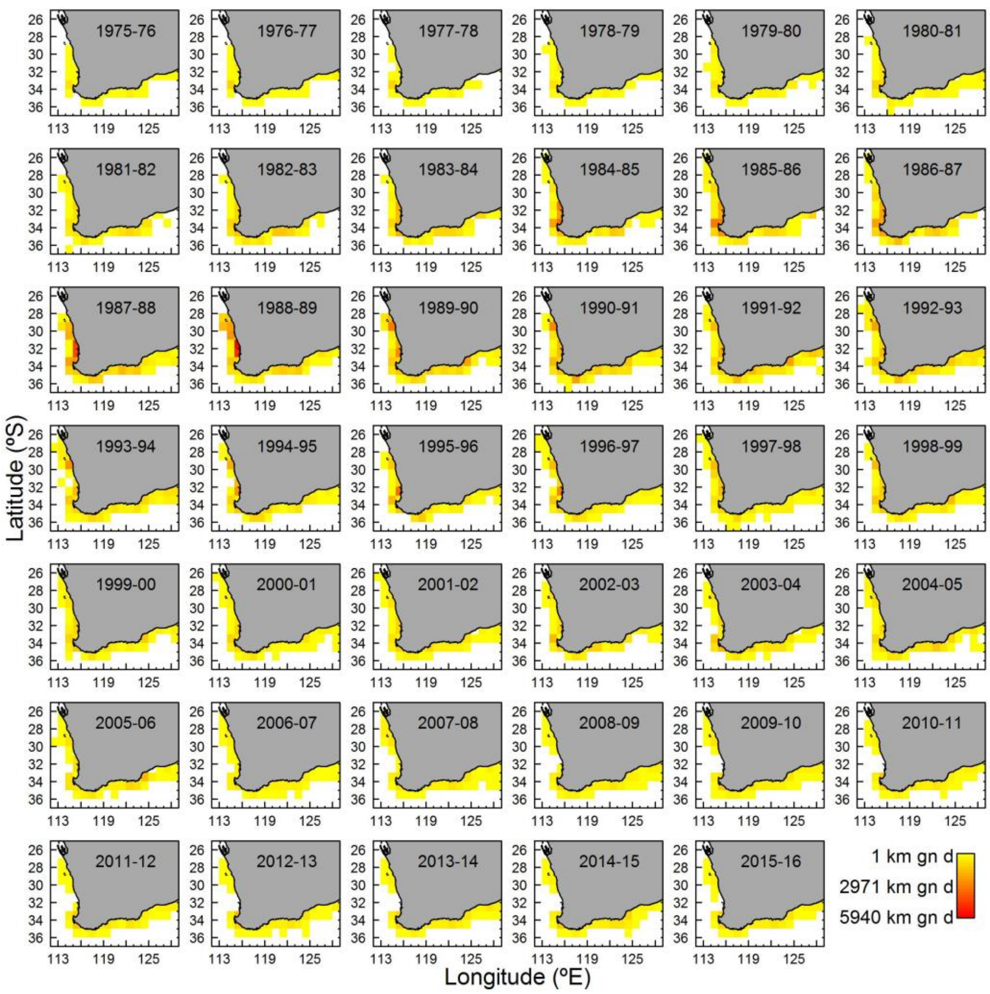


Figure 9.10. Distribution of effort in km gillnet days^{-1} (km gn d) by financial year and 60 nm block in the TDGDLF.

9.3.3 Fishery-Dependent Catch Rate Analyses

This analysis standardises the reported catch rates of whiskery, gummy, dusky and sandbar sharks from catch and effort data recorded in the monthly returns and daily logbooks in the TDGDLF for temporal and spatial shifts in fishing effort that occur from month to month in each season for 60’ × 60’ blocks, and also for the influence of vessel.

Catch and effort data were obtained from statutory fishing return records, which were reported monthly by one-degree spatial blocks between 1975 and 2006 and reported daily by a combination of 10-minute spatial blocks (herein referred to as ‘block10’) and GPS coordinates since 2006. Rather than producing an overall time series, monthly returns and daily logbooks were analysed separately because by aggregating daily records into a single monthly record, information on changes in fishers’ behaviour between fishing trips (e.g. trips targeted at different species) in the same month would be omitted. Also, the transition from monthly returns to daily logbooks in combination with the implementation of several management measures introduced a bias in the reporting of the catch and effort data (Borg & McAuley 2004). Hence, daily logbook records were aggregated by trip because species catch weight (in kg) is recorded on land at the end of the trip.

Due to the overlapping but differing distributions of the four study species within TDGDLF, catch and effort standardisations were done using records from the species’ ‘effective area’ (Simpfendorfer et al. 1996a), which is the effort exerted in the area where the species commonly occur in the catch [south of 28° S to 129° E for whiskery sharks; between 116° and 129° E for gummy sharks; south of 28° S to 120° E for dusky sharks; south of 26° S to 118° E for sandbar sharks; (McAuley 2005)].

In total, catch has been reported in 65, 41, 40, and 38 one-degree spatial blocks by 517, 185, 490, and 184 fishing vessels within the effective areas of whiskery, gummy, dusky and sandbar sharks, respectively. However, the rapid cumulative increase in catch and number of records per block and fishing vessels indicates that shark catches were negligible and infrequent for many blocks and fishing vessels. Hence, to avoid over-parameterization and approximate as possible to a balanced design, for each species we used the ‘reliable’ records from ‘indicative vessels’. For each species, an ‘indicative’ vessel was defined as those reporting catch of that species for at least 10 years for monthly returns and five years for daily logbooks. For these vessels, we selected spatial blocks with at least 10 years of reported catch. Finally, years with records from less than 5 indicative vessels were discarded from the analyses (1, 2, 2, and 5 years were removed from the monthly returns of whiskery, gummy, dusky and sandbar sharks, respectively; no years were removed from the daily logbooks).

Generalised linear modelling was used to standardise the catch and effort data. The response variable was the logged catch and the logged effort was modelled as an offset. The explanatory variables considered were financial year, block (60 nm), vessel and month. As the proportion of records with zero catch was small for monthly returns but higher for daily logbooks, 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 a lognormal distribution.

The multispecies nature of the TDGDLF makes it uncertain if catch rates represent an index of abundance for these shark species. In addition, catch and effort data available from the monthly returns (up to 2005-06) are not directly comparable to the data available in daily logbooks (post 2006-07). Hence, monthly returns and daily logbooks were analysed separately.

For whiskery sharks, standardised catch rates based on monthly returns declined between the late-1970s and mid-1980s (Figure 9.11). However, this is attributable to a change in targeting behaviour (i.e. fishing different habitat types/depths), with fishers shifting from whiskery sharks to dusky sharks. Standardised catch rates were stable at lower levels between the late 1980s and 2005-06. For daily logbooks, the standardised catch rate series have fluctuated at similar levels since 2006-07 (Figure 9.11).

For gummy sharks, standardised catch rates based on monthly returns declined between the early- and late-1980s, they fluctuated until the early 2000s and then increased to historic levels until the late 2000s (Figure 9.11). This pattern was also observed in the unstandardised catch rates and, based on anecdotal information provided by fishers, it would not be due to changes in technology and/or fishing behaviour. It is unclear, however, if the increase is due to abundance or other factors not accounted for in the model. For the daily logbooks, standardised catch rates dropped between 2007-08 and 2009-10 and have remained stable for the last 7 years (Figure 9.11).

For dusky sharks, standardised catch rates based on monthly returns declined during the 1980s and fluctuated at similar levels between the late 1980s and late 1990s before stabilising from ~2000 onwards (Figure 9.11). For daily logbooks, the standardised catch rate series have been relatively stable (Figure 9.11).

For sandbar sharks, standardised catch rates based on monthly returns increased during the 1990s and declined during the early- and mid-2000s (Figure 9.11). For daily logbooks, standardised catch rates show substantial uncertainty (Figure 9.11).

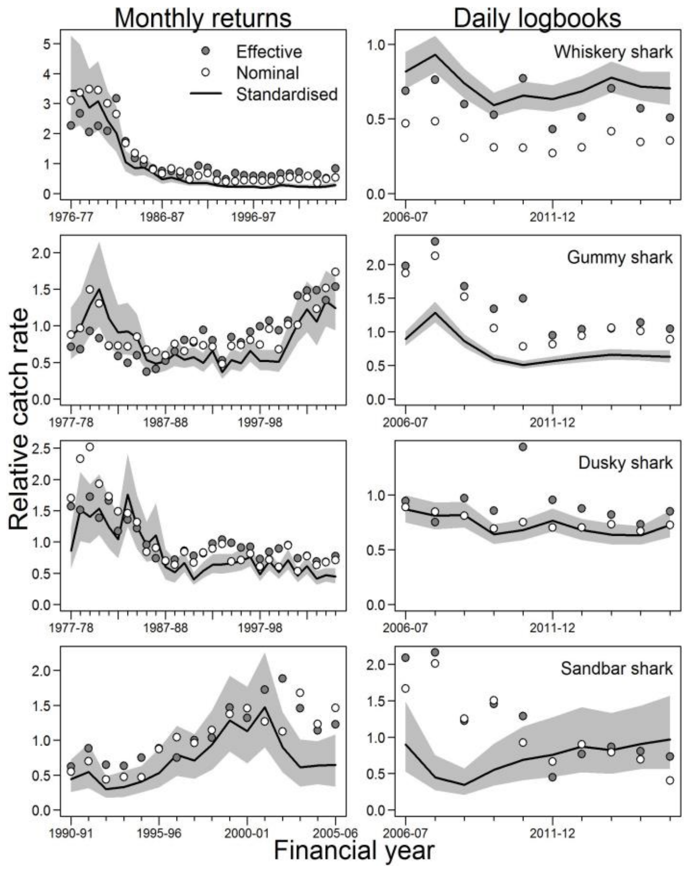


Figure 9.11. Standardised catch rates (mean and 95% CI) for whiskery, gummy, dusky and sandbar sharks taken in the TDGDLF. Also shown are the effective (i.e. sum of annual total catch over total effort within the effective area) and the nominal catch rates.

9.3.4 Fishery-Independent Survey Analyses

Fishery independent survey information on the abundance of large dusky and sandbar sharks (15 years of data, between 2002 and 2017) is currently being analysed and resulted will be published during 2019. Large dusky and sandbar sharks occurred mostly in the northwest but undertake seasonal migrations to the southwest. The fishery-independent survey will provide information on the adult component of the stocks.

9.3.5 Trends in Size and Age Structures

For the TDGDLF catch, the observed size composition of whiskery (Figure 9.12), gummy (Figure 9.13), dusky (Figure 9.14) and sandbar (Figure 9.15) sharks was similar across monitored zones and years. However, size composition samples have been collected opportunistically. It is unclear if these samples are representative of the entire catch size composition of the TDGDLF. Further, any depletion signal (e.g. a decline in the proportion of large individuals caught) could be masked by the size-selective nature of gillnets. Similarly, for the NSF catch, the observed size composition of dusky (Figure 9.16) and sandbar (Figure 9.17) sharks was similar across monitored zones and years. However, size composition samples have been collected opportunistically.

No information is currently available on catch age-composition.

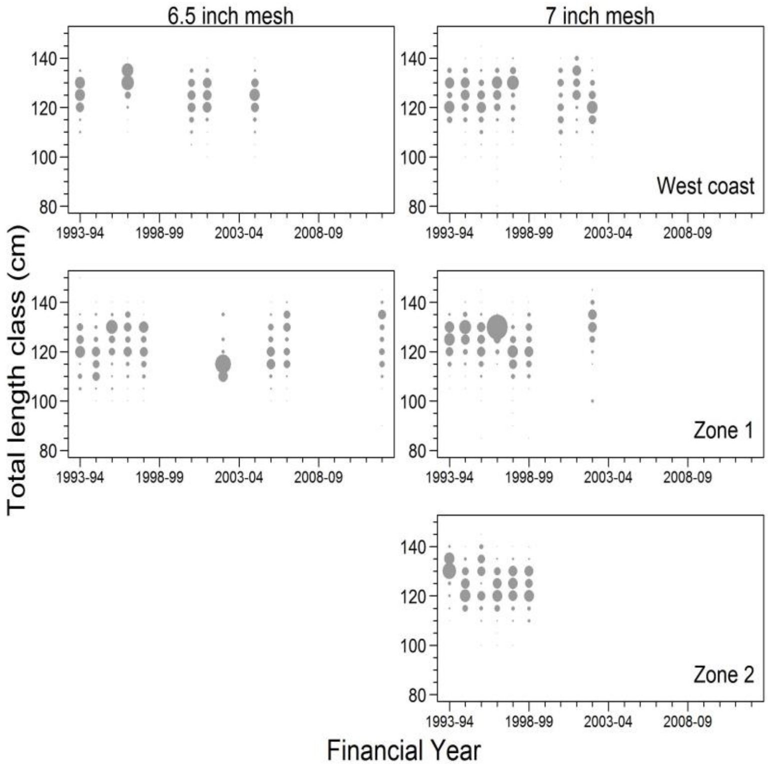


Figure 9.12. Observed size composition of whiskery sharks in the catches of the TDGDLF.

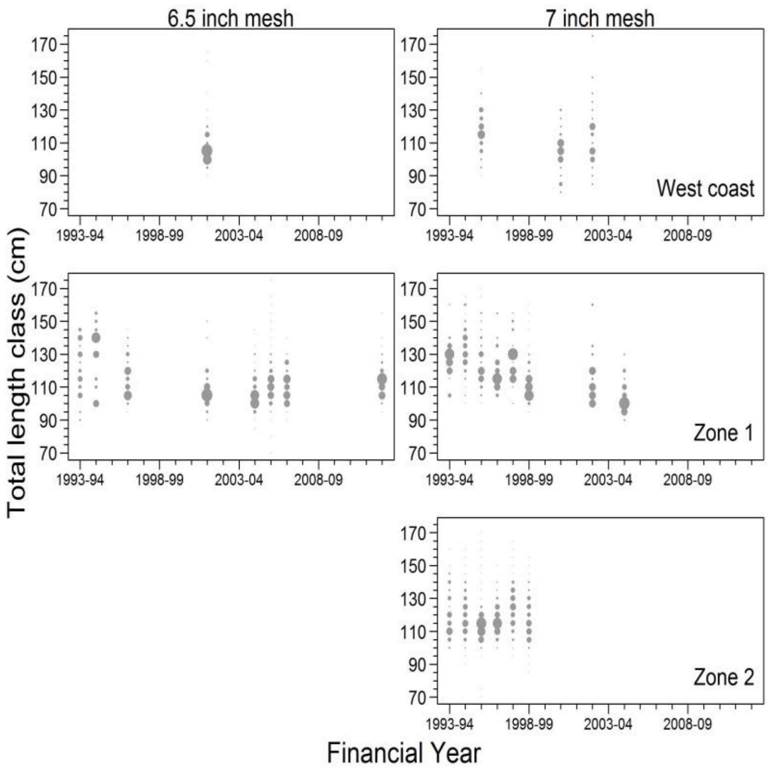


Figure 9.13. Observed size composition of gummy sharks in the catches of the TDGDLF.

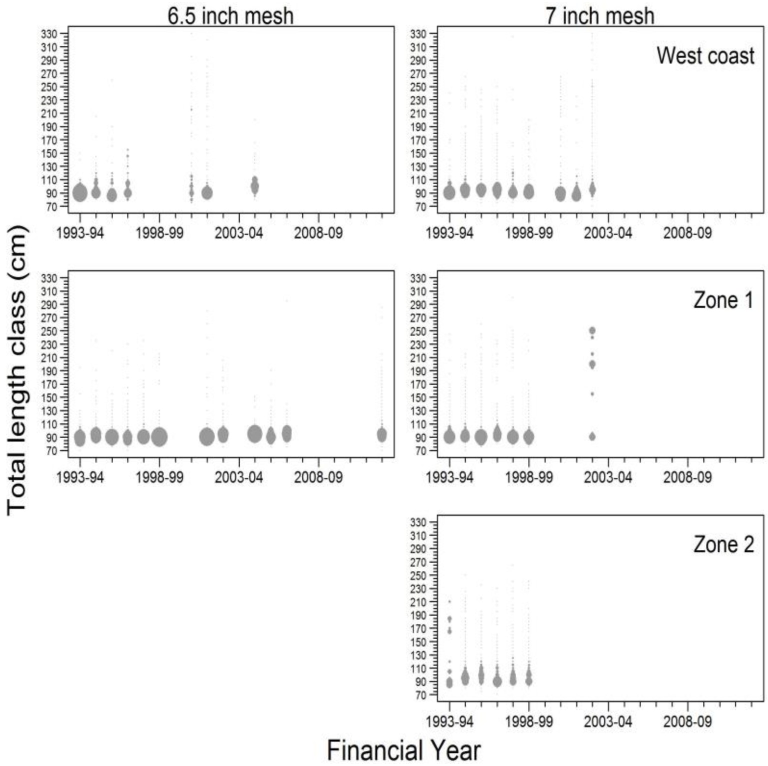


Figure 9.14. Observed size composition of dusky sharks in the catches of the TDGDLF.

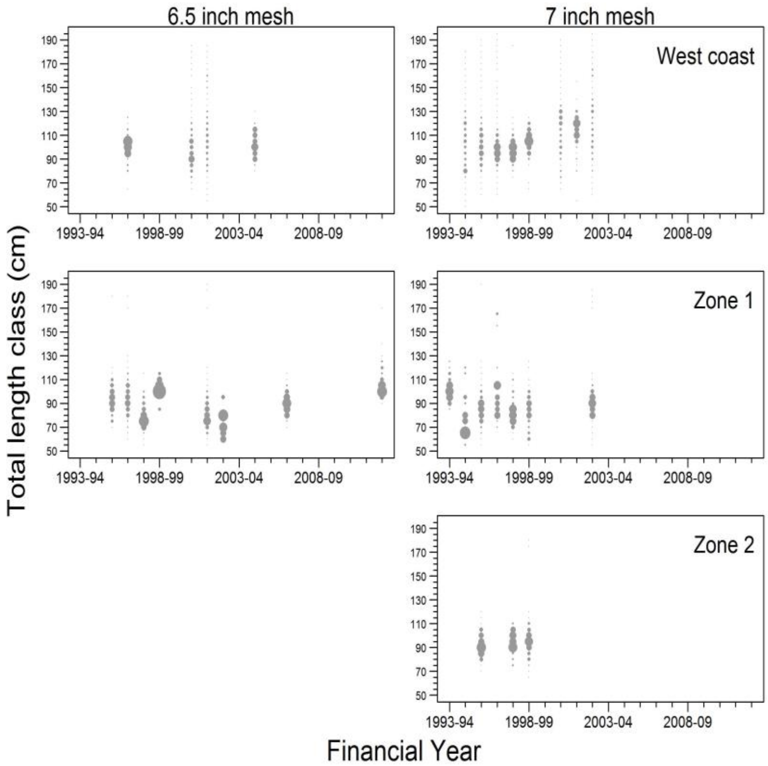


Figure 9.15. Observed size composition of sandbar sharks in the catches of the TDGDLF.

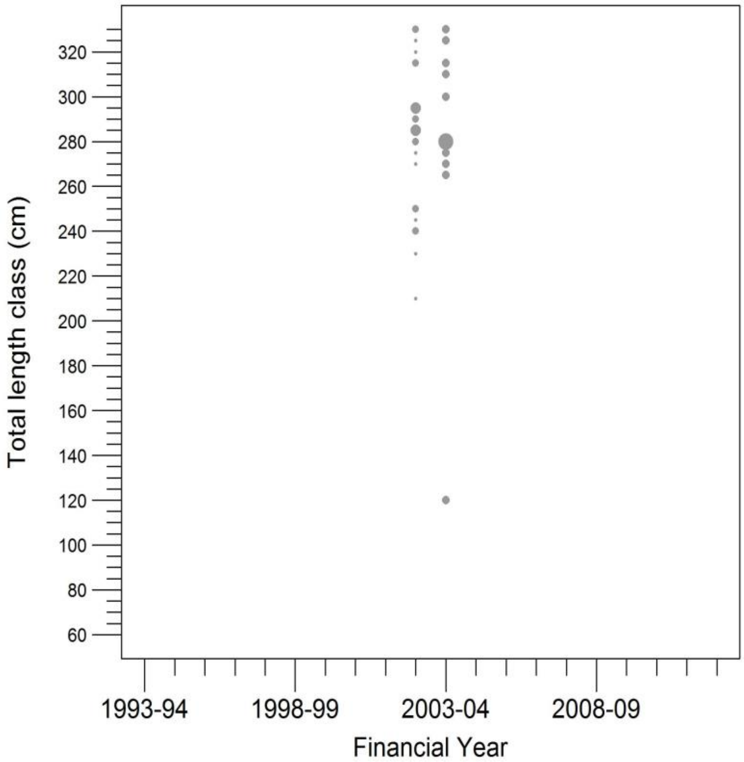


Figure 9.16. Observed size composition of dusky sharks in the catches of the NSF.

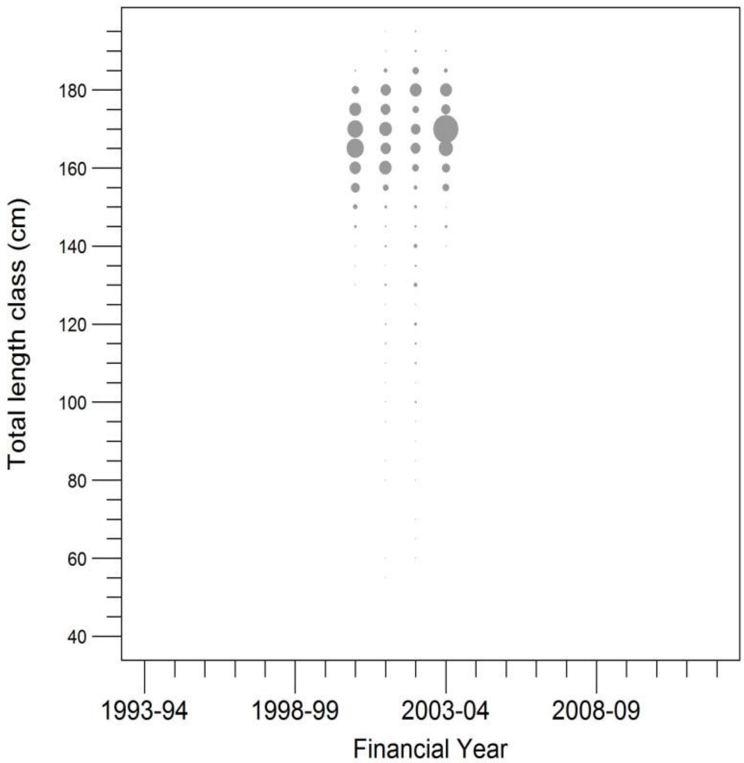


Figure 9.17. Observed size composition of sandbar sharks in the catches of the NSF.

9.3.6 Gear selectivity

Gillnet mesh selectivity parameters were obtained from available empirical estimates (Kirkwood & Walker 1986; Simpfendorfer & Unsworth 1998a; McAuley et al. 2007b). For whiskery and gummy sharks, for which integrated size-based population dynamics models were developed, these parameters were used to calculate mesh selectivity by year (non-spatial model) or year-zone (spatial model). Therefore, for a given zone (West Coast, Zone 1 and Zone 2) and year, gillnet mesh selectivity was calculated using the reported empirical estimates and the proportional annual effort for meshes of 6.5 and 7 inch (Figure 9.18). This information has been reported in daily logbooks since 2005-06. For previous years, following industry consultation, the proportional annual effort for the 6.5 inch mesh was linearly extrapolated using the financial years 2005-06 to 2009-10. The proportional annual effort for the 7 inch mesh was then calculated as 1 – the 6.5 inch proportional annual effort. For whiskery and gummy sharks, the derived overall selectivity is shown in Figure 9.19 and Figure 9.20, respectively.

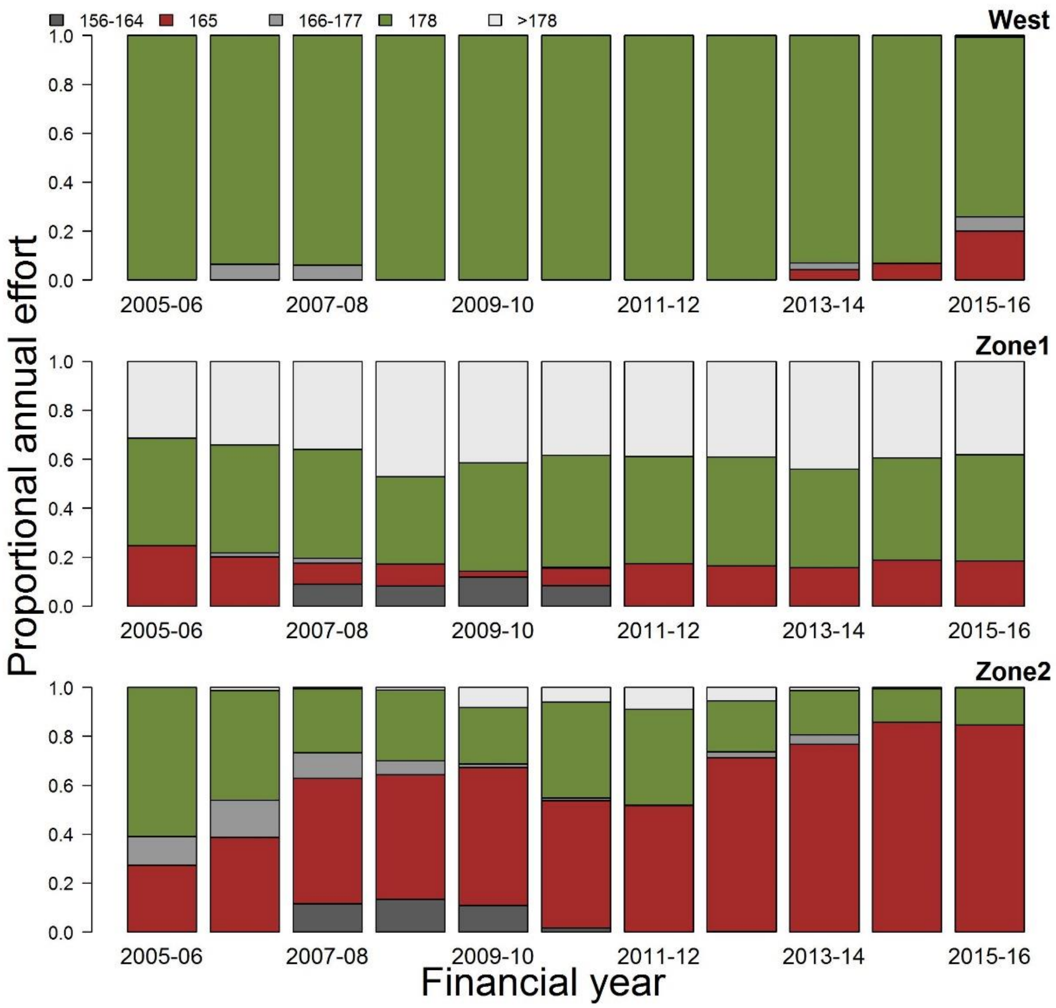


Figure 9.18. Reported mesh size (in mm; 165= 6.5 inch; 178= 7 inch) as a proportion of annual effort for the TDGDLF.

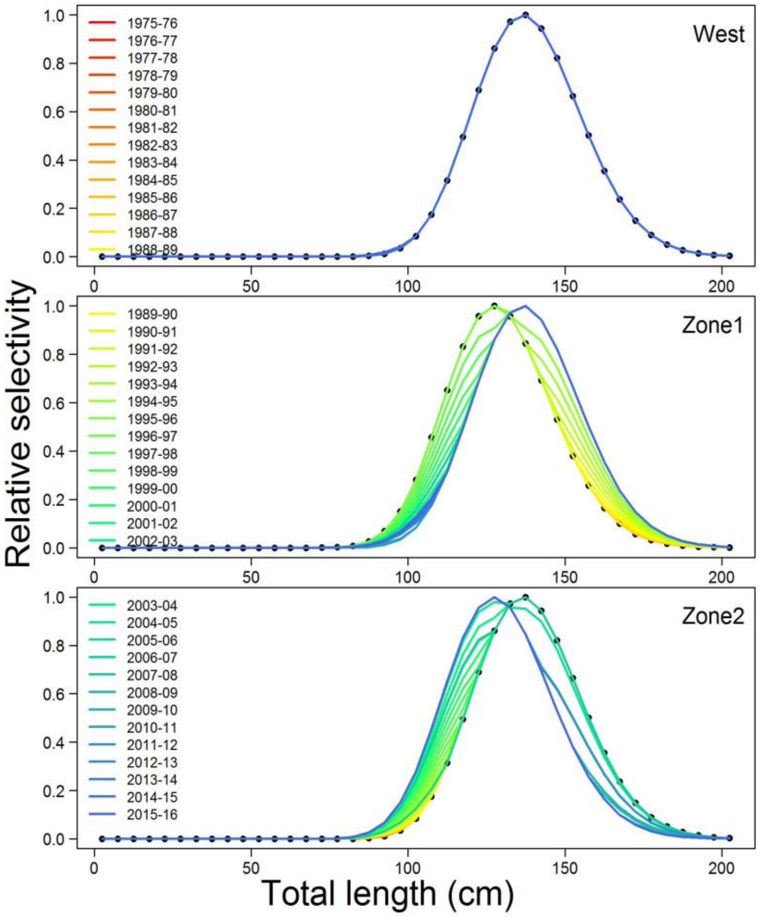


Figure 9.19. Derived mesh selectivity by year and zone for whiskery sharks taken in the TDGDLF.

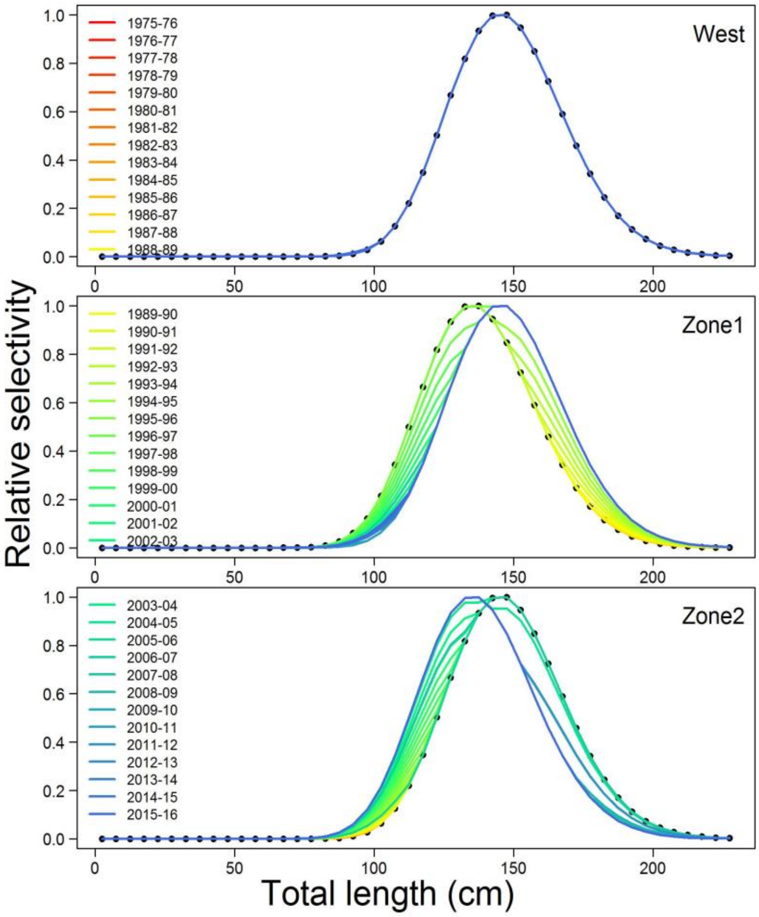


Figure 9.20. Derived mesh selectivity by year and zone for gummy sharks taken in the TDGDLF.

9.3.7 Age and length

Age and length information is reported in the Species Descriptions section.

9.3.8 Tagging

Large-scale conventional tagging programs have been conducted in WA since the 1990s to gain insights into the movement patterns of the local shark populations with a focus on the main commercial species. More recently, a network of acoustic receivers deployed across WA has been used to monitor the movement of acoustically tagged individuals (40 whiskery sharks and 100 gummy sharks) (Braccini et al. 2017a). For whiskery and gummy sharks, for which spatially-structured population dynamics models have been developed, a summary of the number of recaptures (conventional tagging) and detections (acoustic tagging) is shown in Figure 9.21, Figure 9.22, Figure 9.23 and Figure 9.24, respectively. Table 9.1**Error! Reference source not found.** and Table 9.2 show the number of released whiskery and gummy sharks, respectively, with conventional tags.

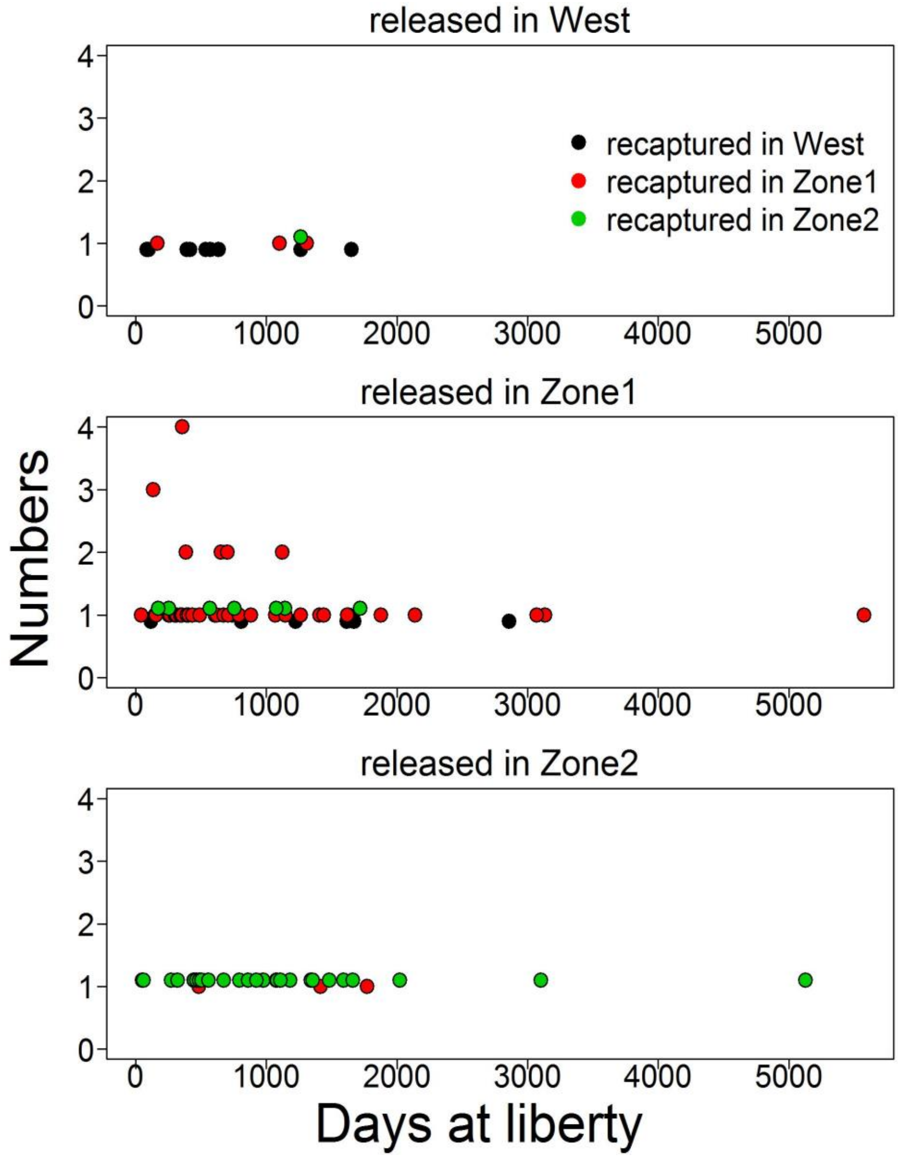


Figure 9.21. Number of whiskery sharks recaptured by zone. West, West Coast Demersal Gillnet and Demersal Longline (Interim) Fishery; Zone1 and Zone2, Zones 1 and 2 of the Joint Authority Southern Demersal Gillnet and Demersal Longline Fishery).

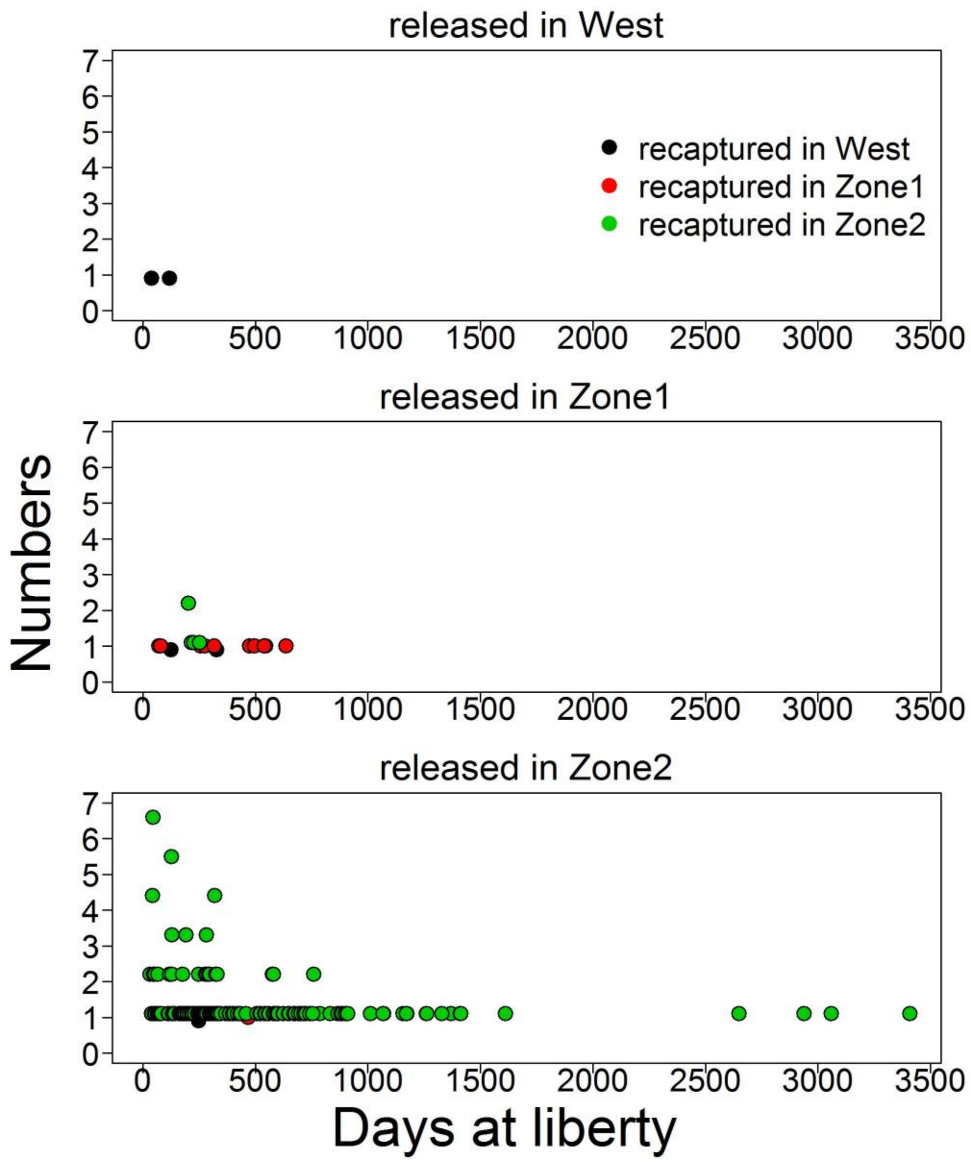


Figure 9.22. Number of gummy sharks recaptured by zone. West, West Coast Demersal Gillnet and Demersal Longline (Interim) Fishery; Zone1 and Zone2, Zones 1 and 2 of the Joint Authority Southern Demersal Gillnet and Demersal Longline Fishery).

Table 9.1 Number of whiskery sharks implanted with conventional tags.

Release zone	Release year	Number
West	1994	38
West	1995	25
West	1996	9
West	1997	21
West	1998	9
West	1999	1
West	2003	1
Zone1	1994	80
Zone1	1995	30
Zone1	1996	35

Zone1	1997	129
Zone1	1998	41
Zone1	1999	25
Zone1	2012	16
Zone1	2013	17
Zone2	1994	2
Zone2	1995	80
Zone2	1996	4
Zone2	1997	28
Zone2	1998	19
Zone2	1999	20
Zone2	2012	8

Table 9.2. Number of gummy sharks implanted with conventional tags.

Release zone	Release year	Number
West	1994	3
West	1995	2
West	2002	1
West	2003	1
Zone1	1993	1
Zone1	1994	15
Zone1	1995	6
Zone1	2012	4
Zone1	2013	29
Zone2	1993	8
Zone2	1994	117
Zone2	1995	489
Zone2	1996	2
Zone2	2012	53
Zone2	2013	3

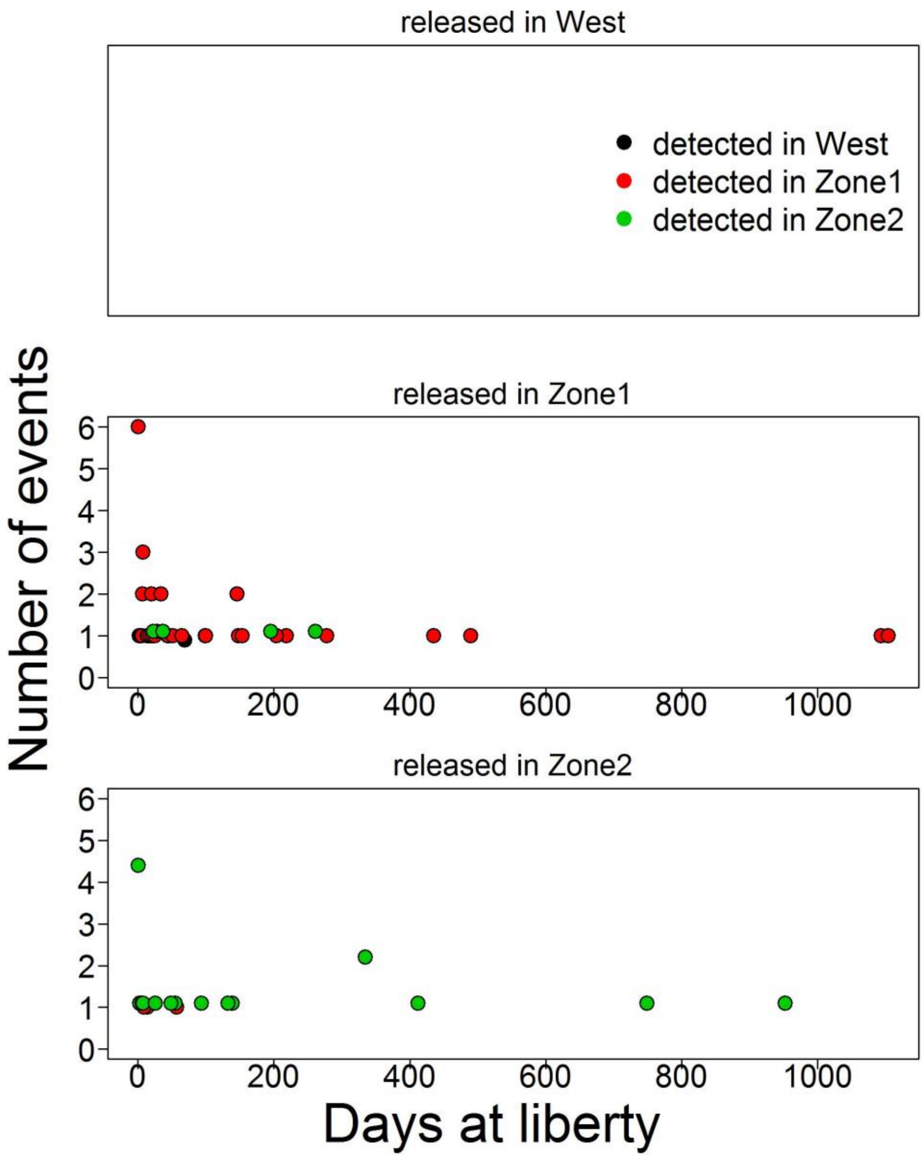


Figure 9.23. Number of whiskery shark detection events by zone. West, West Coast Demersal Gillnet and Demersal Longline (Interim) Fishery; Zone1 and Zone2, Zones 1 and 2 of the Joint Authority Southern Demersal Gillnet and Demersal Longline Fishery).

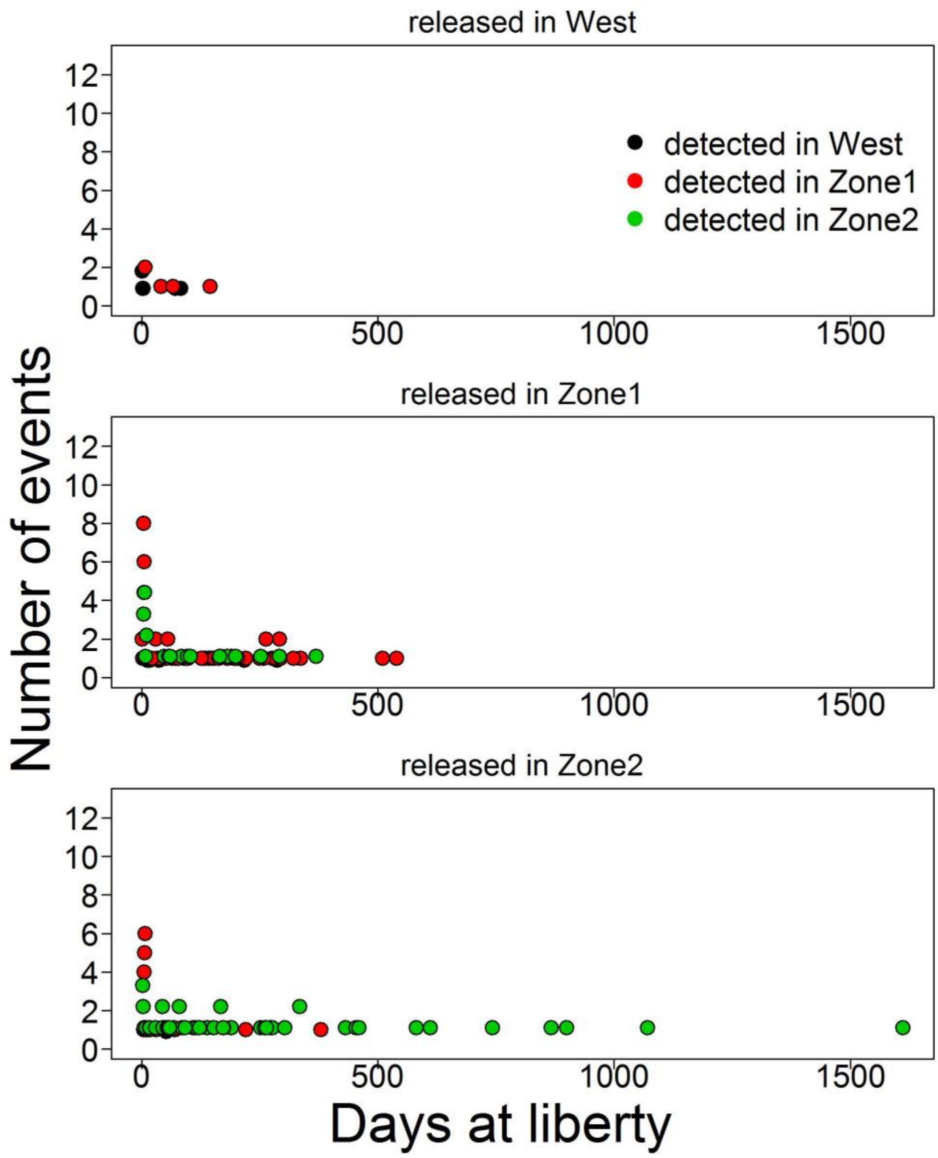


Figure 9.24. Number of gummy shark detection events by zone. West, West Coast Demersal Gillnet and Demersal Longline (Interim) Fishery; Zone1 and Zone2, Zones 1 and 2 of the Joint Authority Southern Demersal Gillnet and Demersal Longline Fishery).

9.3.9 Life history

A summary of the life history information used in the population dynamics models developed for whiskery and gummy sharks is shown in Table 9.3 and Table 9.4 and Figure 9.25 and Figure 9.26, and Figure 9.27 and Figure 9.28, respectively.

Table 9.3. Life history parameter values used in the modelling of population dynamics of whiskery sharks.

Parameter	Value	Source
TL.to.FL.a	1.050	Simpfendorfer et al. 2000
TL.to.FL.b	8.891	Simpfendorfer et al. 2000
TL.to.TwT.F.b	1.63e-05	Simpfendorfer et al. 2000
TL.to.TwT.F.a	2.733	Simpfendorfer et al. 2000
TL.to.TwT.M.b	1.63e-05	Simpfendorfer et al. 2000
TL.to.TwT.M.a	2.733	Simpfendorfer et al. 2000
Min.Max.FL.Max	160	Simpfendorfer et al. 2000

Max.Age.M	13	Simpfendorfer et al. 2000
Max.Age.F	15	Simpfendorfer et al. 2000
Growth.F.k	0.369	Simpfendorfer et al. 2000
Growth.F.FL_inf	120.700	Simpfendorfer et al. 2000
Growth.F.to	-0.544	Simpfendorfer et al. 2000
Growth.F.SD	7.210	Simpfendorfer et al. 2000
Growth.M.k	0.423	Simpfendorfer et al. 2000
Growth.M.FL_inf	121.500	Simpfendorfer et al. 2000
Growth.M.to	-0.472	Simpfendorfer et al. 2000
Breed.freq.Min	0.500	Simpfendorfer & Unsworth 1998
Size.birth	25	Simpfendorfer & Unsworth 1998
Size.birth_SD	5	Assumed
Mat.50.95.L50	125	Simpfendorfer & Unsworth 1998
Mat.50.95.L95	136	Simpfendorfer & Unsworth 1998
Age.50.mat.Min	6	Simpfendorfer et al. 2000
Litter.sz.Min	4	Simpfendorfer & Unsworth 1998
Litter.sz.Max	28	Simpfendorfer & Unsworth 1998
Litter.sz.at.size.a	0.314	Simpfendorfer & Unsworth 1998
Litter.sz.at.size.b	-17.800	Simpfendorfer & Unsworth 1998
Sex.ratio	0.500	Simpfendorfer & Unsworth 1998
Selectivity.alpha	49.239	Simpfendorfer & Unsworth 1998 (6.5 inch)
Selectivity.beta	22.930	Simpfendorfer & Unsworth 1998 (6.5 inch)
Selectivity_7.alpha	56.951	Simpfendorfer & Unsworth 1998 (7 inch)
Selectivity_7.beta	21.350	Simpfendorfer & Unsworth 1998 (7 inch)
Prop.males.in.ktch	0.289	DPRID unpublished
Prop.males.in.ktch	0.268	DPRID unpublished
Prop.males.in.ktch	0.369	DPRID unpublished
Prop.males.in.ktch	0.289	DPRID unpublished
M	0.270	Simpfendorfer et al. 2000
STEEP.mean	0.349	Braccini et al. 2015
Smallest_size_tagged	99	DPRID unpublished

Table 9.4. Life history parameter values used in the modelling of population dynamics of gummy sharks.

Parameter	Value	Source
TL.to.FL.a	1.080	McAuley unpublished
TL.to.FL.b	4.642	McAuley unpublished
TL.to.TwT.F.b	4.62e-07	McAuley unpublished
TL.to.TwT.F.a	3.477	DPRID unpublished
TL.to.TwT.M2	4.21e-06	DPRID unpublished
TL.to.TwT.M1	2.976	DPRID unpublished
Min.Max.FL.Max	180	DPRID unpublished
Max.Age.M	13	Walker 2010
Max.Age.F	16	Walker 2010
Growth.F.k	0.123	Moulton et al. 1992
Growth.F.TL_inf	201.900	Moulton et al. 1992
Growth.F.to	-1.550	Moulton et al. 1992
Growth.F.SD	20	Moulton et al. 1992
Growth.M.k	0.253	Moulton et al. 1992
Growth.M.TL_inf	138.700	Moulton et al. 1992
Growth.M.to	-0.900	Moulton et al. 1992
Breed.freq.Min	1	Lenanton et al. 1990
Size.birth	33	Walker 2007
Size.birth_SD	5	assumed

Mat.50.95.L50	112.900	Walker 2007
Mat.50.95.L95	139.200	Walker 2007
Age.50.mat.Min	4	Braccini et al. 2015
Litter.sz.Min	1	Lenanton et al. 1990
Litter.sz.Max	31	Lenanton et al. 1990
Litter.sz.at.size.a	0.049	Lenanton et al. 1990
Litter.sz.at.size.b	-4.133	Lenanton et al. 1990
Sex.ratio	0.500	Lenanton et al. 1990
Selectivity.alpha	40.809	Walker 2010 (6.5 inch)
Selectivity.beta	29.626	Walker 2010 (6.5 inch)
Selectivity_7.alpha	47.176	Walker 2010 (7 inch)
Selectivity_7.beta	27.599	Walker 2010 (7 inch)
Prop.males.in.ktch	0.221	DPRID unpublished
Prop.males.in.ktch	0.060	DPRID unpublished
Prop.males.in.ktch	0.290	DPRID unpublished
Prop.males.in.ktch	0.235	DPRID unpublished
M	0.283	Walker et al. 2000
STEEP.mean	0.480	Braccini et al. 2015
Smallest_size_tagged	104	DPRID unpublished

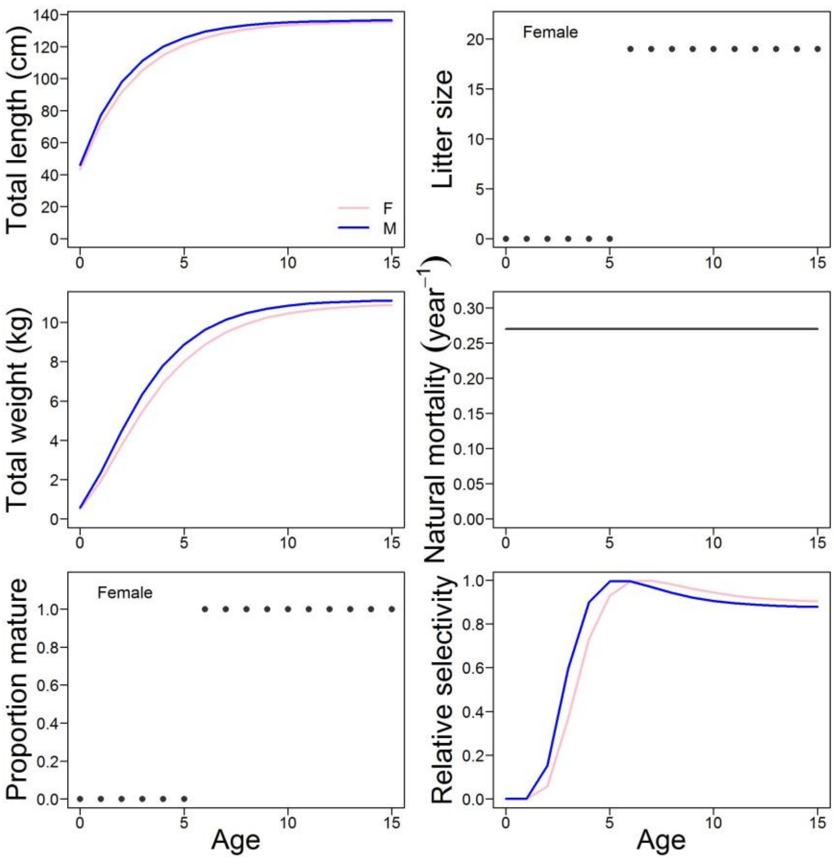


Figure 9.25. Life history at age information used in the whiskery stock assessment.

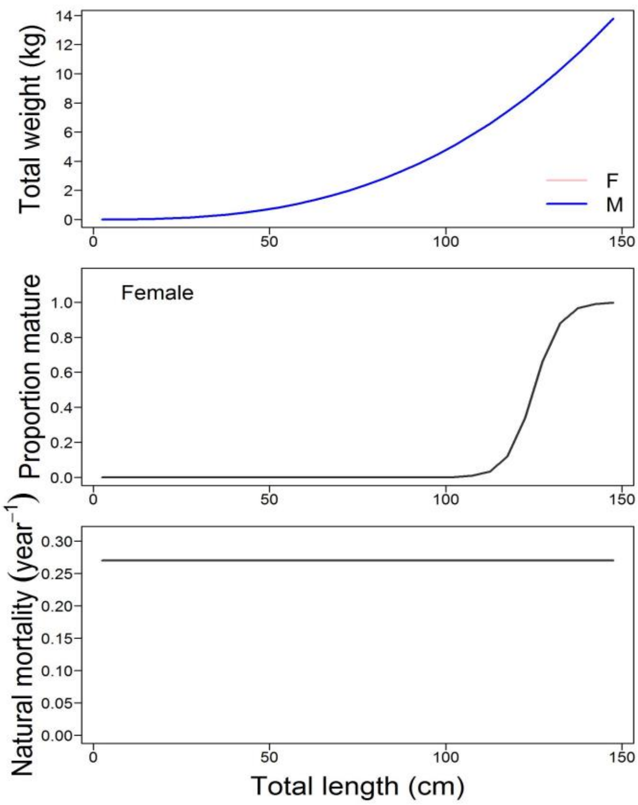


Figure 9.26. Life history at length information used in the whiskery stock assessment.

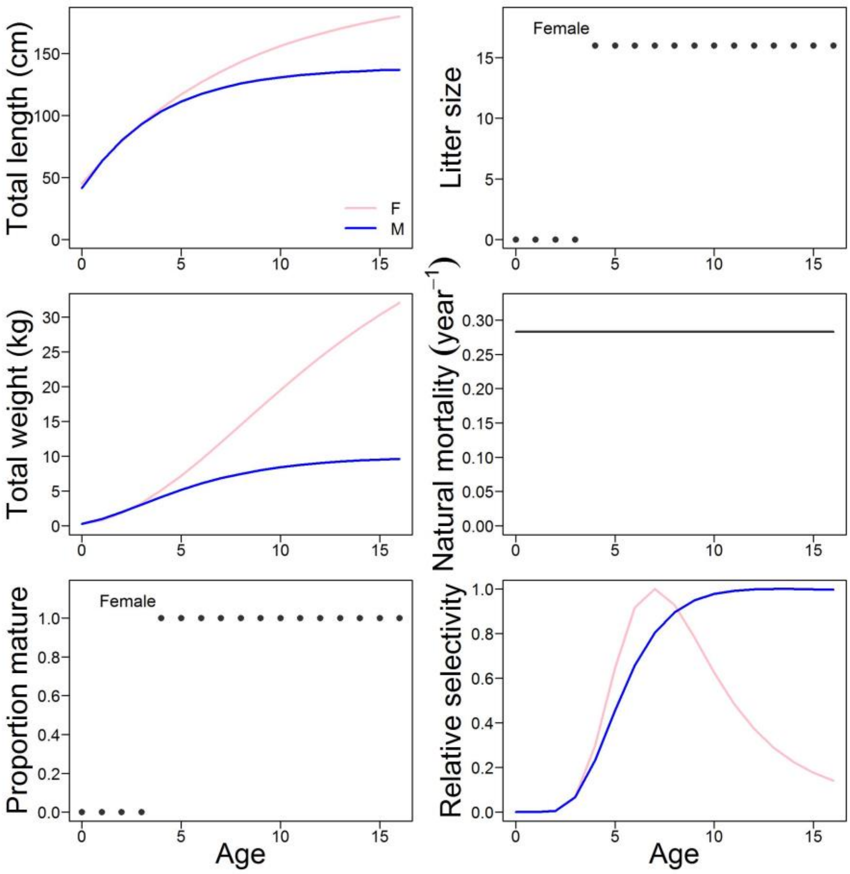


Figure 9.27. Life history at age information used in the gummy stock assessment.

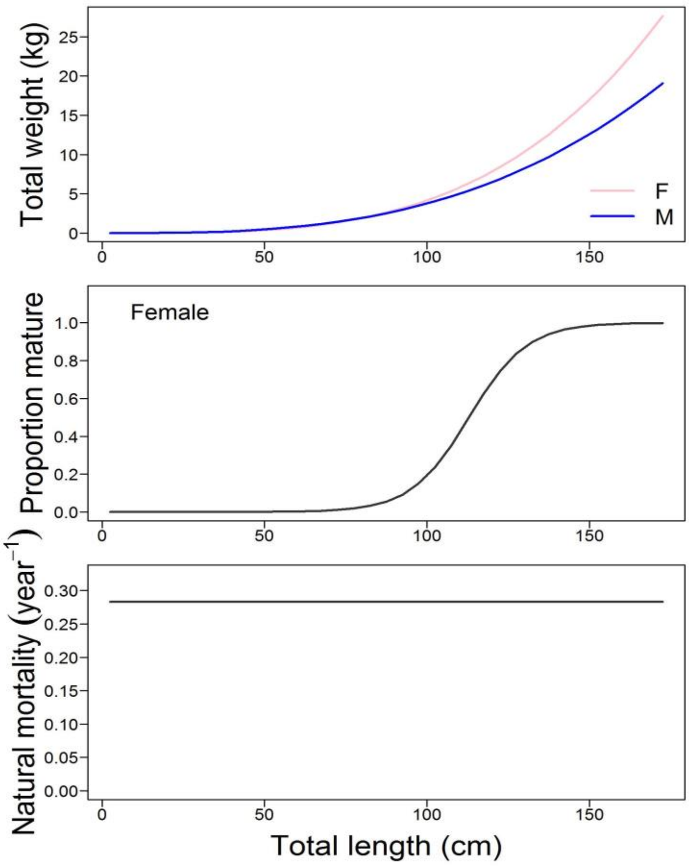


Figure 9.28. Life history at length information used in the gummy stock assessment.

9.3.10 Productivity Susceptibility Analysis (PSA)

Productivity Susceptibility Analysis (PSA) is a semi-quantitative risk analysis originally developed for use in Marine Stewardship Council (MSC) assessments to score data-deficient stocks, i.e. where it is not possible to determine status relative to reference points from available information (Hobday et al. 2011; MSC 2014). The PSA approach is based on the assumption that the risk to a stock depends on two characteristics: (1) the productivity of the species, which will determine the capacity of the stock to recover if the population is depleted, and (2) the extent of the impact on the stock due to fishing, which will be determined by the susceptibility of the species to fishing activities (see Appendix 2. Productivity Susceptibility Analysis (PSA) Scoring TablesAppendix 2. Productivity Susceptibility Analysis (PSA) Scoring Tables).

Although a valuable tool for determining the overall inherent vulnerability of a stock to fishing, the PSA is limited in its usefulness for providing stock status advice. This is because of the simplicity and prescriptiveness of the approach, which means that risk scores are very sensitive to input data and there is no ability to consider management measures implemented in fisheries to reduce the risk to a stock (Bellchambers et al. in prep.). Consequently, the PSA is used by the Department to produce a measure of the vulnerability of a stock to fishing, which is then considered within the overall weight of evidence assessment of stock status.

The sections below outline the PSA scores for whiskery, gummy, dusky and sandbar sharks.

9.3.10.1 Productivity

Whiskery and gummy sharks have moderate vulnerability to fishing as they are moderately long-lived, mature relatively early and are medium-sized viviparous species with low fecundity and high trophic level (see Species Descriptions and Table 9.5). Dusky and sandbar sharks have high vulnerability to fishing as they are long-lived, mature late and have low fecundity and high trophic level (see Species Descriptions and Table 9.5).

Table 9.5. PSA productivity scores for each indicator species

Productivity attribute	Whiskery shark	Gummy shark	Dusky shark	Sandbar shark
Average maximum age	2.00	2.00	3.00	3.00
Average maximum size	2.00	2.00	3.00	2.00
Average age at maturity	2.00	2.00	3.00	3.00
Average size at maturity	2.00	2.00	3.00	2.00
Reproductive strategy	3.00	3.00	3.00	3.00
Fecundity	3.00	3.00	3.00	3.00
Trophic level	3.00	3.00	3.00	3.00
Total productivity	2.43	2.43	3.00	2.71

9.3.10.2 Susceptibility

For the susceptibility analysis, only the TDGDLF are considered because currently the reported catch in other fisheries in negligible.

For whiskery, gummy, dusky and sandbar sharks, the areal overlap with the TDGDLF is high (>30%) (Table 9.6, Table 9.7, Table 9.8, Table 9.9). The vertical overlap is also high as these species are the target species of the TDGDLF. For whiskery and gummy sharks, selectivity is medium as individuals smaller than the size at maturity are regularly caught. For dusky and sandbar sharks, selectivity is high as individuals smaller than the size at maturity are frequently caught. Finally, for these four species, post-capture mortality is high as there are mostly retained. In combination, all these factors yield a high susceptibility for the four species.

Table 9.6. PSA susceptibility scores for each fishery that impact on the stock of whiskery sharks.

Susceptibility attribute	TDGDLF
Areal overlap	3.00
Vertical overlap	3.00
Selectivity	3.00
Post-capture mortality	3.00
Total susceptibility	3.00

Table 9.7. PSA susceptibility scores for each fishery that impact on the stock of gummy sharks.

Susceptibility attribute	TDGDLF
Areal overlap	3.00
Vertical overlap	3.00
Selectivity	2.00
Post-capture mortality	3.00
Total susceptibility	2.33

Table 9.8. PSA susceptibility scores for each fishery that impact on the stock of dusky sharks.

Susceptibility attribute	TDGDLF
Areal overlap	3.00
Vertical overlap	3.00
Selectivity	2.00
Post-capture mortality	3.00
Total susceptibility	2.33

Table 9.9. PSA susceptibility scores for each fishery that impact on the stock of sandbar sharks.

Susceptibility attribute	TDGDLF
Areal overlap	3.00
Vertical overlap	3.00
Selectivity	2.00
Post-capture mortality	3.00
Total susceptibility	2.33

9.3.10.3 Overall PSA Score

The total PSA scores for whiskery, gummy, dusky and sandbar sharks were 3.36, 3.36, 4.24 and 4.05, respectively, with MSC PSA scores of less than 60 out of 100. This classifies these species as being at high risk to over-exploitation.

9.3.11 Demographic and stock-reduction analyses

9.3.11.1 Overview

Life history and catch information was used in a combined demographic and stock-reduction model (SR) to assess stock sustainability because the standardised fishery-dependent catch rate of gummy sharks was concluded to be a poor index of population abundance (see Gummy shark below), limiting the ability of the integrated model to represent population dynamics. For dusky and sandbar sharks, the time series of catch and effort data were insufficient for estimating biomass trends from fitting population dynamics models to abundance indicators, such as catch rates, due to the size-selective nature of the fishing gear used in the TDGDLF (selecting mostly neonates and young juveniles) and longevity of these species. Hence, a SR modelling approach was implemented to determine catch sustainability using life history and catch information up to and including the 2015-16 financial year.

9.3.11.2 Model Description

The SR model is a simpler method that is applicable to data poor situations where a reliable abundance index is not available. Model inputs are a catch time series, prior ranges of r (the intrinsic rate of increase of the population) and K (the carrying capacity of the population), and possible ranges of relative stock sizes in the first and final years of the time series. It then uses the Schaefer production model to calculate annual biomasses for a given set of r and K parameter values (Martell & Froese 2013). Process error was incorporated using a lognormal distribution with standard deviation of 5%.

The method developed by Martell & Froese (2013) for estimating MSY from catch data, species resilience and assumptions about the relative stock size at the first and final year of the catch data time series was combined with demographic modelling used for constructing priors for r (McAllister et al. 2001). First, an r prior was constructed using a Monte Carlo procedure to incorporate uncertainty in life history vital rates (Braccini et al. 2015). Next, Martell & Froese's (2013) model was fit to the total catch time series of each species with a constraint on the r parameter given by the constructed priors and explicit assumptions on other input parameters. The model was projected 5 years into the future by setting future catches to the average total catch of the last 5 years (131, 423, 220 and 48 t, for whiskery, gummy, dusky and sandbar sharks, respectively).

9.3.11.3 Input Data and Parameters

The assumptions made about the upper level of K, and the relative stock size at the first and final year of the catch data time series are shown in Table 9.10.

Table 9.10. Model input parameters.

Species	*K* upper bound	Relative stock size	
		First year of time series	*Last year of time series*
Whiskery	50 times max catch	0.7–0.95 of unfished conditions	0.2–0.7 of unfished conditions
Gummy	50 times max catch	0.8–0.95 of unfished conditions	0.2–0.7 of unfished conditions
Dusky	50 times max catch	0.7–0.95 of unfished conditions	0.2–0.6 of unfished conditions
Sandbar	50 times max catch	0.85–0.95 of unfished conditions	0.2–0.6 of unfished conditions

The constructed r priors for whiskery, gummy, dusky and sandbar sharks are shown in Figure 9.29, Figure 9.30, Figure 9.31 and Figure 9.32, respectively.

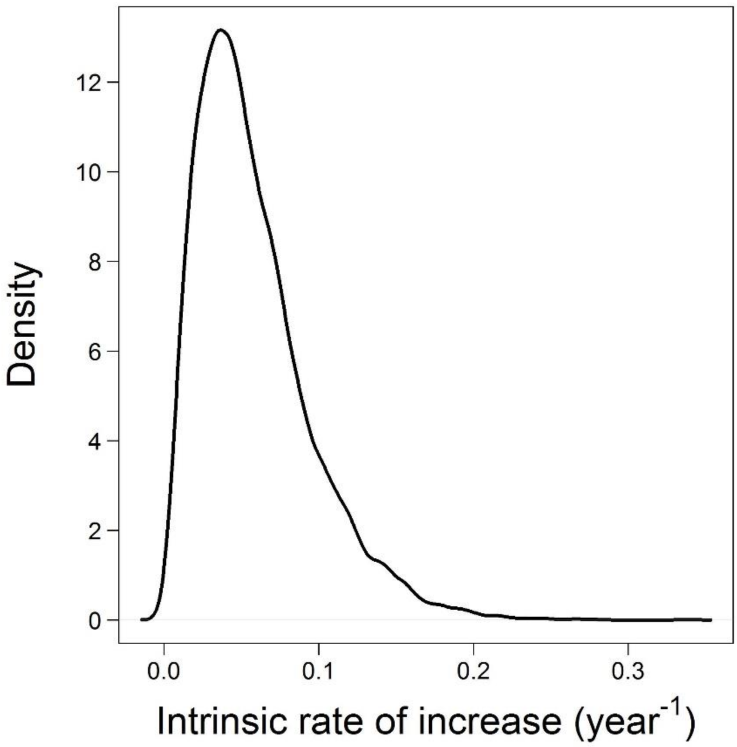


Figure 9.29. Density distribution of the intrinsic rate of population increase of whiskery sharks.

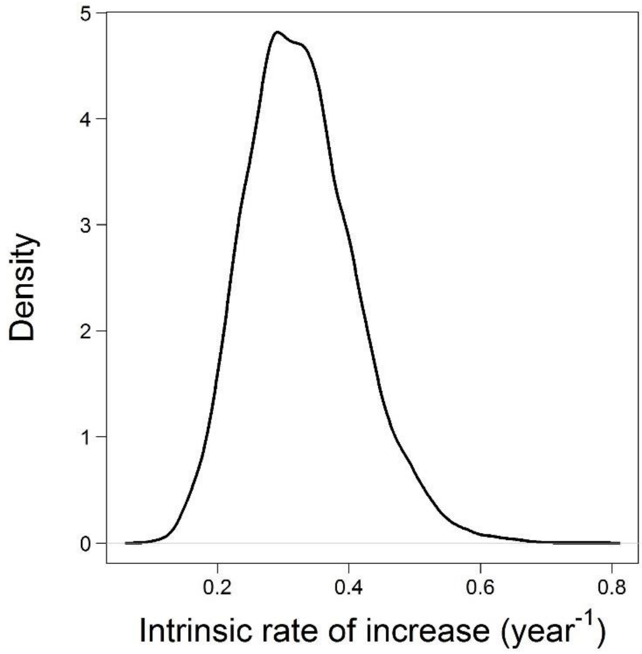


Figure 9.30. Density distribution of the intrinsic rate of population increase of gummy sharks.

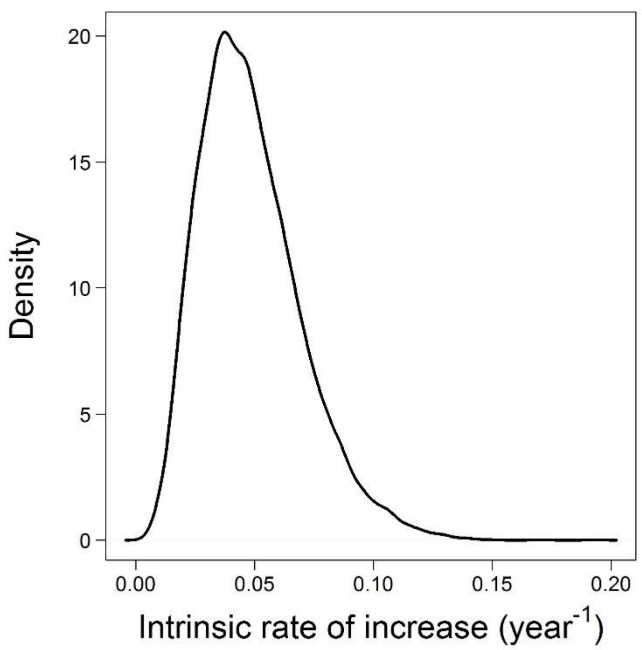


Figure 9.31. Density distribution of the intrinsic rate of population increase of dusky sharks.

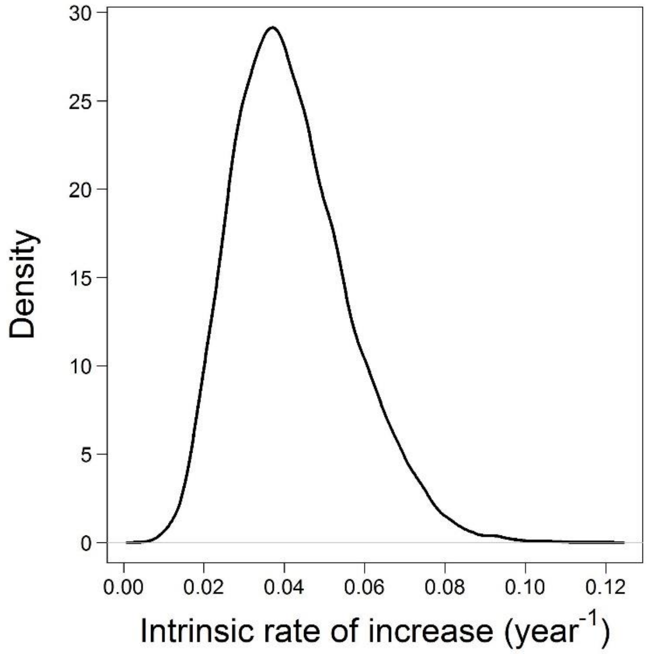


Figure 9.32. Density distribution of the intrinsic rate of population increase of sandbar sharks.

9.3.11.4 Results and Diagnostics

The estimated MSY for whiskery, gummy, dusky and sandbar sharks is shown in Figure 9.33, Figure 9.34, Figure 9.35 and Figure 9.36, respectively. This MSY estimates must be considered as broad guides given the assumptions and limitations of the SR method.

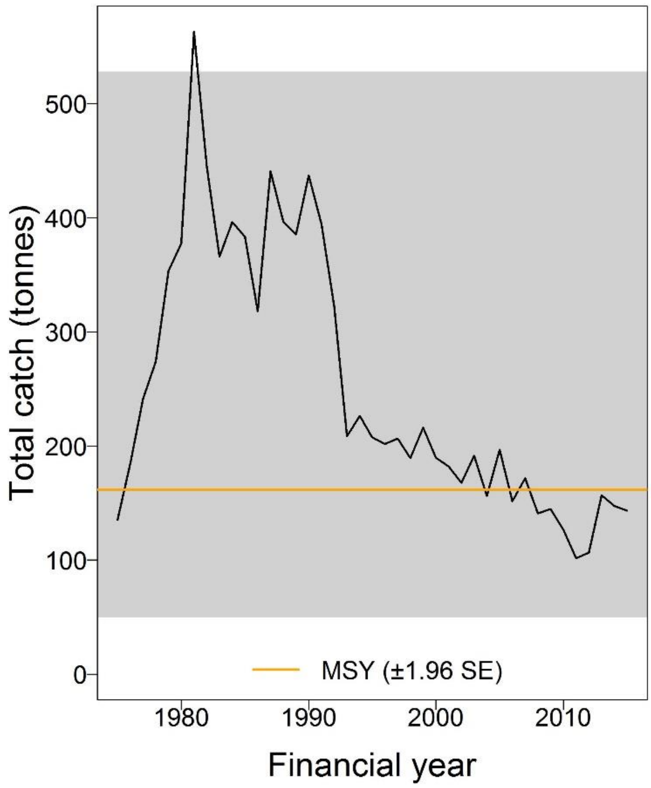


Figure 9.33. Time series of the total catch (all fisheries combined) of whiskery sharks. Also shown is the estimated MSY (geometric mean= 162 t, SE= 50–528 t, shaded in grey) derived from the SR analysis.

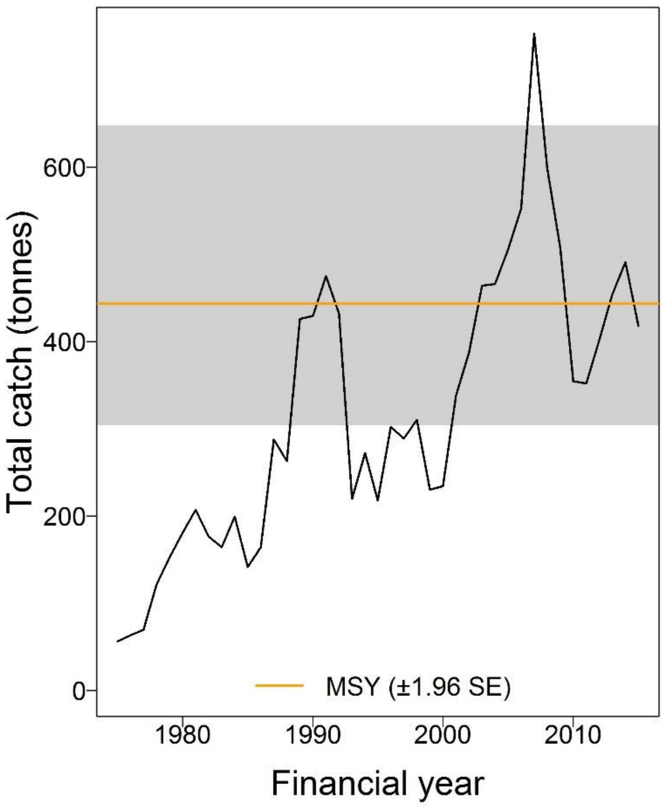


Figure 9.34. Time series of the total catch (all fisheries combined) of gummy sharks. Also shown is the estimated MSY (geometric mean= 443 t, SE= 304–647 t, shaded in grey) derived from the SR analysis.

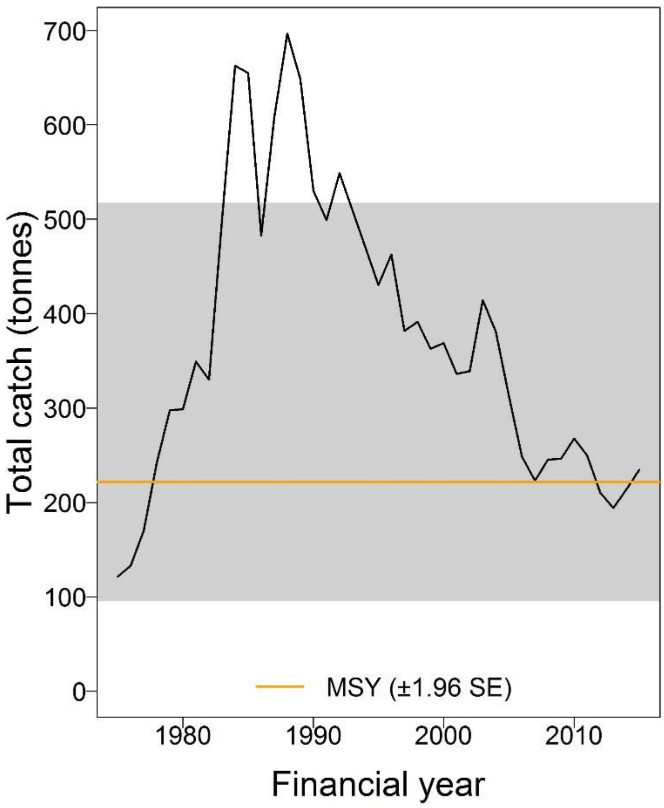


Figure 9.35. Time series of the total catch (all fisheries combined) of dusky sharks. Also shown is the estimated MSY (geometric mean= 222 t, SE= 95–517 t, shaded in grey) derived from the SR analysis.

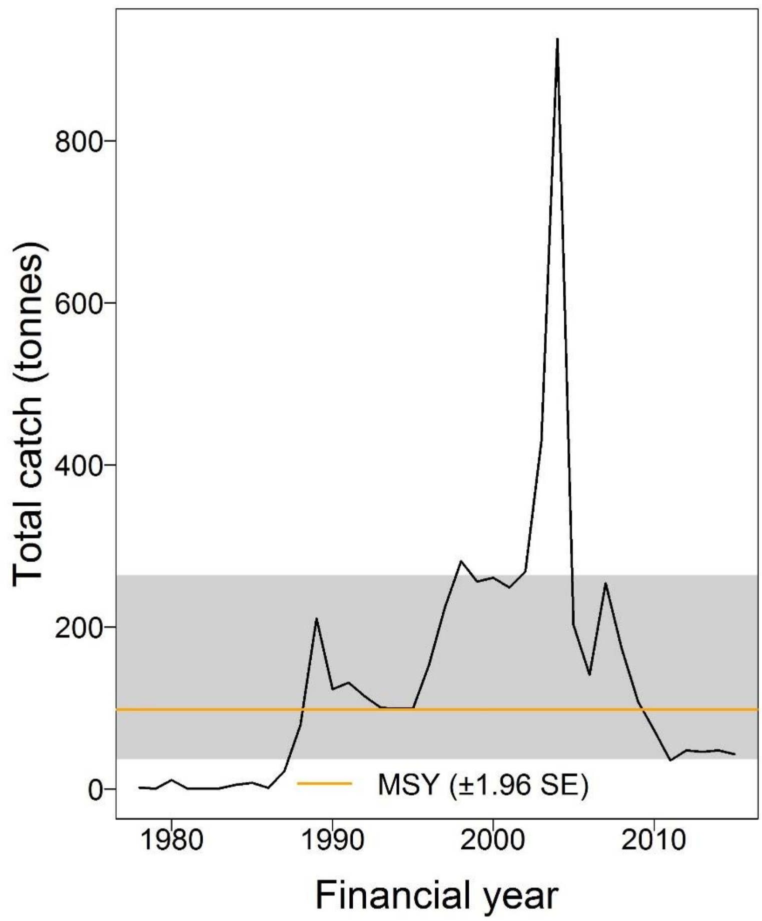


Figure 9.36. Time series of the total catch (all fisheries combined) of sandbar sharks. Also shown is the estimated MSY (geometric mean= 98 t, SE= 37–264 t, shaded in grey) derived from the SR analysis.

The estimated relative biomass trajectories and proportion of model runs above and below the assumed biomass reference points for whiskery, gummy, dusky and sandbar sharks are shown in Figure 9.37, Figure 9.38, Figure 9.39 and Figure 9.40, respectively.

For whiskery shark, relative total biomass declined between the late 1970s and early 1990s before stabilising in recent years (Figure 9.37). For 2015-16, 63%, 82% and 100% of the simulated relative total biomasses were above B_{Tar} (40% unfished biomass), B_{Thre} (30% unfished biomass) and B_{Lim} (20% unfished biomass), respectively. Projections to 2020-21 show stable trends in biomass, with 63%, 79% and 95% of the simulations being above B_{Tar}, B_{Thre} and B_{Lim}, respectively, by 2020-21.

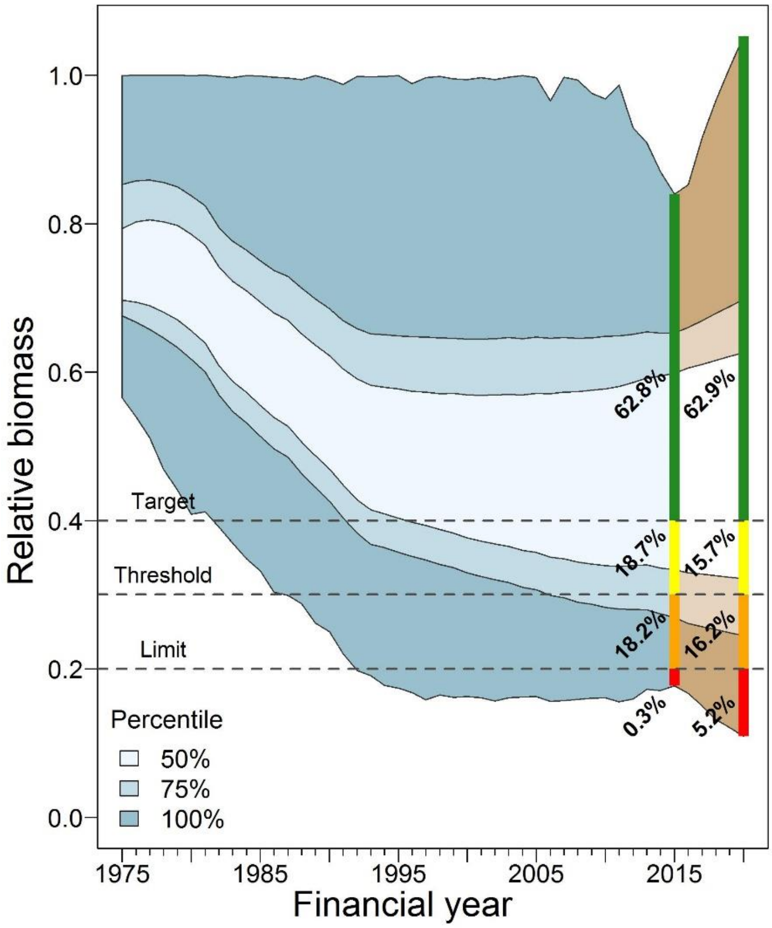


Figure 9.37. Estimated relative total biomass (50%, 75% and 100% model runs) for whiskery sharks between 1975-76 and 2020-21. Forward projections are shown in brown. Also shown is the percentage of model runs above, in between and below reference points for 2015-16 and 2020-21.

For gummy shark, relative total biomass fluctuated at high levels until the early 2000s before declining in recent years (Figure 9.38). For 2015-16, 78%, 92% and 100% of the simulated relative total biomasses were above B_{Tar}, B_{Thre} and B_{Lim}, respectively. Projections to 2020-21 suggest 71%, 79% and 86% of the simulated relative total biomasses will be above B_{Tar}, B_{Thre} and B_{Lim}, respectively.

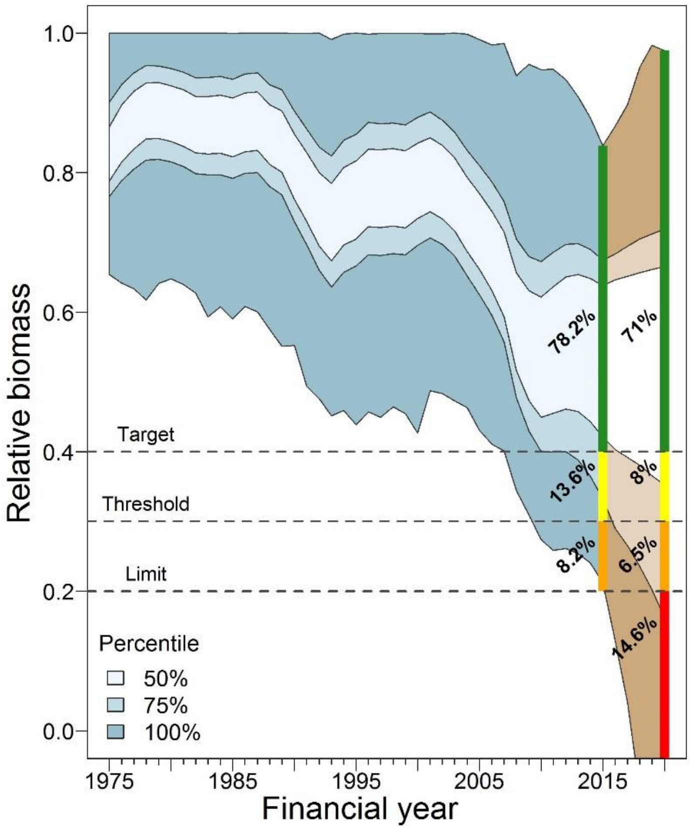


Figure 9.38. Estimated relative total biomass (50%, 75% and 100% model runs) for gummy sharks between 1975-76 and 2020-21. Forward projections are shown in brown. Also shown is the percentage of model runs above, in between and below reference points for 2015-16 and 2020-21.

For dusky shark, relative total biomass fluctuated at high levels in the late 1970s and early 1980s before gradually declining (Figure 9.39). Despite total catches dropping to ~30% the historic peak since the late 2000s, these lower catch levels still equate to fishing mortality levels slightly above/similar to the average population rate of increase due to the very low productivity of dusky sharks. For 2015-16, 51%, 76% and 100% of the simulated relative total biomasses were above B_{Tar}, B_{Thre} and B_{Lim}, respectively. Projections to 2020-21 suggest 50%, 71% and 92% of the simulated relative total biomasses will be above B_{Tar}, B_{Thre} and B_{Lim}, respectively.

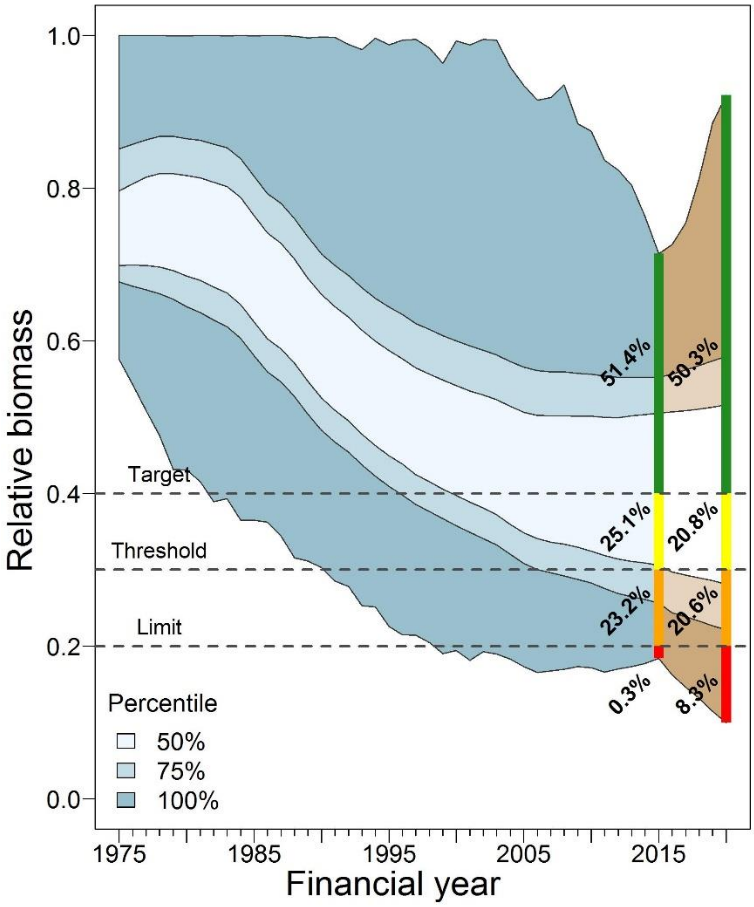


Figure 9.39. Estimated relative total biomass (50%, 75% and 100% model runs) for dusky sharks between 1975-76 and 2020-21. Forward projections are shown in brown. Also shown is the percentage of model runs above, in between and below reference points for 2015-16 and 2020-21.

For sandbar shark, relative total biomass fluctuated at high levels up to the early 1990s; it then declined through the 1990s and early 2000s before stabilising (Figure 9.40). For 2015-16, 63%, 83% and 99% of the simulated relative total biomasses were above B_{Tar}, B_{Thre} and B_{Lim}, respectively. Projections to 2020-21 show an increasing trend in biomass with 67%, 84% and 98% of the simulations being above B_{Tar}, B_{Thre} and B_{Lim}, respectively.

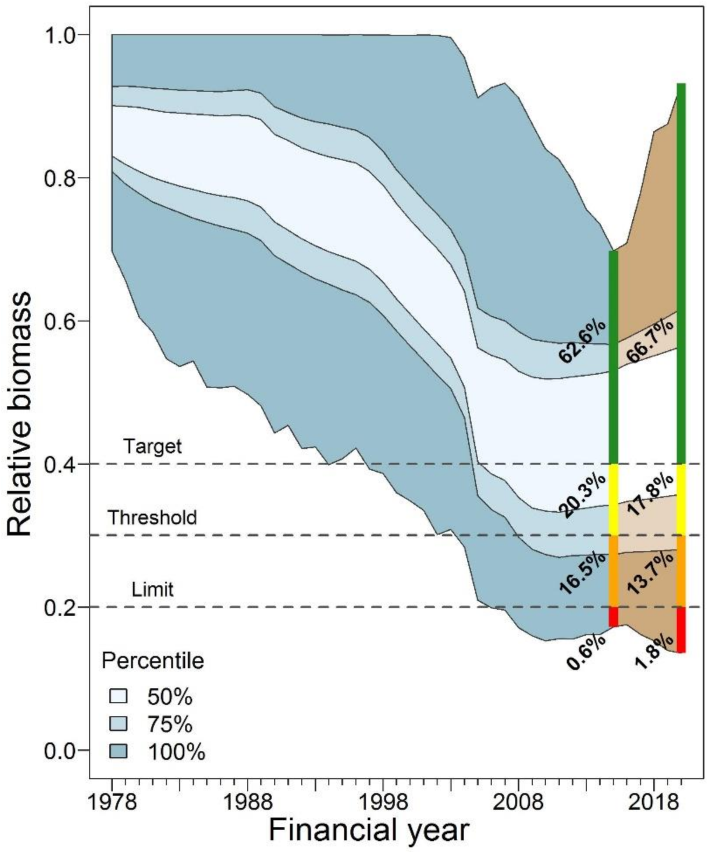


Figure 9.40. Estimated relative total biomass (50%, 75% and 100% model runs) for sandbar sharks between 1975-76 and 2020-21. Forward projections are shown in brown. Also shown is the percentage of model runs above, in between and below reference points for 2015-16 and 2020-21.

9.3.11.5 Accounting for Uncertainty

Uncertainty was accounted for by running the models for 100,000 iterations. In each iteration, random samples of the input parameters were drawn. Parameter combinations that were able to maintain the population such that it neither collapsed nor exceeded the assumed carrying capacity over the catch time series period were retained (Martell & Froese 2013).

9.3.11.6 Conclusion

For whiskery shark, the SR model indicates that unacceptable stock depletion ($B<B_{Thre}$) is unlikely for 2015-16 and for the projection period (until 2020-21).

For gummy shark, the SR analysis indicates that unacceptable stock depletion is unlikely for 2015-16 and for the projection period (until 2020-21).

For dusky shark, the SR analysis indicates that unacceptable stock depletion is possible for 2015-16 and for the projection period (until 2020-21).

For sandbar shark, the SR analysis indicates that unacceptable stock depletion is unlikely for 2015-16 and for the projection period (until 2020-21).

9.3.12 Age and Size Structured Integrated Model

9.3.12.1 Overview

9.3.12.1.1 Age-structured model

Historically, a single-area, sex- and age-structured population dynamics model fitted to CPUE and catch data, a common approach for assessing shark stocks, has been used for the assessment of gummy and whiskery shark stocks in WA (Simpfendorfer et al. 1996b, 2000b). This model has been mostly used for assessing whiskery sharks because the model fit to the gummy shark CPUE resulted in highly uncertain parameter estimates and derived quantities (e.g. total biomass).

For whiskery sharks, the model estimates five parameters: the initial fishing mortality before the start of the catch time series (F_{init}), two catchability coefficients (q_{first} from 1975-76 to 1982-83, and q_{second} since 1983-84), corresponding to two periods of different targeting behaviour (first period targeted at whiskery shark, second period targeted at dusky shark), the recruitment in virgin conditions (r_{star}) and z, a parameter from a re-parameterisation of the Beverton-Holt stock-recruitment relationship (NB: refer to Appendix 4. Equations for a complete model description). This model was originally implemented in Microsoft Excel and its built-in Solver function was used for parameter estimation. As Solver does not provide uncertainty around parameter estimates, this was calculated based on the bootstrapping of CPUE residuals. Currently, alternative packages are available of which Automatic Differentiation Model Builder (ADMB) is considered one of the most robust, providing speed, precision and stability in nonlinear optimization problems, such as fisheries stock assessments (Fournier et al. 2012). In addition, ADMB offers a range of options (Hessian-based asymptotic errors, profile likelihoods and MCMC) for estimating uncertainty in parameter estimates and derived quantities. Hence, the model developed by (Simpfendorfer et al. 1996b, 2000b) in Excel was implemented in ADMB, which is widely used for assessment modelling throughout the world and is the platform on which SS3 (probably the most widely used assessment software application) is based.

As a first step, the same data used by Simpfendorfer et al. (1996b, 2000b) for assessing whiskery shark was used in the ADMB implementation. This showed that the ADMB implementation of the model was able to replicate very closely the results of the Excel model (Figure 9.41).

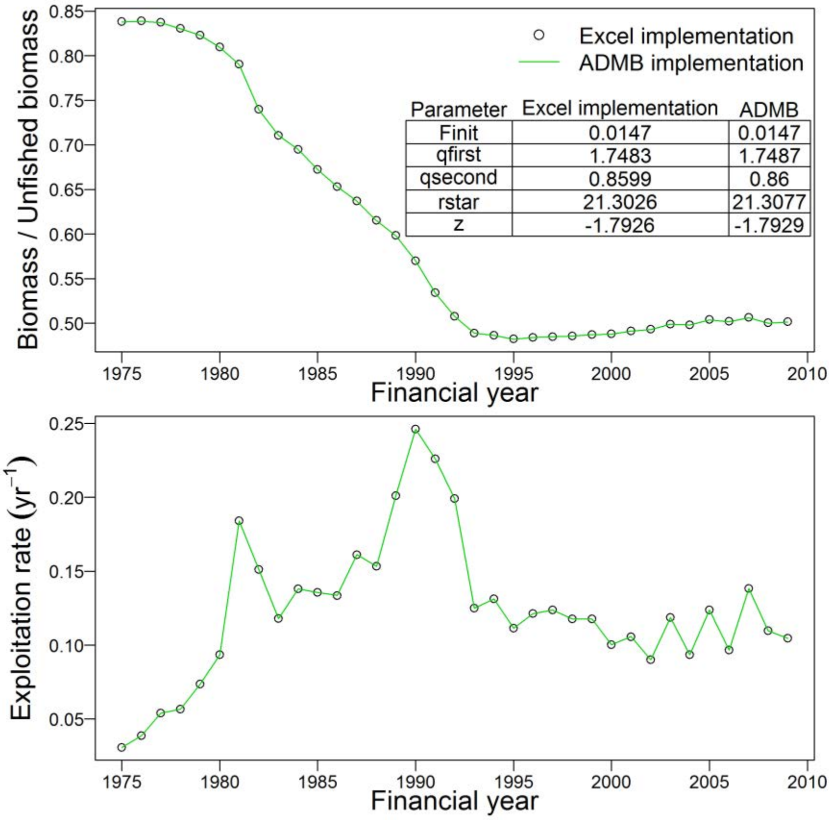


Figure 9.41. Comparison between the age-structured models implemented in Excel for the assessment of whiskery shark by Simpfendorfer et al. (1996b, 2000b) and ADMB. The inset table shows the values of maximum likelihood estimates (MLE).

The ADMB model was then updated with the latest 'effective' CPUE and catch series to recreate the original assessment. It must be noted that the updated catch series differs from the catch series used by Simpfendorfer et al. (1996b, 2000b) (Figure 9.42) due to new implemented processes for improving validation of catch and effort data.

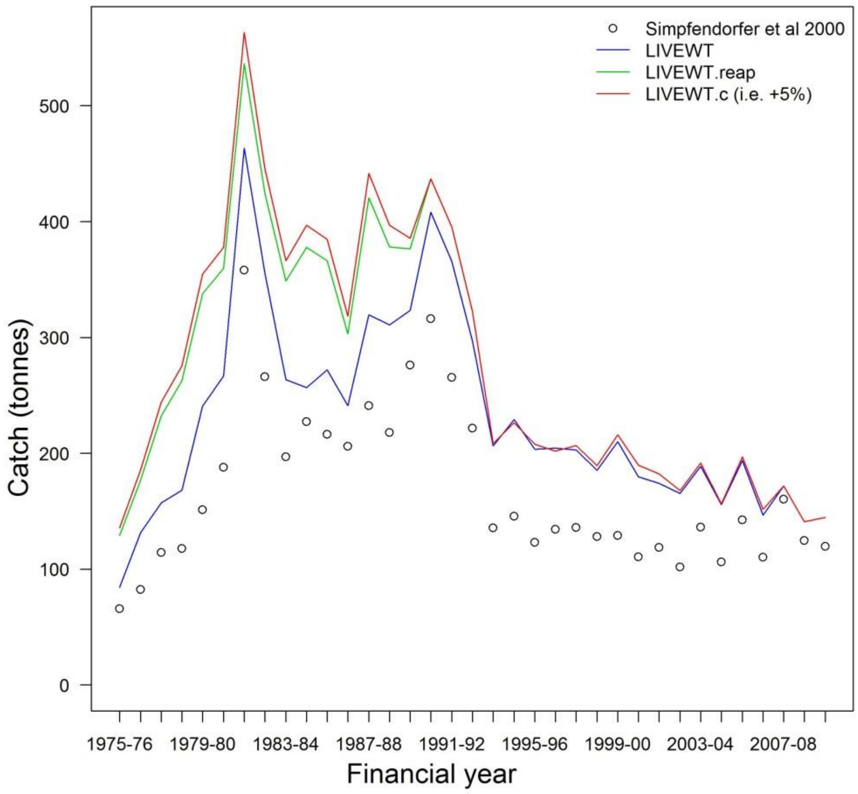
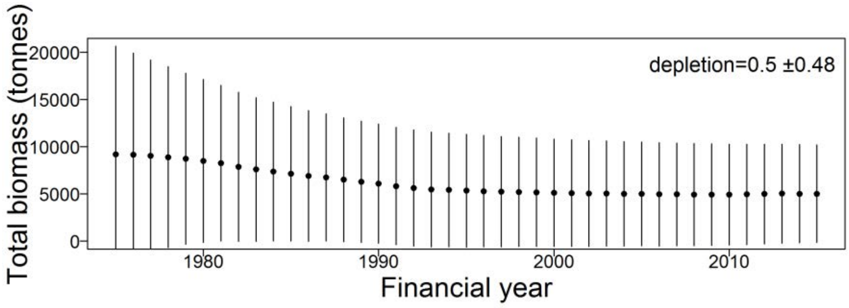


Figure 9.42. Comparison of total whiskery shark catches. LIVEWT, whiskery shark catch information as obtained from monthly reports and daily records; LIVEWT.reap, total catch after the application of business rules derived by (Simpfendorfer & Donohue 1998; Simpfendorfer et al. 2000b; McAuley et al. 2005) to reapportion the catch of sharks reported as ‘unidentified shark’; LIVEWT.c, total catch after the application a 5% increase to records prior to 1990 to account for unreported fishing (McAuley 2005).

When the updated CPUE and catch series were used in the ADMB model, estimation uncertainty increased substantially (Figure 9.43). In addition, prior to 1975-76 shark landings (all species combined) were not negligible (Figure 9.44). Reported shark landings steadily increased from less than 100 tonnes in the 1940s to up to more than 600 tonnes in the early 1970s. In the late 1970s and early 1980s, whiskery sharks accounted for a considerable proportion of shark landings (~ 0.37 on average). Given the level of historic catches prior to the start of the catch time series data (1975-76), it is unrealistic to assume that in 1975-76 the stock was in virgin conditions. If the species composition of the catch prior to 1975-76 was similar to that of the late 1970s and early 1980s, then annual landings of whiskery sharks prior to 1975-76 could have ranged between 9.3 and 239 tonnes. Hence, F_{init} for whiskery sharks may have not been as low as estimated by Simpfendorfer et al. (1996b, 2000b) (Figure 9.45). When the ADMB model was fit to the data using a F_{init} starting value of 0.1, instead of the lower value used by Simpfendorfer et al. (1996b, 2000b), the model failed to converge. This was further explored by testing the effect of varying the initial value of F_{init} during model fitting. It must be noted that in the age-based model, the estimates of F_{init} are seemingly unfeasibly low, and may reflect a strong constraint previously used for this parameter in order to improve model stability.



Parameter	MLE
rstar	49.877 ±31.308
z	0.70615 ±0.47348
qfirst	0.32929 ±0.20159
qsecond	0.15299 ±0.089043
Finit	0.003914 ±0.044833

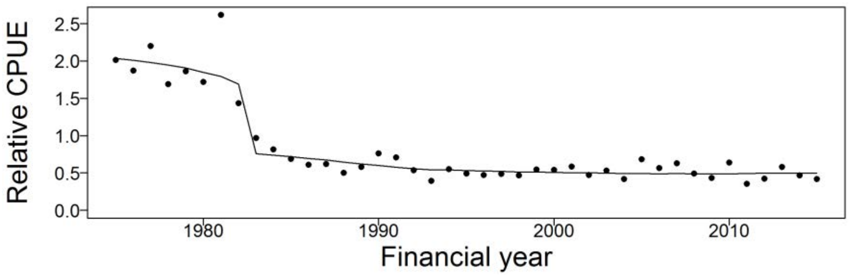


Figure 9.43. Reconstructed biomass trajectory (±1.96 standard errors, se), parameter estimates (±se), and observed (points) and predicted (lines) CPUE based on the implementation in ADMB of the model used by Simpfendorfer et al. (1996b, 2000b) for the assessment of whiskery shark.

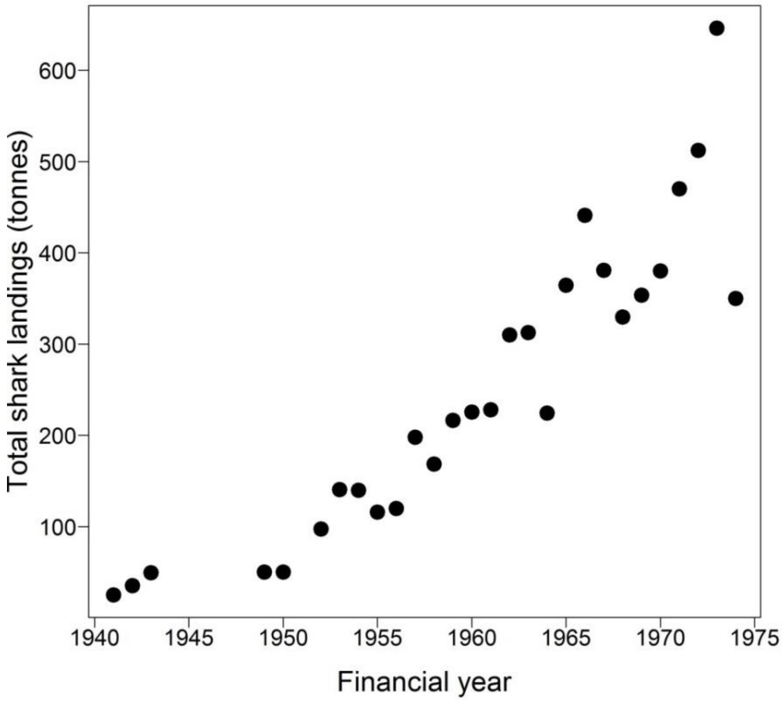


Figure 9.44. Reported shark landings (all species combined) prior to 1975-76.

Three scenarios (0.001, 0.01, 0.1 y^{-1}) were considered for the initial value of F_{init}. Given that natural mortality (M), as derived from Hoenig (1983) method, is 0.27 y^{-1} and that $F = M$ is a rough approximation to maximum sustainable yield (MSY) conditions, the upper value of 0.1 y^{-1} is not considered an excessively large level of fishing mortality. In any case, larger values of F_{init} could not be considered because current model parameterisation does not allow F_{init} to be larger than 0.12 y^{-1}given the co-dependence between F_{init} and r_{star} through the stock-recruitment relationship (see Appendix 4. Equations). This is an issue in that, because in its current state, this model is not suitable for any situation where there has been considerable exploitation before the start of the data time series.

For the three scenarios considered, initial values of F_{init} of 0.001 and 0.01 yielded identical results; however, setting the initial value of F_{init} at 0.1 yielded very different results (Figure 9.45). Setting the initial value of F_{init} at 0.1 changed the shape of the stock-recruitment relation, which had flow-on effects on all model quantities. Under this scenario, the estimated unfished recruitment (r_{star}) was considerably higher (Figure 9.45 inset table). Virgin biomass is a function of r_{star} only so for this scenario it was calculated at a very high value; for 1975 (start of the time series) and subsequent years, biomass is a function of both r_{star} and Z , through the stock-recruitment relation. This resulted in the predicted biomass starting in 1975 at a very low level (i.e. very high depletion), ~10% of the virgin conditions, which is unlikely to be feasible given the catch history.

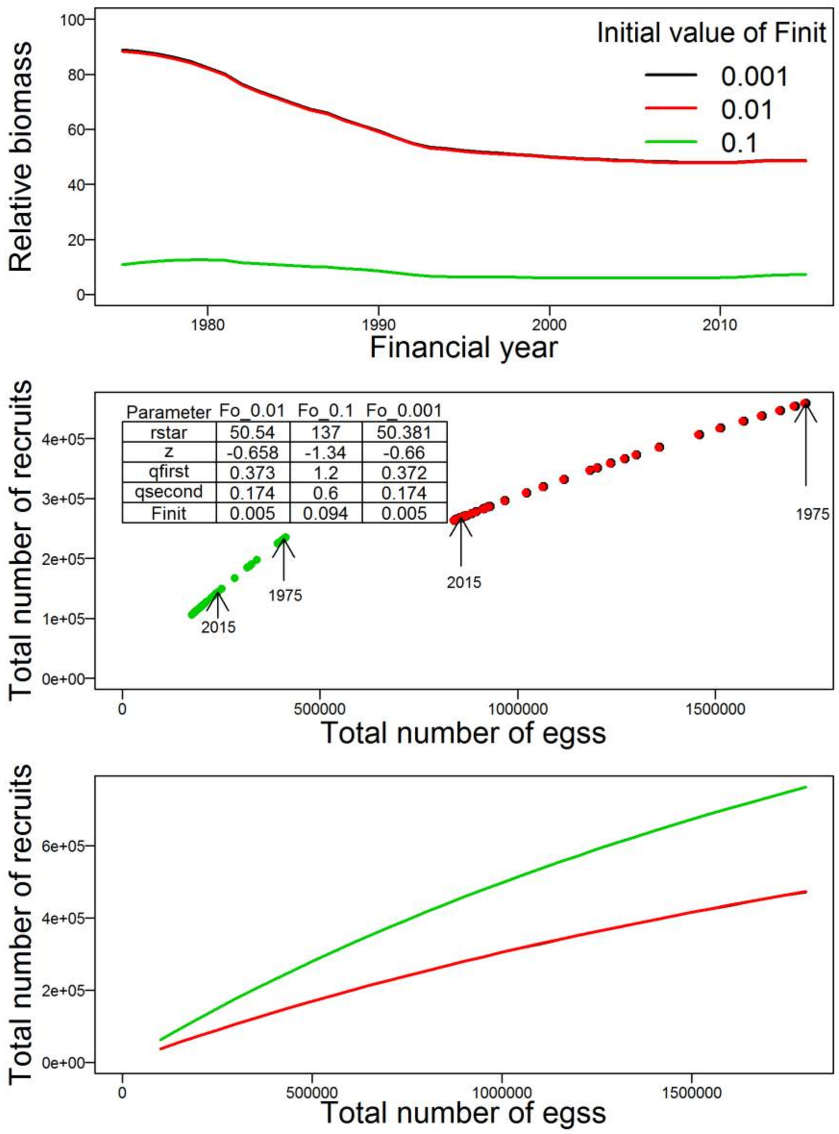


Figure 9.45. Predicted relative biomass through time (upper panel) and stock-recruitment relationship (mid panel) for three scenarios of initial values of F_{init} based on the implementation in ADMB of the model used by Simpfendorfer et al. (1996b, 2000b) for the assessment of whiskery shark. The inset table shows the values of maximum likelihood estimates. For comparison purposes, the lower panel shows the stock-recruitment curve derived from the three scenarios over the same range of egg production. (NB, the F_{init} =0.001 is masked by the F_{init} =0.01 scenario)

Based on the evidence, the current parametrisation of the age-structured model of Simpfendorfer et al. (1996b, 2000b) seems unreliable and, in its present form, should not be used for stock assessments due to the influence of F_{init} on the shape of the stock-recruitment curve. Future effort could be dedicated to reparametrizing this model. For example, the stock-recruitment relationship could be modified by fixing the steepness parameter. Finally, all biological (e.g. fecundity, maturity) and fisheries (catch size composition) data are collected as a function of size, not age, hence, a size-based model for this fishery may be more appropriate than an age-structured model which requires the conversion of -at-size quantities to -at-age quantities and therefore introduces further uncertainty.

9.3.12.1.2 Integrated size-based model

In the past, quantitative assessments of whiskery and gummy shark stocks in WA had been done using an age- and sex-structured population dynamics model fitted only to 'effective' CPUE (Simpfendorfer et al. 1996b, 2000b). Since the application of this model, additional information useful for calibrating population dynamics model has become available. Hence, to incorporate this information in the assessment process, an integrated stock assessment model was developed. A series of sensitivity tests were also done to illustrate the effect of incorporating new data and making different assumptions about key quantities, and to test uncertainty in model structure (Table 9.11 and Table 9.12 for whiskery and gummy sharks, respectively). For whiskery shark, the assumption of change in targeting behaviour from 1982 to 1983 (Simpfendorfer et al. 1996b, 2000b) implies that all fishers moved from targeting whiskery sharks to targeting dusky sharks. It is more likely that this transition was gradual. Hence, two alternative scenarios were considered: disregarding the 1975-1982 data in the model fitting, and disregarding the transitional period (1981-1983). The level of fishing mortality at the start of the catch time series, F_{init}, could not be reliably estimated because the available data are very limited and there is insufficient information to estimate this parameter well. Hence, the model was run for a feasible range of fixed values given that the commercial exploitation of sharks in WA commenced in the early 1940s (Whitley 1943) (Figure 9.46 and Figure 9.47 for whiskery and gummy sharks, respectively).

Table 9.11. Table showing the sensitivity tests done for whiskery shark. Q, catchability.

Model		Spatial	Movement	Data						Input parameters				Q
Name	Type	structure		Size composition	CPUE	CPUE years not used in likelihood	Age & growth	Prop. male in catch	Tagging	M	h	F_{init}	Maturity	
S2	Age-structured	Single zone	N/A	No	Effective	None	No	Equal	No	0.27	N/A	estimated	knife edge	2 periods
S3	Length-based	Single zone	No	Yes	Stand.	None	Yes	Observed	No	0.27	0.351	0.03	at length	3 periods
S4	Length-based	Single zone	No	Yes	Stand.	1975-82	Yes	Observed	No	0.27	0.351	0.03	at length	2 periods
S5	Length-based	Single zone	No	Yes	Effective	None	Yes	Observed	No	0.27	0.351	0.03	at length	2 periods
S6	Length-based	Single zone	No	Yes	Stand.	1980-83	Yes	Equal	No	0.27	0.351	0.03	at length	3 periods
S7	Length-based	Single zone	No	Yes	Stand.	1980-83	Yes	Observed	No	0.23	0.351	0.03	at length	3 periods
S8	Length-based	Single zone	No	Yes	Stand.	1980-83	Yes	Observed	No	0.35	0.351	0.03	at length	3 periods
S9	Length-based	Single zone	No	Yes	Stand.	1980-83	Yes	Observed	No	0.27	0.351	0.003	at length	3 periods
S10	Length-based	Single zone	No	Yes	Stand.	1980-83	Yes	Observed	No	0.27	0.351	0.05	at length	3 periods
S11	Length-based	Single zone	No	Yes	Stand.	1980-83	Yes	Observed	No	0.27	0.29	0.03	at length	3 periods
S12	Length-based	Single zone	No	Yes	Stand.	1980-83	Yes	Observed	No	0.27	0.41	0.03	at length	3 periods
S13	Length-based	Three zones	Yes	Yes	Stand.	1980-83	Yes	Observed	Yes	0.27	0.351	0.03	at length	3 periods
Base case	Length-based	Single zone	No	Yes	Stand.	1980-83	Yes	Observed	No	0.27	0.351	0.03	at length	3 periods

Table 9.12. Table showing the sensitivity tests done for gummy shark. Q, catchability.

Model		Spatial	Movement	Data					Input parameters				Q
Name	Type	structure		Size composition	CPUE	Age & growth	Prop. male in catch	Tagging	M	h	F_{init}	Maturity	
S2	Age-structured	Single zone	No	No	Effective	No	Equal	No	0.283	N/A	0.004	knife edge	1 period
S3	Length-based	Single zone	No	Yes	No	Yes	Observed	No	0.283	0.481	0.05	at length	N/A
S4	Age-structured	Single zone	No	No	Stand.	No	Equal	No	0.283	N/A	0.004	knife edge	2 periods
S5	Length-based	Single zone	No	Yes	Stand. hours	Yes	Observed	No	0.283	0.481	0.05	at length	2 periods
Base case	Length-based	Single zone	No	Yes	Stand.	Yes	Observed	No	0.283	0.481	0.05	at length	2 periods

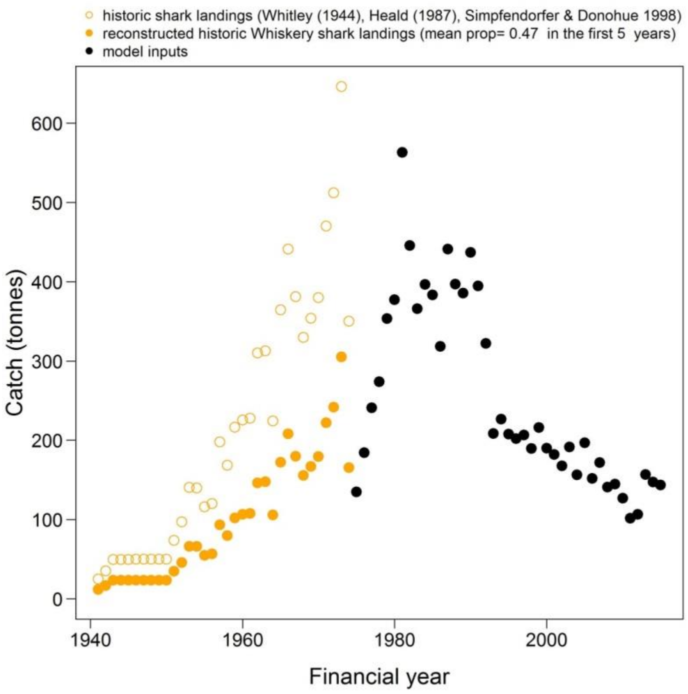


Figure 9.46. Reported catches of whiskery sharks (1975-76 to 2015-16) and reported shark landings (all species combined) for WA prior to 1975-76 (open orange dots). Also shown are reconstructed historic landings of whiskery sharks calculated as the reported shark landings prior to 1975-76 multiplied by the average proportion of whiskery sharks in the annual catch for the years 1975-76 to 1980-81.

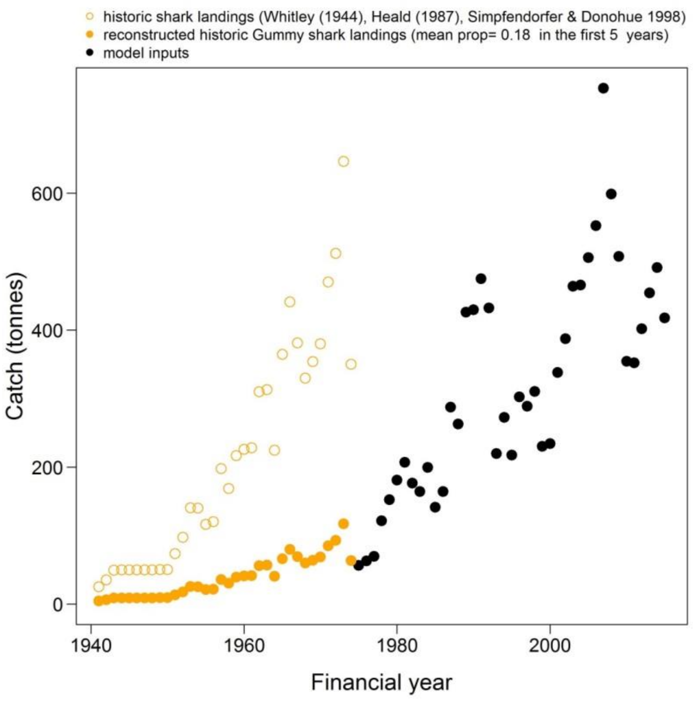


Figure 9.47. Reported catches of gummy sharks (1975-76 to 2015-16) and reported shark landings (all species combined) for WA prior to 1975-76 (open orange dots). Also shown are reconstructed historic landings of gummy sharks calculated as the reported shark landings prior to 1975-76 multiplied by the average proportion of gummy sharks in the annual catch for the years 1975-76 to 1980-81.

9.3.12.2 Model Description

A detailed description of the models is provided in Appendix 4. EquationsAppendix 4. Equations. A size-based model is considered appropriate because the available biological (e.g. fecundity, maturity) and fishery (e.g. gillnet selectivity) relationships are functions of size. 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 the age-structured model where a growth curve is required for converting at-size information to at-age information. Also, an integrated approach makes use of all available information, in addition to 'effective' CPUE.

Population were projected into the future for 5 years assuming a constant catch set at the average catch of the last 5 years of available data. All models were developed in ADMB (Fournier et al. 2012).

9.3.12.3 Input Data and Parameters

A description of the data used in the models and the input parameters are given in the Input Data and Parameters section and Appendix 4. EquationsAppendix 4. Equations.

9.3.12.4 Results and Diagnostics

9.3.12.4.1 Whiskery shark

The assessment was most sensitive to the model structure considered, the use of 'effective' or standardised CPUE, and the specified values of natural mortality (M) and steepness (h) (Figure 9.48).

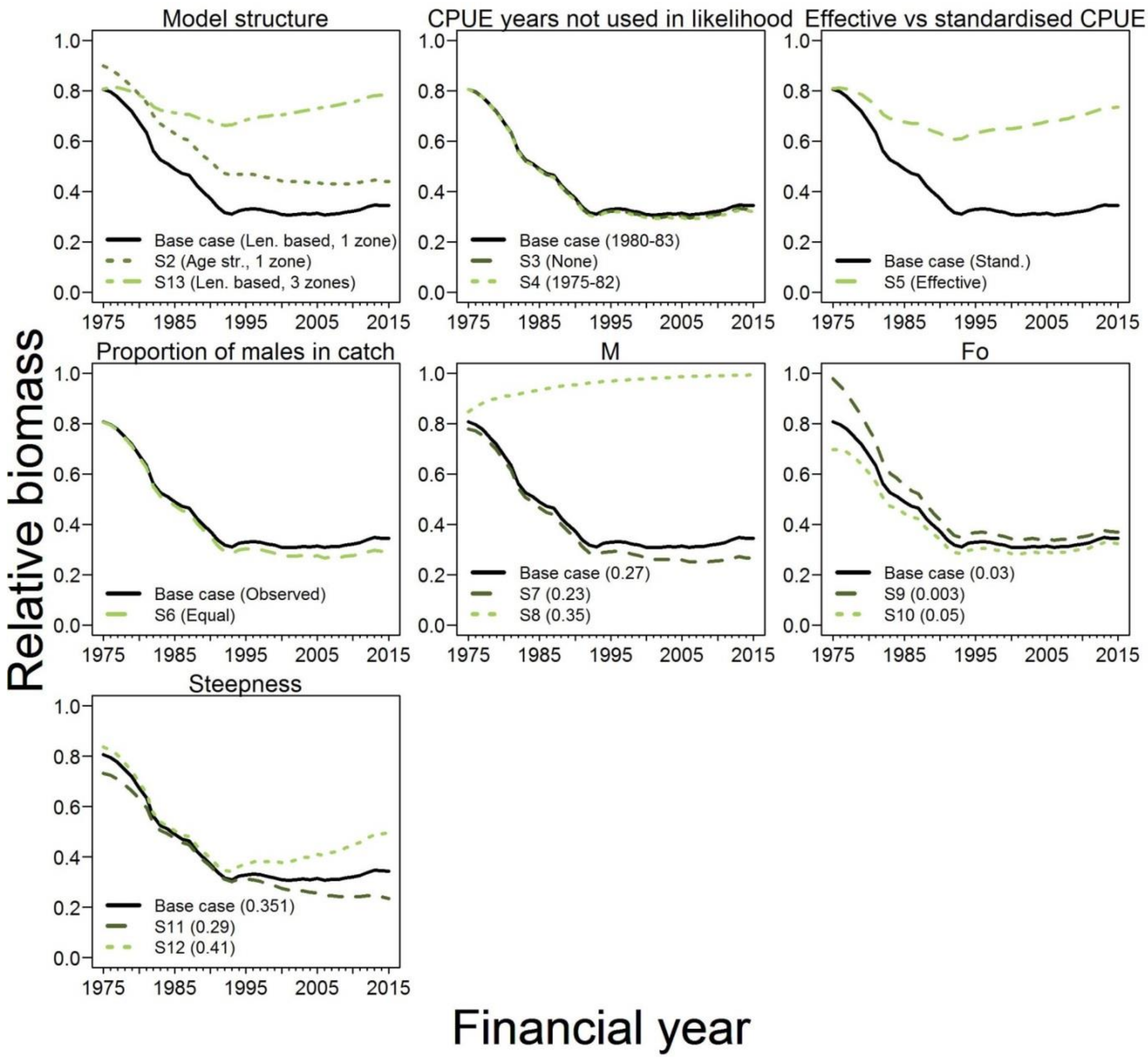


Figure 9.48. Model predictions of whiskery shark relative female mature biomass for the range of scenarios tested for the period 1975-76 to 2015-16.

As explained above, the current parametrisation of the age-structured model (scenario S2) seems unreliable and, in its present form, should not be used for stock assessments. Scenario

S13, the spatially-structured size-based model, yielded a poor fit to the standardised CPUE (

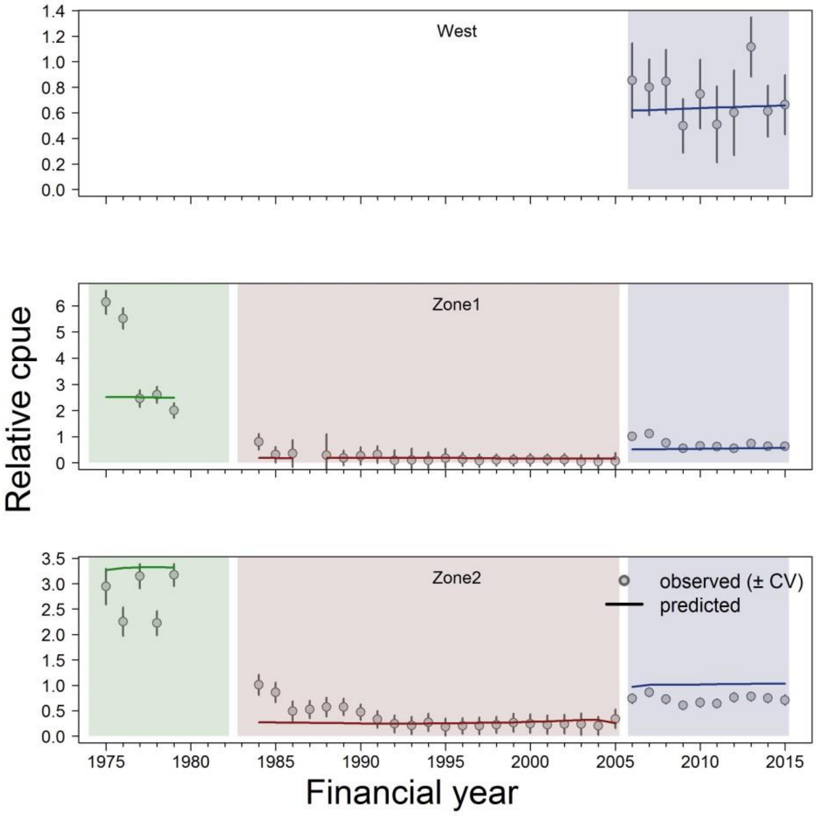


Figure 9.49). This, in combination with the limited data available to parametrise movement (17 and 109 individuals for acoustic and conventional tagging, respectively) yielded highly unreliable estimates of population trajectories (Figure 9.50). Hence, current available data cannot support the use of a spatial (more complex) model over a non-spatial model.

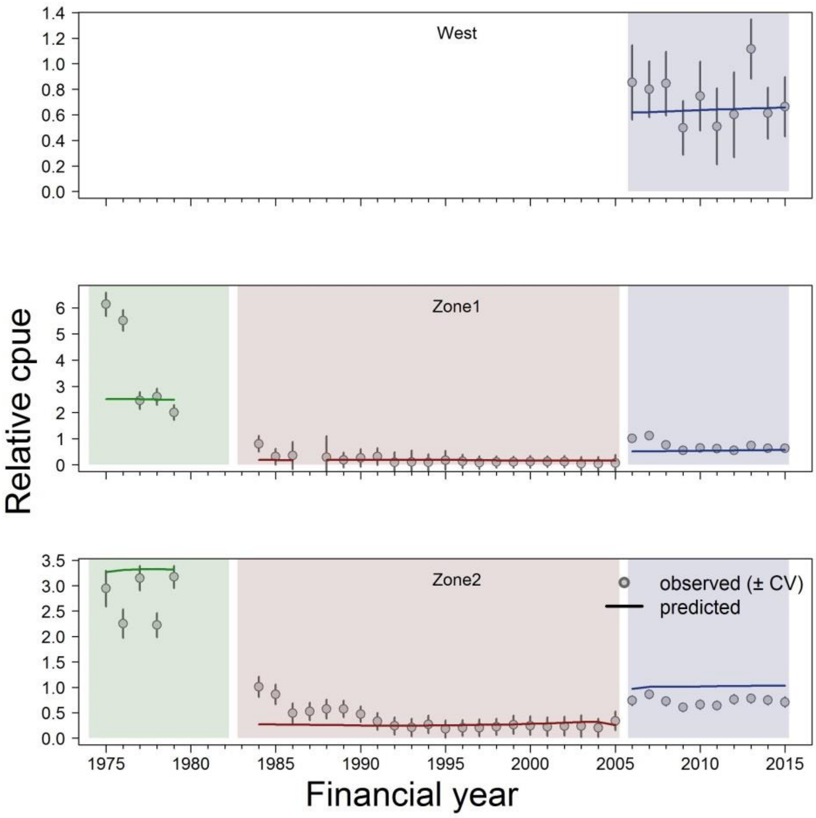


Figure 9.49. S13 model fit to the standardised CPUE of whiskery sharks in the West coast, Zone 1 and Zone 2. The three assumed catchability periods are highlighted in green, red and blue. (NB, no data available in the West zone prior to 2006-07 due to very small sample sizes and lack of convergence for the GLM models used to standardise catch and effort).

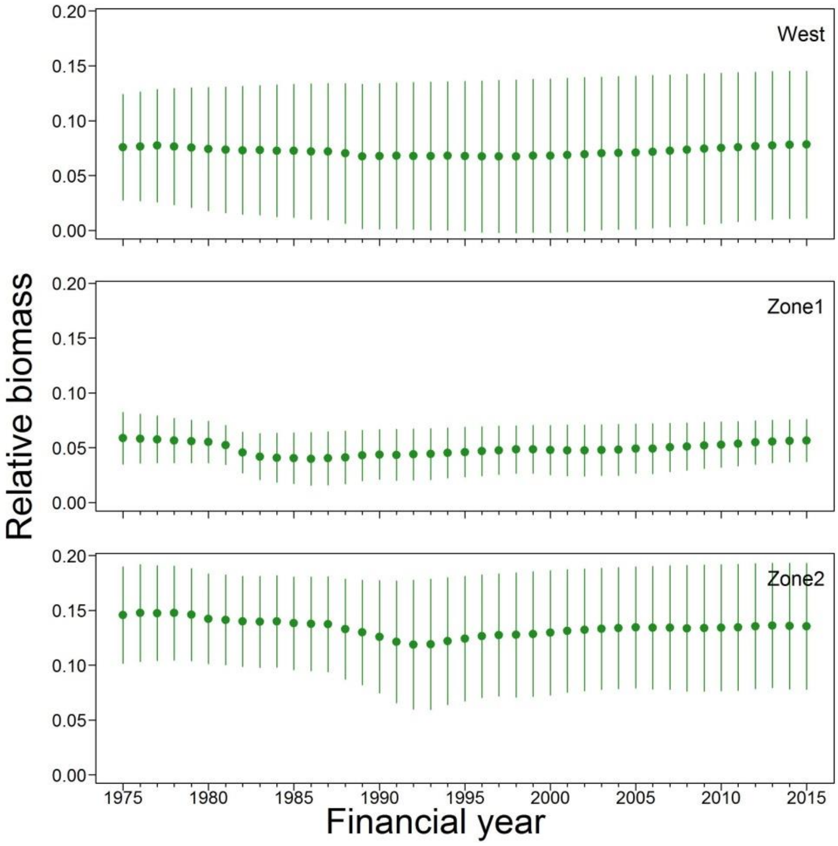


Figure 9.50. S13 estimated relative female mature biomass (±1.96 SE) for whiskery sharks between 1975-76 and 2015-16 for each zone considered.

The use of 'effective' CPUE (S5) yielded in a poor fit (Figure 9.51) and highly unreliable estimates of population trajectories (Figure 9.52).

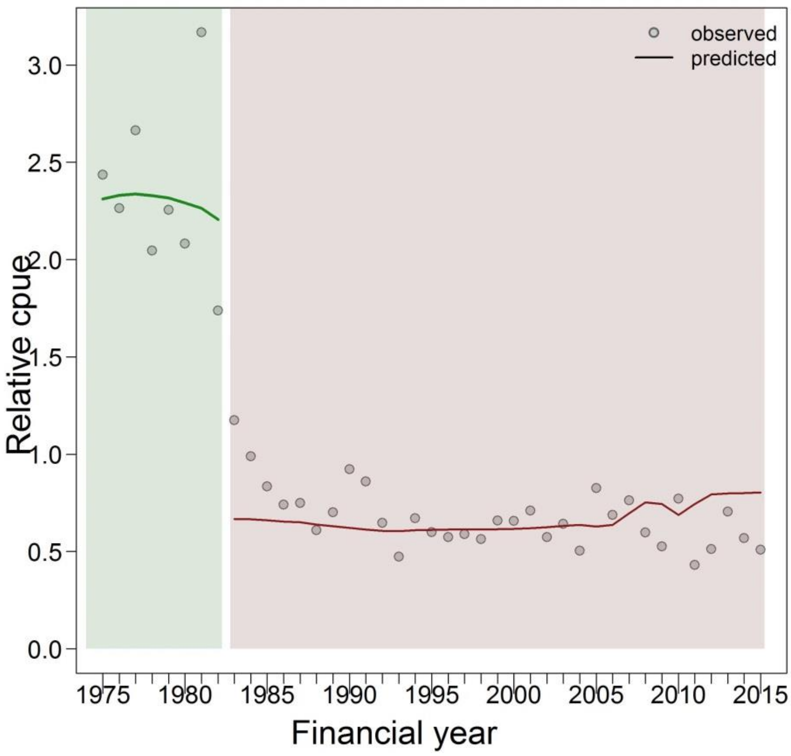


Figure 9.51. S5 model fit to the standardised CPUE of whiskery sharks. The two assumed catchability periods are highlighted in green and red.

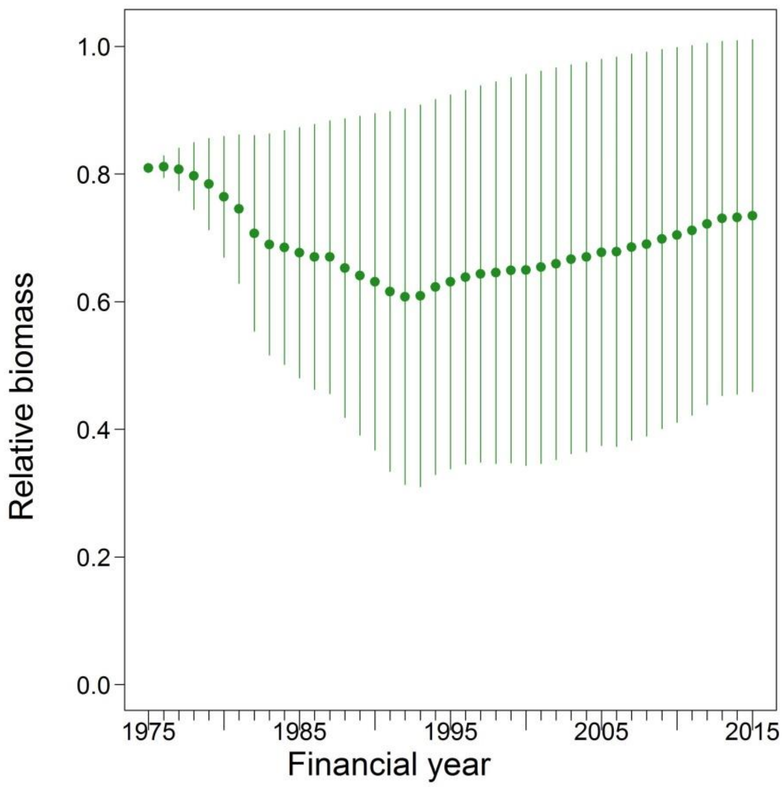


Figure 9.52. S5 estimated relative female mature biomass (±1.96 SE) for whiskery sharks between 1975-76 and 2015-16.

Setting M at 0.35 y^{-1} yielded a relatively poor fit to the standardised CPUE (Figure 9.53) and model convergence was only possible when R^*, the model-estimated unfished recruitment, was three orders or magnitude larger than the base case (Table 9.13). Setting M at 0.23 y^{-1} yielded similar outcomes as the base case.

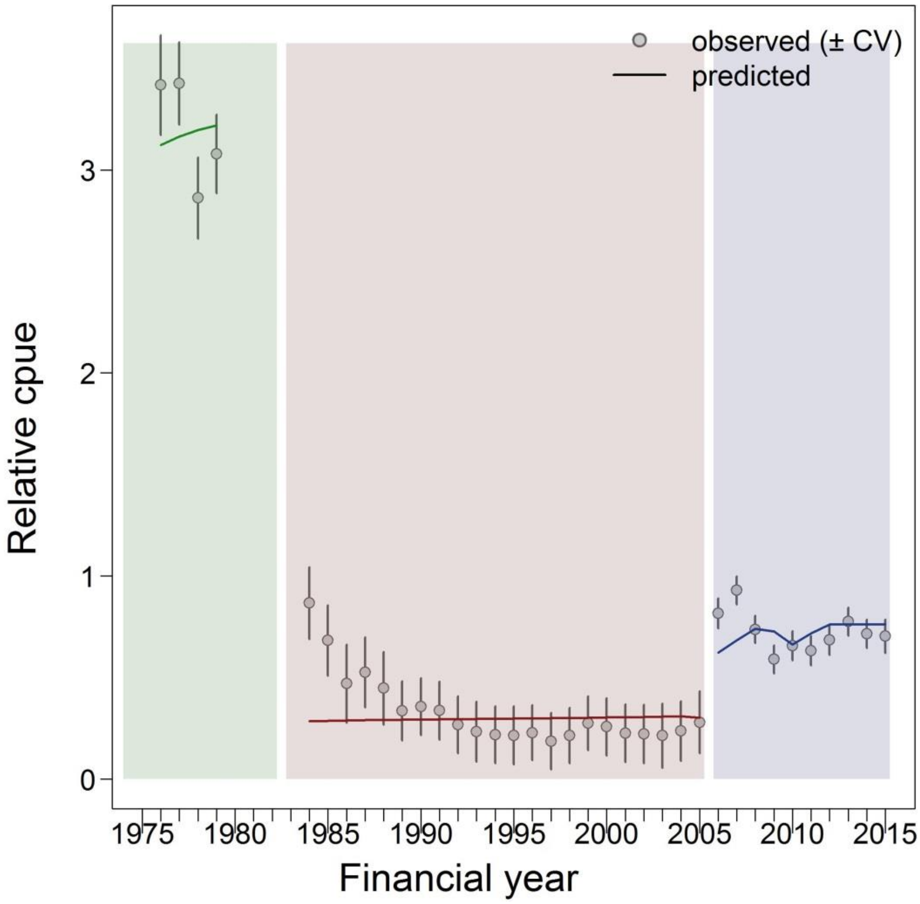


Figure 9.53. S8 model fit to the standardised CPUE of whiskery sharks. The three assumed catchability periods are highlighted in green, red and blue.

Table 9.13. Estimated value of R^* for Base case, S7 and S8.

Scenario	R*	95% CI
Base case	5.73 e+02	5.04 e+02 – 6.51 +02
S7	4.40 e+02	4.00 e+02 – 4.81 e+02
S8	1.78 e+05	1.44 e+05 – 2.19 e+05

Finally, specifying different values of h yielded similar model fits but different current relative biomasses levels as higher values of h translate in a faster response to a reduction in fishing pressure than lower values of h. The h values chosen for the base case, S11 and S12, correspond to the median and upper and lower 80 percentile estimates obtained by (Braccini et al. 2015). Hence, the value used in the base case corresponds to the most likely value but the sensitivity to the h value used must be considered when interpreting assessment outputs.

For the base case, model fits are presented in Figure 9.54, Figure 9.55, Figure 9.56 and Figure 9.57. For the standardised CPUE, the model fitted the data well most years with the exception of the first two years of the second and third catchability periods (Figure 9.54). For the growth data, the model fitted the data well (Figure 9.55). Finally, for the catch size composition data, the model showed an overall good fit for most years for females (Figure 9.56) and males (Figure 9.57) but tended to underestimate the mean size of the catch in some years. It must be noted that overall sample sizes are relatively small.

Relative total biomass declined from ~90% in the late 1970s to ~49% in early 2000s, before increasing to ~50% in 2015-16 (Figure 9.58). There was an 85%, 99% and 100% probability that the relative biomass in 2015-16 was above B_{Tar}, B_{Thre} and B_{Lim}, respectively (Figure 9.59). Projections to 2020-21 show increasing trends in biomass (Figure 9.58), with an 87%, 99% and 100% probability that the relative biomass will be above B_{Tar}, B_{Thre} and B_{Lim}, respectively, by 2020-21 (Figure 9.60).

Relative female mature biomass declined from ~80% in the late 1970s to ~30% in early 2000s, before increasing to ~37% in 2015-16 (Figure 9.58). There was a 38%, 77% and 98% probability that the relative biomass in 2015-16 was above B_{Tar}, B_{Thre} and B_{Lim}, respectively (Figure 9.59). Projections to 2020-21 show increasing trends in female biomass, with a 47%, 82% and 98% probability that the relative biomass will be above B_{Tar}, B_{Thre} and B_{Lim}, respectively, by 2020-21 (Figure 9.60).

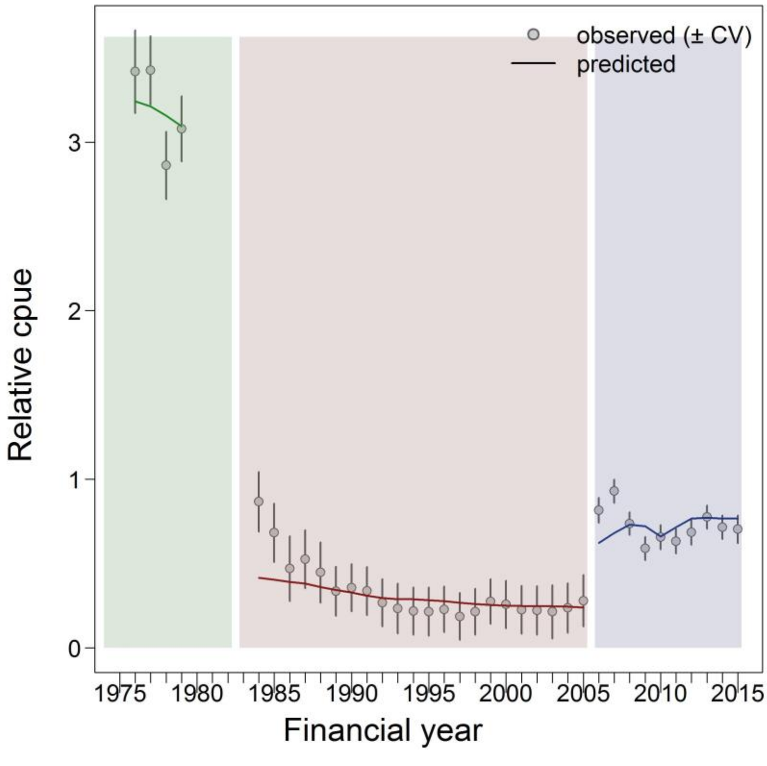


Figure 9.54. Base case model fit to the standardised CPUE of whiskery sharks. The three assumed catchability periods are highlighted in green, red and blue.

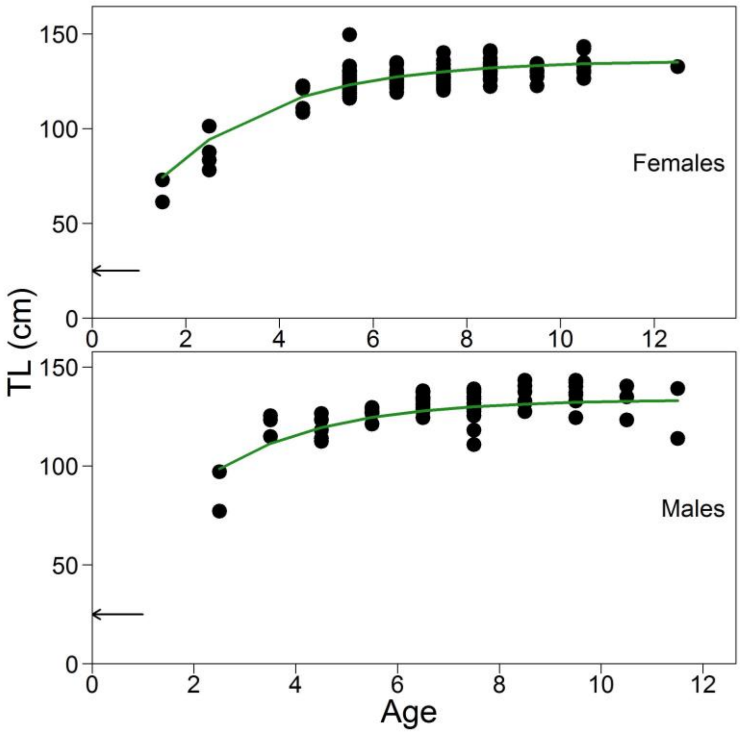


Figure 9.55. Base case predicted (green line) and observed length at age. Arrows indicate the size at birth.

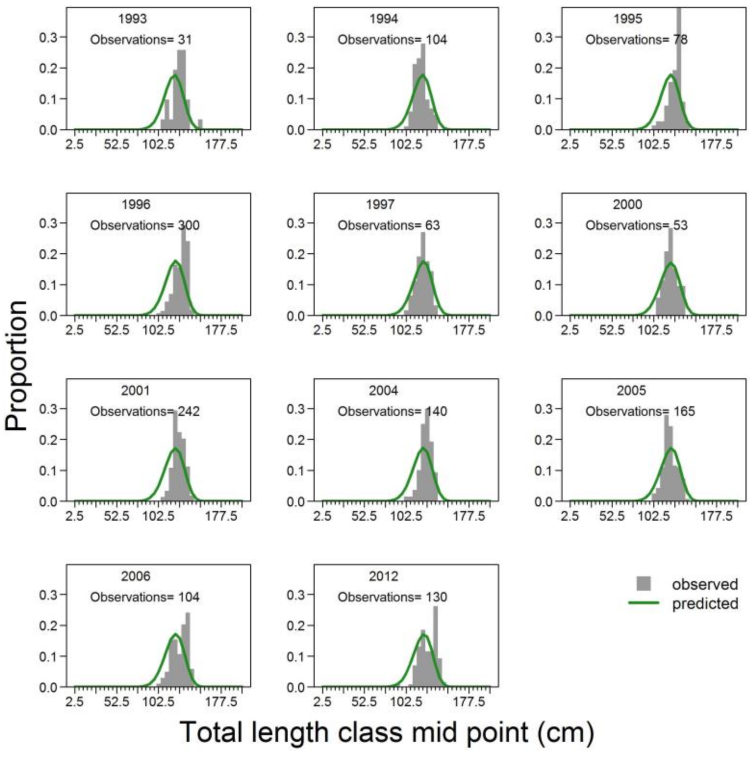


Figure 9.56. Base case size composition of female whiskery sharks taken by 6.5 inch gillnets.

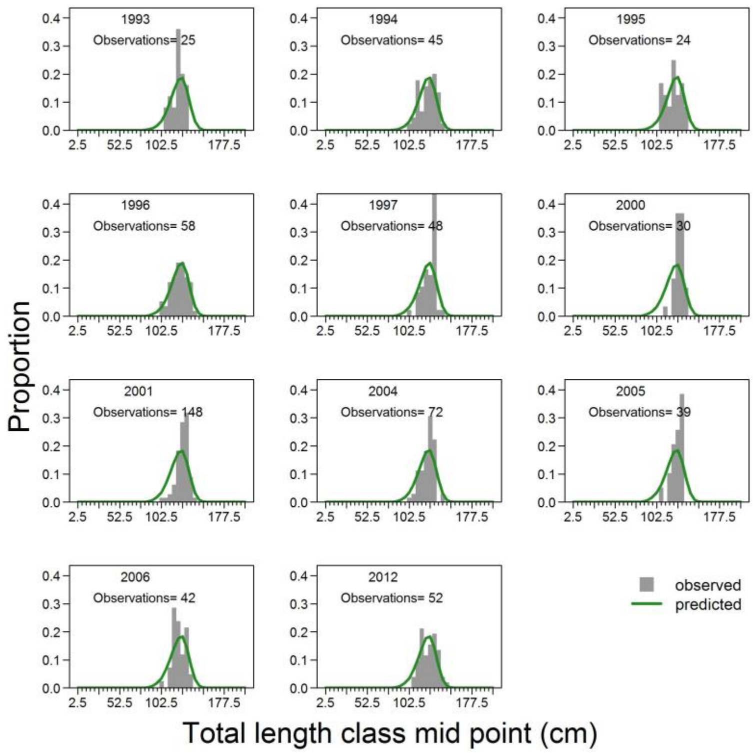


Figure 9.57. Base case size composition of male whiskery sharks taken by 6.5 inch gillnets.

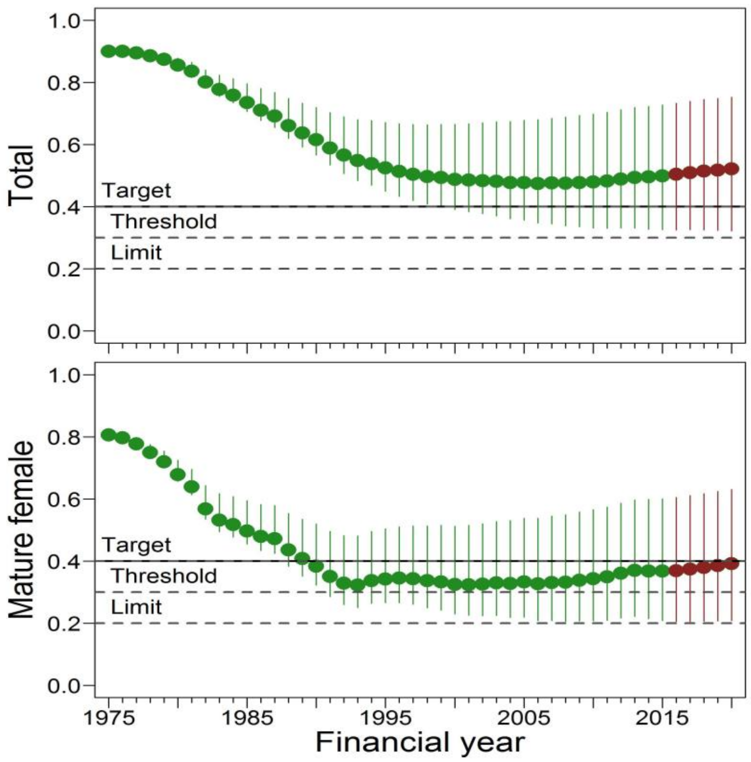


Figure 9.58. Base case relative biomass (total and mature female, ± 95% credibility intervals) for whiskery sharks between 1975-76 and 2020-21. Forward projections are shown in red.

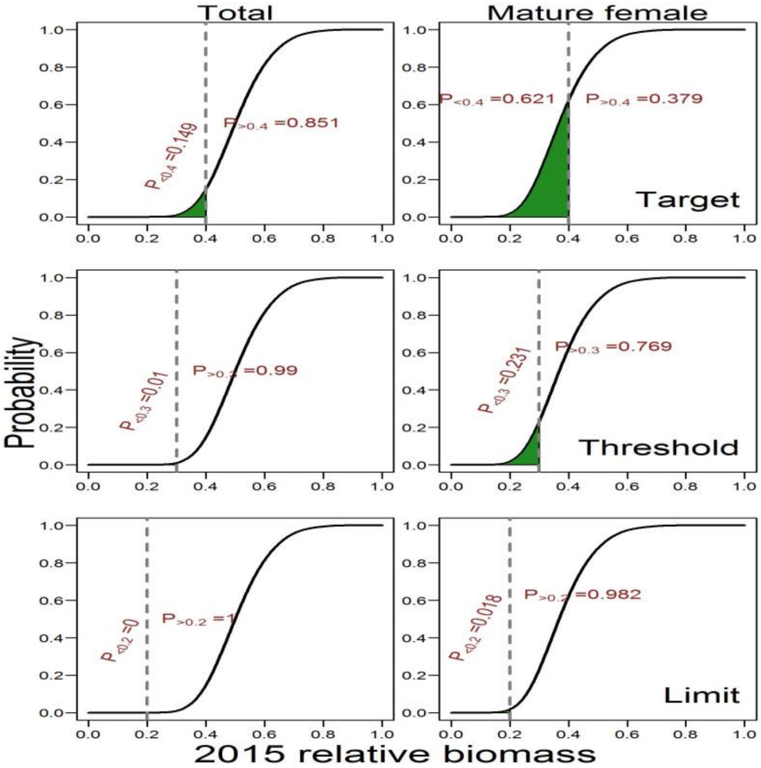


Figure 9.59. Base case estimated probability of being above and below the assumed biomass reference points for the 2015-16 relative biomass (total and mature female) of whiskery sharks. The green area shows the probability of being below the reference points.

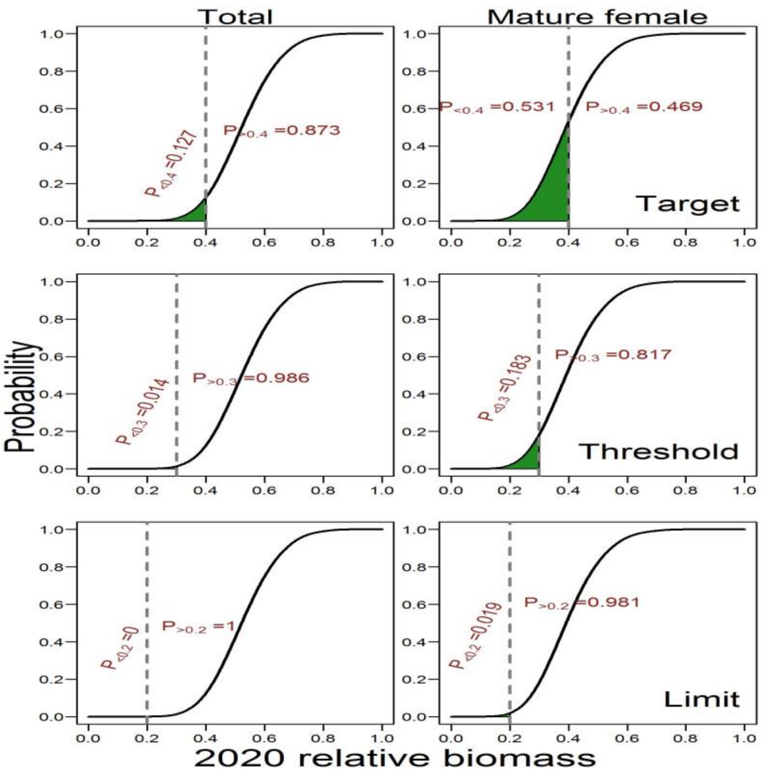


Figure 9.60. Base case estimated probability of being above and below the assumed biomass reference points for the 2020-21 relative biomass (total and mature female) of whiskery sharks. The green area shows the probability of being below the reference points.

9.3.12.4.2 Gummy shark

A range of sensitivity tests were conducted (Table 9.12). However, none of the tested models and scenarios provided a good fit to the CPUE series (Figure 9.61). In particular, no model could explain the peak in CPUE observed during the mid-2000s which corresponds to the historic peak in catches (Figure 9.62). Based on anecdotal information provided by fishers, this peak would not be due to changes in technology and/or targeting behaviour so it is unclear if the observed increase in CPUE is due to abundance or other factors not accounted for in the model used for the standardisation of catch and effort. Therefore, the standardised catch rate of gummy sharks appears to be a poor index of population abundance, hampering the ability of the integrated model to represent population dynamics.

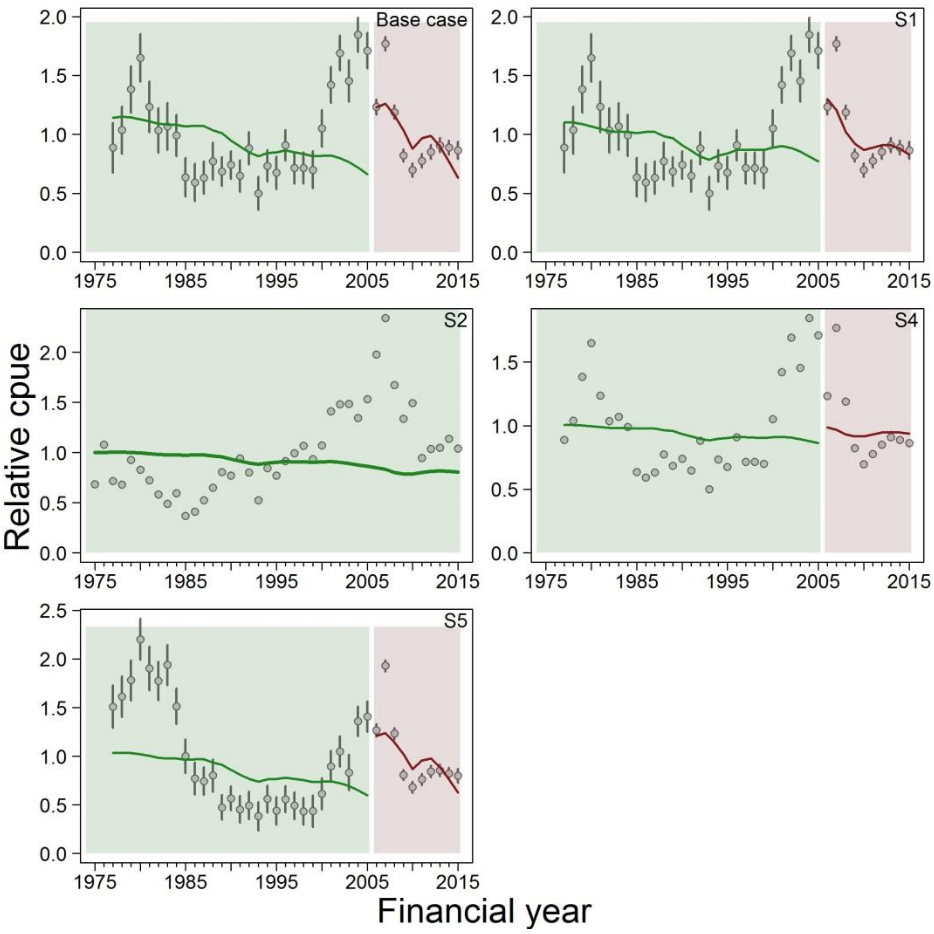


Figure 9.61. Model fits to the standardised CPUE of gummy sharks for the range of scenarios tested. The assumed catchability periods are highlighted in green and red (if applicable).

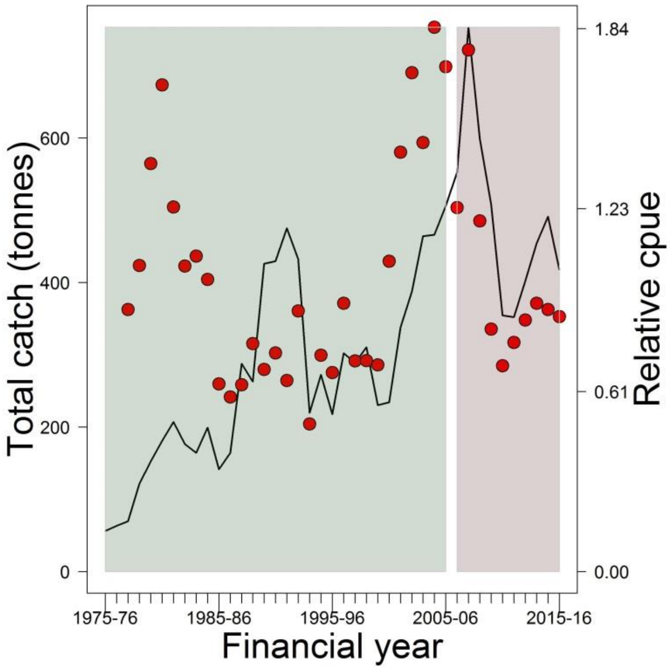


Figure 9.62. Time series of gummy shark catches (black line) and standardised CPUE (red dots).

In addition, several biological (growth) and fishing (selectivity schedules) parameters are not available for WA so they were borrowed from south-eastern Australia. This may have resulted in the relatively poor fit to the size composition data where the model is underestimating small classes and overestimating large classes in some years (Figure 9.63 and Figure 9.64).

For the reasons listed above, a quantitative assessment based on an integrated modelling approach is not advisable.

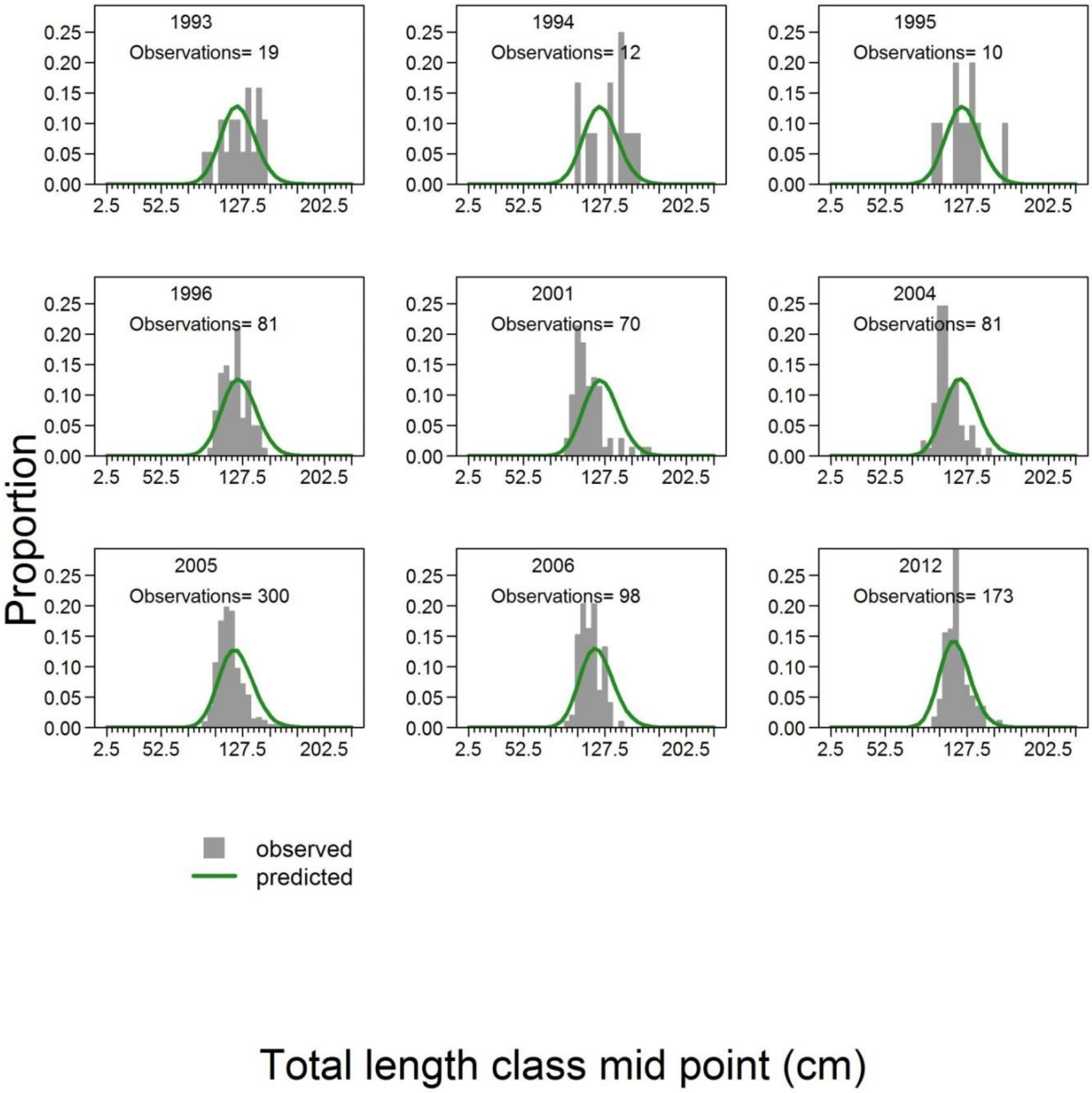


Figure 9.63. Base case size composition of female gummy sharks taken by 6.5 inch gillnets.

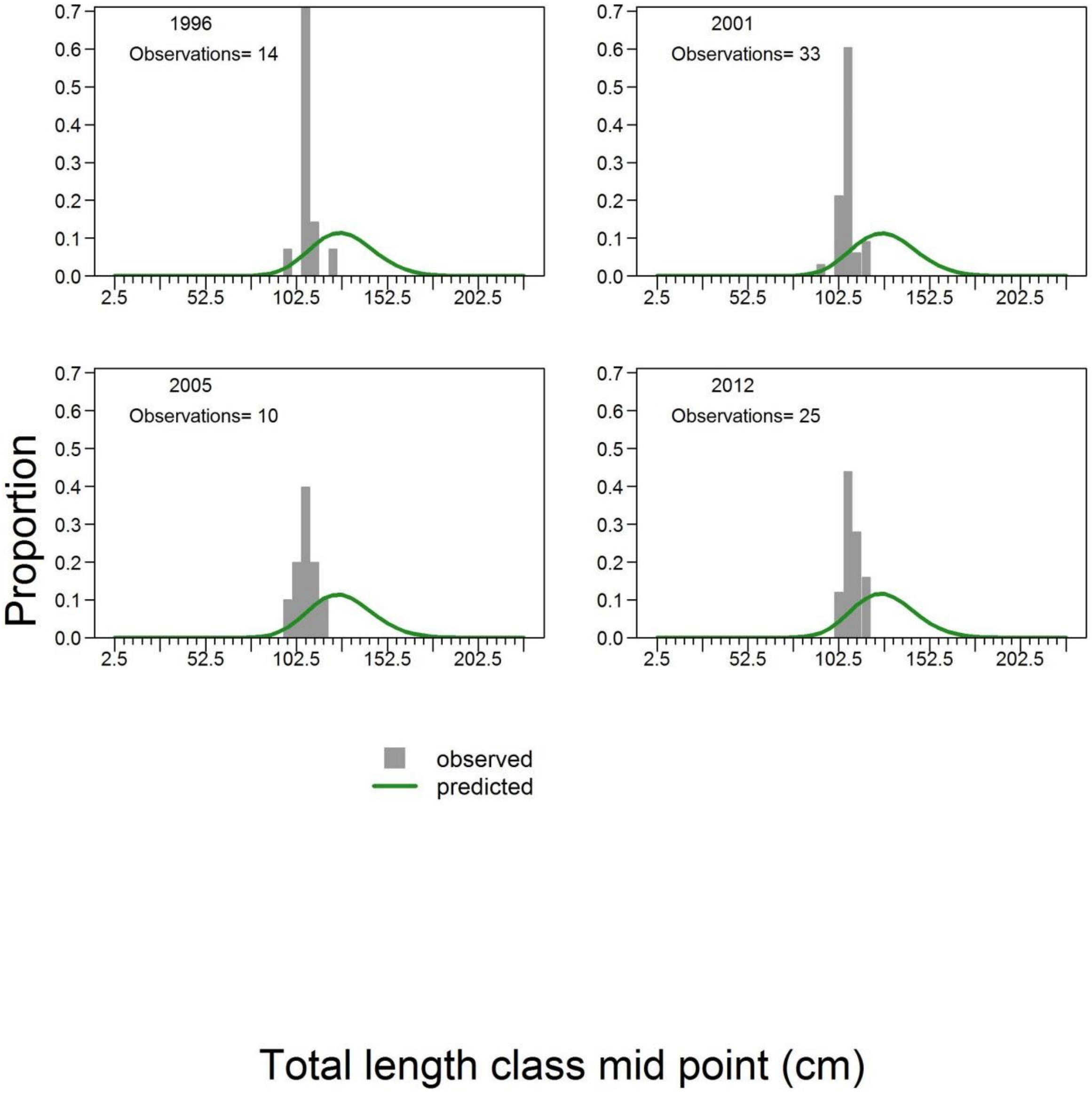


Figure 9.64. Base case size composition of male gummy sharks taken by 6.5 inch gillnets.

9.3.12.5 Accounting for Uncertainty

The estimation process consists of a maximum likelihood step (all scenarios) followed by MCMC sampling (used to better characterise uncertainty; base case only) with posterior estimates based on 1,000,000 samples run, a burn in of 5% and a thinning of 10 for ensuring acceptance ratios of about 0.3. MCMC chains are analysed using the 'coda' package of the software R.

9.3.12.6 Conclusion

For whiskery shark, the integrated base case model indicated that unacceptable stock depletion ($P<B_{Thre}$) is remote (total biomass) and unlikely (female mature biomass) for 2015-16 and for the projection period (until 2020-21).

9.4 Stock Status Summary

9.4.1 Previous Assessment

Historically, a single-area, sex- and age-structured population dynamics model fitted to CPUE and catch data, a common approach for assessing shark stocks, has been used for the assessment of gummy and whiskery shark stocks in WA (Simpfendorfer et al. 1996b, 2000b). This model has been mostly used for assessing whiskery sharks because the model fit to the gummy shark CPUE resulted in highly uncertainty parameter estimates and derived quantities (e.g. total biomass). A comparison between previous and current assessment is shown in 9.3.12.1.

9.4.2 Weight of Evidence Risk Assessment

9.4.2.1 Whiskery shark

Category	Lines of evidence (Consequence/Status)
Catch	Almost all of the reported catch of whiskery sharks in WA is taken by the TDGDLF. For these fisheries, annual catches increased from over 100 t in 1975-76 to over 500 t in 1981-82. Between the mid 1980s and early 1990s annual catches fluctuated at ~400 t. Given the rapid increase in catches between the mid 1970s and early 1990s, and sustainability concerns around the vulnerability of shark species, management measures were introduced in the early 1990s and late 2000s to reduce effort (and therefore catches). Whiskery shark catches subsequently decreased to between ~150 and 200 t since the early 1990s and have fluctuated around these levels ever since. The catch reported by the TDGDLF for 2015-16 was 143 t. In addition, recent catches have been maintained below the recommended target catch ranges (175–225 t), reflecting the outcomes of management measures to allow recovery, in particular, the introduction of the annual 'pupping' closure (two-month closure between 2006-07 and 2011-12 and a one-month closure between 2012-13 and 2013-14), which was in place during the traditional peak in whiskery catch rates. Hence, the lower catches are likely to be due to a considerable decline in targeted fishing effort. Reported catches from other commercial fisheries and the estimated recreational catches are negligible. **The reduction in the catch of whiskery shark in recent years is largely due to management actions and a reduction in targeted effort. Therefore, there is no indication of unacceptable stock depletion within the catch data for recent years**.
Catch distribution	For the TDGDLF, the spatial distribution of reported catches of whiskery shark changed over the period of the fishery's earliest development, corresponding to an expansion phase of the fisheries. However, it has remained relatively stable since the 1990s, with catches being reported throughout most of the species' range. **Catch distributions provide no indication of any marked expansion/contraction in areas fished in recent years and is not indicative of unacceptable stock depletion.**
Effort	TDGDLF fishing effort rapidly increased between 1975-76 and the late 1980s. Between the early 1990s and late 2000s management measures were introduced to reduce effort due to sustainability concerns. Specifically, effort limits (equivalent to 2001-02 levels, considered likely to deliver sustainable catches) were introduced in 2006-07. Subsequently, effort showed a substantial decline, remaining relatively constant since the mid-2000s (at ~ 25–30% of the historic effort peak) and within effort limits. The 2015-16 total TDGDLF effort was 79% (km gn d) and 65% (km gn hr) of the effort limit (88% km gn d or 59% km gn hr for Zones 1 & 3 of the JASDGDLF; 87% km gn d or 79% km gn hr for Zone 2 of the JASDGDLF; 46% km gn d or 40% km gn hr for WCDGDLF).

	Current effort is ~25–30% of the historical peak (associated with management changes) and within effort limits. It is unlikely that current effort levels are unacceptably high.
Effort distribution	For the TDGDLF, the spatial distribution of fishing effort changed over the period of the fishery's earliest development, corresponding to the expansion phase of the fisheries. However, it has remained stable and widely distributed since the 1990s. It must be noted that the Metropolitan Area (31°–33° S inshore of 250 m depth) was closed commercial to fishing in November 2007. **Effort distribution provides no indication of any marked expansion/contraction in areas fished in recent years and is therefore not indicative of unacceptable fishing levels.**
Standardised catch rates	The multispecies nature of the TDGDLF makes it uncertain if catch rates represent an index of abundance for whiskery sharks. In addition, catch and effort data available from the monthly returns (up to 2005-06) are not directly comparable to the data available in daily logbooks (post 2006-07). For monthly returns, standardised catch rates declined between the late-1970s and mid-1980s. However, this is attributable to a change in targeting behaviour, with fishers shifting from whiskery sharks to dusky sharks. Standardised catch rates were stable at lower levels between the late 1980s and 2005-06. For daily logbooks, the standardised catch rate series have fluctuated at similar levels since 2006-07. **Standardised (and nominal) catch rates provide no indication of unacceptable stock depletion.**
Size composition	For the TDGDLF catch, the observed size composition of whiskery sharks was similar across monitored zones and years. However, size composition samples have been collected opportunistically. It is unclear if these samples are representative of the entire catch size composition of the TDGDLF. Further, any depletion signal (e.g. a decline in the proportion of large individuals caught) can be masked by the size-selective nature of gillnets. **Size composition provides no clear evidence of stock depletion**.
Vulnerability	Whiskery sharks are moderately long-lived (~15 years). Females mature at ~6–7 years of age. Individuals are fully selected by gillnets (the dominant fishing method in the TDGDLF) at ~ 5 years of age. With a productivity score of 2.43 and a susceptibility score of 2.33, the derived Productivity Susceptibility Analysis (PSA) score is 3.36. **This level of vulnerability indicates a likely level of unacceptable stock depletion if there had been no effective fisheries management in place**.
Total biomass	Based on the SR analysis, relative total biomass declined between the late 1970s and early 1990s before stabilising in recent years. For 2015-16, 63%, 82% and 100% of the simulated relative total biomasses were above B_{Tar} (40% unfished biomass), B_{Thre} (30% unfished biomass) and B_{Lim} (20% unfished biomass), respectively. Projections to 2020-21 show stable trends in biomass, with 63%, 79% and 95% of the simulations being above B_{Tar}, B_{Thre} and B_{Lim}, respectively, by 2020-21. Based on the integrated model, relative total biomass declined from ~90% in the late 1970s to ~ 49% in early 2000s, before increasing to ~ 50% in 2015-16. For this year, there was an 85%, 99% and 100% probability that the relative biomass was above B_{Tar}, B_{Thre} and B_{Lim}, respectively. Projections to 2020-21 show increasing trends in biomass, with an 87%, 99% and 100% probability that the relative biomass will be above B_{Tar}, B_{Thre} and B_{Lim}, respectively, by 2020-21.

	The SR model indicates that unacceptable stock depletion ($B<B_{Thre}$) is unlikely for 2015-16 and for the projection period (until 2020-21). The integrated model indicates that unacceptable stock depletion is remote for 2015-16 and for the projection period (until 2020-21).
Female mature biomass	Based on the integrated model, relative female mature biomass declined from ~80% in the late 1970s to ~33% in the early 2000s, before increasing to 37% in 2015-16. For this year, there was a 38%, 77% and 98% probability that the relative biomass was above B_{Tar}, B_{Thre} and B_{Lim}, respectively. Projections to 2020-21 show increasing trends in female biomass, with a 47%, 82% and 98% probability that the relative biomass will be above B_{Tar}, B_{Thre} and B_{Lim}, respectively, by 2020-21. **The integrated model indicates that unacceptable stock depletion ($P<B_{Thre}$) is unlikely for 2015-16 and for the projection period (until 2020-21).**

9.4.2.1.1 Risk-based Weight of Evidence Stock Assessment

Whiskery shark risk matrix					
Consequence (stock depletion) Level	Likelihood				
	L1 Remote (<5%)	L2 Unlikely (5-20%)	L3 Possible (20-50%)	L4 Likely (≥50%)	**Max Risk Score**
C1 Minor ($B_{Current}>B_{Tar}$)				X	4
C2 Moderate ($B_{Thre}<B_{Current}<B_{Tar}$)		X			4
C3 High ($B_{Lim}<B_{Current}<B_{Thre}$)		X			6
C4 Major ($B_{Current}<B_{Lim}$)	X				4

C1 (Minor Depletion): For the current (2015-16) relative total biomass, it was **Likely** that there is a minor level of stock depletion. Future projections also indicate a **Likely** minor level of stock depletion in 2020-21. This was based on the results from the SR model and the integrated model and is a result of the extended period of lower catches and effort (as a result of management actions). The catch history, catch distribution, effort history, effort distribution and catch rate history lines of evidence support this.

C2 (Moderate Depletion): For the current (2015-16) relative total biomass, it was **Unlikely** that there is a moderate level of stock depletion. Future projections also indicate an **Unlikely** moderate level of stock depletion in 2020-21. This was based on the results from the SR model and the integrated model and is a result of the extended period of lower catches and effort (as a result of management actions). The catch history, catch distribution, effort history, effort distribution and catch rate history lines of evidence support this.

C3 (High Depletion): For the current (2015-16) relative total biomass, it was **Unlikely** that there is a high level of stock depletion. Future projections also indicate an **Unlikely** high level of stock depletion in 2020-21. This was based on the results from the SR model and the integrated model and is a result of the extended period of lower catches and effort (as a result of management actions). The catch history, catch distribution, effort history, effort distribution and catch rate history lines of evidence support this.

C4 (Major Depletion): For the current (2015-16) relative total biomass, there was a **Remote** likelihood that there is a major level of stock depletion. Future projections also indicate a **Remote** likelihood of a major level of stock depletion in 2020-21. This was based on the results from the SR model and the integrated model and is a result of the extended period of lower catches and effort (as a result of management actions). The catch history, catch distribution, effort history, effort distribution and catch rate history lines of evidence support this.

9.4.2.1.2 Future monitoring and assessment recommendations

The size-based integrated model was mostly sensitive to the assumed value of steepness (i.e. the fraction of recruitment from a virgin population obtained when the spawners are at 20% of the virgin level), affecting biomass trends from the early 1990s depending on the value used. The steepness value chosen for the base case model corresponds to the median estimates obtained by Braccini et al. (2015). Although this steepness value corresponds to the most likely value based on currently available (though limited) information, a representative age composition sample from the contemporary catches could help better define the steepness parameter by anchoring the estimate of fishing mortality and hence allowing to match the steepness values that would generate that fishing mortality estimate.

In addition, the whiskery shark assessment is relatively information-limited due to the need to estimate three catchability parameters, corresponding to the different periods of targeting behaviour and the separation of the monthly returns and daily logbooks for the standardisation of catch and effort data. Additional data (e.g. providing information on mortality for a certain period, as could be generated from new age composition data), would assist in further reducing uncertainty in the model results. While collecting the age composition data, there will be scope to collect similar information for the other indicator species, in addition to biological information for updating life history parameters.

9.4.2.2 Gummy shark

Category	Lines of evidence (Consequence/Status)
Catch	Almost all of the reported catch of gummy sharks in WA is taken by the TDGDLF, specifically Zone 2 of the Joint Authority Southern Demersal Gillnet and Demersal Longline Managed Fishery (JASDGDLF). For these fisheries, annual catches gradually increased from just over 50 t in 1975-76 to over 750 t in 2007-08. Management measures were introduced in the early 1990s and late 2000s to reduce effort (and therefore catches). The historic peak observed in 2007-08 was perceived to be due to an increase in abundance/availability as effort since the early 2000s has remained relatively constant at ~ 25–30% of the historic effort peak observed in the late 1980s. Since 2010-11, catches have been maintained within or just above the recommended target catch ranges (350–450 t). The catch reported by the TDGDLF for 2015-16 was 419 t. Reported catches from other commercial fisheries and the estimated recreational catches are negligible. **There is no indication of unacceptable stock depletion within the catch data for recent years**.
Catch distribution	For the TDGDLF, the spatial distribution of reported catches of gummy shark changed over the period of the fishery's earliest development, corresponding to an expansion phase of the fisheries. However, it has remained relatively stable since the 1990s, with catches being reported throughout most of the species' range. **Catch distributions provide no indication of any marked expansion/contraction in areas fished in recent years and is not indicative of unacceptable stock depletion.**
Effort	TDGDLF fishing effort rapidly increased between 1975-76 and the late 1980s. Between the early 1990s and late 2000s management measures were introduced to reduce effort due to sustainability concerns. Specifically, effort limits (equivalent to 2001-02 levels, considered likely to deliver sustainable catches) were introduced in 2006-07. Subsequently, effort showed a substantial decline, remaining relatively constant since the mid-2000s (at ~ 25–30% of the historic effort peak) and within effort limits. The 2015-16 total TDGDLF effort was 79% (km gn d) and 65% (km gn hr) of the effort limit (88% km gn d or 59% km gn hr for Zones 1 & 3 of the JASDGDLF; 87% km gn d or 79% km gn hr for Zone 2 of the JASDGDLF; 46% km gn d or 40% km gn hr for WCDGDLF). **Current effort is ~25–30% of the historical peak (associated with management changes) and within effort limits. It is unlikely that current effort levels are unacceptably high.**
Effort distribution	For the TDGDLF, the spatial distribution of fishing effort changed over the period of the fishery's earliest development, corresponding to the expansion phase of the fisheries. However, it has remained stable and widely distributed since the 1990s. It must be noted that the Metropolitan Area (31°–33° S inshore of 250 m depth) was closed to commercial fishing in November 2007. **Effort distribution provides no indication of any marked expansion/contraction in areas fished in recent years and is therefore not indicative of unacceptable fishing levels.**
Standardised catch rates	The multispecies nature of the TDGDLF makes it uncertain if catch rates represent an index of abundance for gummy sharks. In addition, the catch and effort data available from the monthly returns (up to 2005-06) are not directly comparable to the data available in daily logbooks (post 2006-07). For the monthly returns, standardised catch

	rates declined between the early- and late-1980s, they fluctuated until the early 2000s and then increased to historic levels until the late 2000s. This pattern was also observed in the unstandardised catch rates and, based on anecdotal information provided by fishers, it would not be due to changes in technology and/or fishing behaviour. For the daily logbooks, standardised catch rates dropped between 2007-08 and 2009-10 and have remained stable for the last 7 years. **The historic peak in catch rates in the early 2000s cannot be explained, casting doubt on the reliability of standardised (and nominal) catch rates as an index of gummy shark abundance. Hence, standardised (and nominal) catch rates provided no clear evidence of stock depletion.**
Size composition	For the TDGDLF catch, the observed size composition of gummy sharks was similar across monitored zones and years. However, size composition samples have been collected opportunistically. It is unclear if these samples are representative of the entire catch size composition of the TDGDLF. Further, any depletion signal (e.g. a decline in the proportion of large individuals caught) can be masked by the size-selective nature of gillnets. **Size composition provides no clear evidence of stock depletion**.
Vulnerability	Gummy sharks are moderately long-lived (~16 years). Females mature at ~4–6 years of age. Females and males are fully selected by gillnets (the dominant fishing method in the TDGDLF) at ~6 and 10 years of age, respectively. With a productivity score of 2.43 and a susceptibility score of 2.33, the derived PSA score is 3.36. **This level of vulnerability indicates a likely level of unacceptable stock depletion if there had been no effective fisheries management in place**.
Total biomass	Based on the SR analysis, relative total biomass fluctuated at high levels until the early 2000s before declining in recent years. For 2015-16, 78%, 92% and 100% of the simulated relative total biomasses were above B_{Tar}, B_{Thre} and B_{Lim}, respectively. Projections to 2020-21 suggest 71%, 79% and 86% of the simulated relative total biomasses will be above B_{Tar}, B_{Thre} and B_{Lim}, respectively. **The SR analysis indicates that unacceptable stock depletion ($B<B_{Thre}$) is unlikely for 2015-16 and for the projection period (until 2020-21).**

9.4.2.2.1 Risk-based Weight of Evidence Stock Assessment

Gummy shark risk matrix					
Consequence (stock depletion) Level	Likelihood				
	L1 Remote (<5%)	L2 Unlikely (5-<20%)	L3 Possible (20-<50%)	L4 Likely (≥50%)	**Risk Score**

C1 Minor ($B_{Current}>B_{Tar}$)				X	4
C2 Moderate ($B_{Thre}<B_{Current}<B_{Tar}$)		X			4
C3 High ($B_{Lim}<B_{Current}<B_{Thre}$)		X			6
C4 Major ($B_{Current}<B_{Lim}$)					NP

C1 (Minor Depletion): For the current (2015-16) relative total biomass, it was **Likely** that there is a minor level of stock depletion. Future projections also indicate a **Likely** minor level of stock depletion in 2020-21. This was based on the results from the SR model and the extended period of lower effort (as a result of management actions). The catch history, catch distribution, effort history and effort distribution lines of evidence support this.

C2 (Moderate Depletion): For the current (2015-16) relative total biomass, it was **Unlikely** that there is a moderate level of stock depletion. Future projections also indicate an **Unlikely** moderate level of stock depletion in 2020-21. This was based on the results from the SR model and the extended period of lower effort (as a result of management actions). The catch history, catch distribution, effort history and effort distribution lines of evidence support this.

C3 (High Depletion): For the current (2015-16) relative total biomass, it was **Unlikely** that there is a high level of stock depletion. Future projections also indicate an **Unlikely** high level of stock depletion in 2020-21. This was based on the results from the SR model and the extended period of lower effort (as a result of management actions). The catch history, catch distribution, effort history and effort distribution lines of evidence support this.

C4 (Major Depletion): No lines of evidence are consistent with the stock currently (2015-16) having a major level of depletion. Future projections, however, indicate an **Unlikely** level of major stock depletion in 2020-21. This was based on the results from the SR model and the extended period of lower effort (as a result of management actions). The catch history, catch distribution, effort history and effort distribution lines of evidence support this.

9.4.2.2.2 Future monitoring and assessment recommendations

The effective, nominal and standardised catch rate series of gummy sharks appear to be poor indices of stock abundance, limiting the ability to represent population dynamics for any dynamic model fit to these time series. In addition, growth and gillnet mesh selectivity parameters are not available for gummy sharks in WA so information from gummy sharks from SA and Victoria was used (Kirkwood & Walker 1986; Moulton et al. 1992). In order to conduct stock assessments based on best available information (instead of only life history and catch as done in the SR model), it is suggested that field sampling be undertaken to collect samples of catch age-composition, biological and gillnet mesh selectivity information. While collecting the age composition data, there will be scope to collect similar information for the other indicator species, in addition to biological information for updating life history parameters.

9.4.2.3 Dusky shark

Category	Lines of evidence (Consequence/Status)
Catch	Almost all of the reported catch of dusky sharks in WA is taken by the TDGDLF although up to almost 40 t were taken in the Northern Shark Fisheries (NSF) in the early 2000s (NB dusky shark, C. obscurus**,** catches include catches of bronze whaler, C. brachyurus, which cannot be accurately separated in catch returns data prior to 2006-07). For the TDGDLF, annual catches gradually increased from ~110 t in 1975-76 to over 670 t in 1988-89. Management measures were introduced in the early 1990s and late 2000s to reduce effort, allow recovery and mitigate cryptic mortality of older individuals (Statewide protection of whaler sharks with an interdorsal fin length> 70 cm). Dusky shark catches subsequently decreased, and have fluctuated at ~ 200 t since the late 2000s remaining within the recommended target catch ranges (200–300 t). The catch reported by the TDGDLF for 2015-16 was 220 t. Reported catches from other commercial fisheries and the estimated recreational catches are negligible. **There is some indication of unacceptable stock depletion within the catch data prior to management actions in 2006-07**. **Subsequent catch data show no indication of unacceptable depletion, noting that recovery is estimated to be in the order of decades.**
Catch distribution	For the TDGDLF, the spatial distribution of reported catches of dusky shark changed over the period of the fishery's earliest development, corresponding to an expansion phase of the fisheries. However, it has remained relatively stable since the early 2000s, with catches being reported throughout most of the species' range. **Catch distributions provide no indication of any marked expansion/contraction in areas fished in recent years and is not indicative of unacceptable stock depletion.**
Effort	TDGDLF fishing effort rapidly increased between 1975-76 and the late 1980s. Between the early 1990s and late 2000s management measures were introduced to reduce effort due to sustainability concerns. Specifically, effort limits (equivalent to 2001-02 levels, considered likely to deliver sustainable catches) were introduced in 2006-07. Subsequently, effort showed a substantial decline, remaining relatively constant since the mid-2000s (at ~ 25–30% of the historic effort peak) and within effort limits. The 2015-16 total TDGDLF effort was 79% (km gn d) and 65% (km gn hr) of the effort limit (88% km gn d or 59% km gn hr for Zones 1 & 3 of the JASDGDLF; 87% km gn d or 79% km gn hr for Zone 2 of the JASDGDLF; 46% km gn d or 40% km gn hr for WCDGDLF). **Current effort is ~25–30% of the historical peak (associated with management changes) and within effort limits. It is unlikely that current effort levels are unacceptably high.**
Effort distribution	For the TDGDLF, the spatial distribution of fishing effort changed over the period of the fishery's earliest development, corresponding to the expanding phase of the fisheries. However, it has remained stable and widely distributed since the 1990s. It must be noted that the Metropolitan Area (31°–33° S inshore of 250 m depth) was closed to commercial fishing in November 2007. **Effort distribution provides no indication of any marked expansion/contraction in areas fished in recent years and is therefore not indicative of unacceptable fishing levels.**
Standardised catch rates	The multispecies nature of the TDGDLF makes it uncertain if catch rates represent an index of abundance for dusky sharks. In addition, the catch and effort data available

	from the monthly returns (up to 2005-06) are not directly comparable to the data available in daily logbooks (post 2006-07). For monthly returns, standardised catch rates declined during the 1980s and fluctuated at similar levels between the late 1980s and late 1990s before stabilising from ~2000 onwards. For daily logbooks, the standardised catch rate series have been relatively stable. **Standardised (and nominal) catch rates provide some indication of unacceptable stock depletion early in the history of the fisheries.**
Size composition	For the TDGDLF and NSF catches, the observed size compositions of dusky sharks were similar across monitored zones and years. However, size composition samples have been collected opportunistically. It is unclear if these samples are representative of the entire catch size composition of these fisheries. Further, any depletion signal (e.g. a decline in the proportion of large individuals caught) from the TDGDLF data can be masked by the size-selective nature of gillnets. **Size composition provides no clear evidence of stock depletion**.
Vulnerability	Dusky sharks are long-lived (up to 55 years). Females mature at ~26–35 years of age. Individuals are fully selected by gillnet fishing (the dominant fishing method in the TDGDLF) at around 0–3 years with relative selectivity rapidly decreasing with age and by ~6 years of age it is negligible. With a productivity score of 3.00 and a susceptibility score of 3.00, the derived PSA score is 4.24. **This level of vulnerability indicates a likely level of unacceptable stock depletion if there had been no effective fisheries management in place**.
Total biomass	Based on the SR analysis, relative total biomass fluctuated at high levels in the late 1970s and early 1980s before gradually declining. Despite total catches dropping to ~30% the historic peak since the late 2000s, these lower catch levels still equate to fishing mortality levels slightly above/similar to the average population rate of increase due to the very low productivity of dusky sharks (see distribution of intrinsic rate of population increase). For 2015-16, 51%, 76% and 100% of the simulated relative total biomasses were above B_{Tar}, B_{Thre} and B_{Lim}, respectively. Projections to 2020-21 suggest 50%, 71% and 92% of the simulated relative total biomasses will be above B_{Tar}, B_{Thre} and B_{Lim}, respectively. **The SR analysis indicates that unacceptable stock depletion ($B<B_{Thre}$) is possible for 2015-16 and for the projection period (until 2020-21).**

9.4.2.3.1 Risk-based Weight of Evidence Stock Assessment

Dusky shark risk matrix					
Consequence (stock depletion) Level	Likelihood				
	L1 Remote (<5%)	L2 Unlikely (5-<20%)	L3 Possible (20-<50%)	L4 Likely (≥50%)	**Risk Score**

C1 Minor ($B_{Current}$>B_{Tar})		X			2
C2 Moderate (B_{Thre}<$B_{Current}$<B_{Tar})			X		6
C3 High (B_{Lim}<$B_{Current}$<B_{Thre})		X			6
C4 Major ($B_{Current}$<B_{Lim})	X				4

C1 (Minor Depletion): For the current (2015-16) relative total biomass, it was **Unlikely** that there is a minor level of stock depletion. Future projections also indicate an **Unlikely** minor level of stock depletion in 2020-21. While the SR model suggested a possible minor level of stock depletion, the catch history and standardised catch rates indicated some level of unacceptable depletion.

C2 (Moderate Depletion): For the current (2015-16) relative total biomass, it was **Possible** that there is a moderate level of stock depletion. Future projections also indicate a **Possible** moderate level of stock depletion in 2020-21. This was based on the results from the SR model and the extended period of lower effort and catches since the mid 2000s (as a result of management actions).

C3 (High Depletion): For the current (2015-16) relative total biomass, it was **Unlikely** that there is a high level of stock depletion. Future projections also indicate an **Unlikely** high level of stock depletion in 2020-21. Based on the SR model, there was a Possible (27% and 24% for 2015-16 and 2020-21, respectively) high level of stock depletion. However, the SR analysis assumes that catch is a proxy of stock abundance so any decline in catches is interpreted as a decline in stock abundance and not a response to management or market fluctuations. Management measures were introduced in the early 1990s and late 2000s to reduce effort and mitigate cryptic mortality of older individuals. Since the late 2000s, dusky shark catches have subsequently decreased to ~30% the historic peak whereas the standardised catch rates have been fluctuating but stable since the late 1980s. In addition, fishing effort also declined, remaining relatively constant since the mid 2000s at ~ 25–30% of the historic effort peak and within effort limits.

C4 (Major Depletion): For the current (2015-16) relative total biomass, there was a **Remote** likelihood of a major level of stock depletion. Future projections also indicate a **Remote** likelihood of a major level of stock depletion in 2020-21. Based on the SR model, there was a **Remote** likelihood of major level of stock depletion for 2015-16 but a **Possible** major level of stock depletion for 2020-21. However, the SR analysis assumes that catch is a proxy of stock abundance so any decline in catches is interpreted as a decline in stock abundance and not a response to management or market fluctuations. Management measures were introduced in the early 1990s and late 2000s to reduce effort and mitigate cryptic mortality of older individuals. Since the late 2000s, dusky shark catches have subsequently decreased to ~30% the historic peak whereas the standardised catch rates have been fluctuating but stable since the late 1980s. In addition, fishing effort also declined, remaining relatively constant since the mid 2000s at ~ 25–30% of the historic effort peak and within effort limits.

9.4.2.3.2 Future monitoring and assessment recommendations

The current quantitative assessment of the dusky shark stock is based on demographic and stock reduction modelling. The SR model uses a surplus production model and assumes that catch trajectories indicate stock biomass trajectories. The use of a surplus production model may not be appropriate for a long-lived species, such as dusky sharks, which is captured in a highly size-selective fishery, where nets select mostly neonates and young juveniles, and large juveniles and adults are mostly not selected. Also, the assumption that catch is a proxy for abundance ignores the range of management measures introduced to reduced fishing mortality. In addition to standardised catch rates, there is fishery-independent abundance information for large dusky sharks (large juveniles and adults) from longline surveys undertaken in north-western WA since the early 2000s. This information could be used in future stock assessments. Particularly for a long-lived species such as dusky sharks, an age catch composition sample could be informative for future assessments to better define fishing mortality. Future assessments could consider these additional sources of information in order to develop an integrated model and be able to corroborate the population trends derived from the SR model.

9.4.2.4 Sandbar shark

Category	Lines of evidence (Consequence/Status)
Catch	Significant catches of sandbar shark were reported from the NSF. Catches in these fisheries increased rapidly from negligible levels in the 1980s and early 1990s to more than 750 t in 2004-05. Catches then rapidly declined (as a result of management intervention) and no catches have been reported since 2008-09. Almost all reported catches of sandbar sharks in WA is now taken by the TDGDLF, specifically the West Coast Demersal Gillnet and Demersal Longline (Interim) Fishery (WCDGDLF). For these fisheries, annual catches fluctuated between ~100 t and more than 200 t between 1989-90 and 2009-10. Management measures were introduced in the early 1990s and late 2000s to reduce effort and allow recovery. Sandbar shark catches subsequently decreased, fluctuating at ~40 t since 2011-12 and remaining below the recommended target catch limit (<120 t). The catch reported by the TDGDLF for 2015-16 was 41 t. Reported catches from other commercial fisheries and the estimated recreational catches are negligible. **There were strong indications of unacceptable catch levels in the early- to mid-2000s as a result of the NSF. Since the late 2000s, however, total catches have been maintained at less than 10% the history peak. Hence, current catch trajectories provide no evidence of unacceptable stock depletion in recent years.**
Catch distribution	For the TDGDLF, the spatial distribution of reported catches of sandbar shark changed over the period of the fishery's earliest development, corresponding to an expansion phase of the fisheries. However, it has remained relatively stable since the late 1980s, with catches reported throughout most of the species' range. **Catch distributions provide no indication of any marked expansion/contraction in areas fished in recent years and is not indicative of unacceptable stock depletion.**
Effort	TDGDLF fishing effort rapidly increased between 1975-76 and the late 1980s. Between the early 1990s and late 2000s management measures were introduced to reduce effort due to sustainability concerns. Specifically, effort limits (equivalent to 2001-02 levels, considered likely to deliver sustainable catches) were introduced in 2006-07. Subsequently, effort showed a substantial decline, remaining relatively constant since the mid-2000s (at ~ 25–30% of the historic effort peak) and within effort limits. The 2015-16 total TDGDLF effort was 79% (km gn d) and 65% (km gn hr) of the effort limit (88% km gn d or 59% km gn hr for Zones 1 & 3 of the JASDGDLF; 87% km gn d or 79% km gn hr for Zone 2 of the JASDGDLF; 46% km gn d or 40% km gn hr for WCDGDLF). In addition, the NSF have not operated since 2008-09. **Current effort is ~25–30% of the historical peak (associated with management changes) and within effort limits. It is unlikely that current effort levels are unacceptably high.**
Effort distribution	For the TDGDLF, the spatial distribution of fishing effort changed over the period of the fishery's earliest development, corresponding to the expansion phase of the fisheries. However, it has remained stable and widely distributed since the 1990s. It must be noted that the Metropolitan Area (31°–33° S inshore of 250 m depth) was closed to commercial fishing in November 2007. **Effort distribution provides no indication of any marked expansion/contraction in areas fished in recent years and is therefore not indicative of unacceptable fishing levels.**

Standardised catch rates	The multispecies nature of the TDGDLF makes it uncertain if catch rates represent an index of abundance for sandbar sharks. In addition, catch and effort data available from the monthly returns (up to 2005-06) are not directly comparable to the data available in daily logbooks (post 2006-07). For monthly returns, standardised catch rates increased during the 1990s and declined during the early- and mid-2000s. For daily logbooks, standardised catch rates show substantial uncertainty. **Standardised (and nominal) catch rates provide no clear evidence of stock depletion.**
Size composition	For the TDGDLF and NSF catches, the observed size compositions of sandbar sharks were similar across monitored zones and years. However, size composition samples have been collected opportunistically. It is unclear if these samples are representative of the entire catch size composition of these fisheries. Further, any depletion signal (e.g. a decline in the proportion of large individuals caught) from the TDGDLF data can be masked by the size-selective nature of gillnets. **Size composition provides no clear evidence of stock depletion**.
Vulnerability	Sandbar sharks are long-lived (up to 39 years). Females mature at ~13–19 years of age. Individuals are fully selected by gillnet fishing (the dominant fishing method in the TDGDLF) at ~ 6 years of age with relative selectivity gradually decreasing with age and by ~30 years of age it is negligible. With a productivity score of 2.71 and a susceptibility score of 3.00, the derived PSA score is 4.05. **This level of vulnerability indicates a likely level of unacceptable stock depletion if there had been no effective fisheries management in place**.
Total biomass	Based on the SR analysis, relative total biomass declined fluctuated at high levels up to the early 1990s; it then declined through the 1990s and early 2000s before stabilising. For 2015-16, 63%, 83% and 99% of the simulated relative total biomasses were above B_{Tar}, B_{Thre} and B_{Lim}, respectively. Projections to 2020-21 show an increasing trend in biomass with 67%, 84% and 98% of the simulations being above B_{Tar}, B_{Thre} and B_{Lim}, respectively. **The SR analysis indicates that unacceptable stock depletion ($B<B_{Thre}$) is unlikely for 2015-16 and for the projection period (until 2020-21).**

9.4.2.4.1 Risk-based Weight of Evidence Stock Assessment

Sandbar shark risk matrix					
Consequence (stock depletion) Level	Likelihood				
	L1 Remote (<5%)	L2 Unlikely (5-<20%)	L3 Possible (20-<50%)	L4 Likely (≥50%)	**Risk Score**

C1 Minor ($B_{Current}>B_{Tar}$)			X		3
C2 Moderate ($B_{Thre}<B_{Current}<B_{Tar}$)			X		6
C3 High ($B_{Lim}<B_{Current}<B_{Thre}$)		X			6
C4 Major ($B_{Current}<B_{Lim}$)	X				4

C1 (Minor Depletion): For the current (2015-16) relative total biomass, it was **Possible** that there is a minor level of stock depletion. Future projections also indicate a **Possible** minor level of stock depletion in 2020-21. Based on the SR model, there was a **Likely** (62% and 66% for 2015-16 and 2020-21, respectively) minor level of stock depletion. This was supported by the catch distribution, the effort time series and effort distribution. However, the catch history indicated unacceptable depletion during the early- to mid-2000s (mainly a result of catches in the NSF, which have now been controlled); making it less likely that current biomass is above target levels.

C2 (Moderate Depletion): For the current (2015-16) relative total biomass, it was **Possible** that there is a moderate level of stock depletion. Future projections indicate an **Unlikely** moderate level of stock depletion in 2020-21. This was based on the results from the SR model and the extended period of lower effort (as a result of management actions).

C3 (High Depletion): For the current (2015-16) relative total biomass, it was **Unlikely** that there is a high level of stock depletion. Future projections also indicate an **Unlikely** high level of stock depletion in 2020-21. This was based on the results from the SR model and the extended period of lower effort (as a result of management actions).

C4 (Major Depletion): For the current (2015-16) relative total biomass, there was a **Remote** likelihood of a major level of stock depletion. Future projections also indicate a **Remote** likelihood of major level of stock depletion in 2020-21. This was based on the results from the SR model and the extended period of lower effort (as a result of management actions).

9.4.2.4.2 Future monitoring and assessment recommendations

The current quantitative assessment of the sandbar shark stock is based on demographic and stock reduction modelling. Similar to the dusky shark model, this method may also not be appropriate for sandbar sharks, which are long-lived and are captured in a highly size-selective fishery, where nets select mostly juveniles. In addition to standardised catch rates, there is fishery-independent abundance information for large sandbar sharks (large juveniles and adults) from longline surveys undertaken in north-western WA since the early 2000s. This information could be used in future stock assessments. Particularly for a long-lived species such as sandbar sharks, an age catch composition sample could be informative for future assessments to better define fishing mortality. Future assessments could consider these additional sources of information in order to develop an integrated model and be able to corroborate the population trends derived from the SR model.

9.4.3 Conclusion / Advice

For the whiskery shark stock, the current risk level is estimated to be Medium (C3 × L2) (see Appendix 3. Consequence, Likelihood and Risk Levels (based on AS 4360 / ISO 31000) modified from Fletcher et al. (2011) and Fletcher (2015)). Hence, the current stock status is acceptable and current risk control measures in place are adequate (i.e. no new management required). Forward projections indicate an increasing trend in biomass under current management settings.

For the gummy shark stock, the current risk level is estimated to be Medium (C3 × L2). Hence, the current stock status is acceptable and the current management settings are adequate.

For the dusky shark stock, the current risk level is estimated to be Medium (C3 × L2). Hence, the current stock status is acceptable and the current management settings are adequate.

For the sandbar shark stock, the current risk level is estimated to be Medium (C3 × L2). Hence, the current stock status is acceptable and the current management settings are adequate.

9.5 Research and Monitoring Implications

Finalisation of the harvest strategy that considers and defines RPs and control rules for managing the resource (which also considers economic and social objectives) is required and will likely be part of the transiting of the JA fisheries to WA.

There is currently a single reference point for assessing any shark species (i.e. 40% unfished biomass) which is not explicitly defined as a target, threshold or limit in the current management settings. Noting that shark species with different biological characteristics may require different reference points (Braccini et al. 2015), species-specific target, threshold and limit reference points may need to be defined. In addition, unlike other resources for which the reference points relate to the spawning biomass (equivalent to the female mature biomass for sharks), the current reference point in the TDGDLF relates to total biomass. This also needs to be reviewed.

Additional data (e.g. providing information on mortality for a certain period, as could be generated from representative age composition data), would assist in reducing model uncertainties. While collecting the age composition data, there will be scope to collect additional biological and fisheries information.

Finally, an investigation of an index of abundance on large juvenile and adult dusky and sandbar sharks based on existing fishery-independent longline survey data will be undertaken for the next stock assessment. For future assessments, an integrated model should be developed.

Next assessment is proposed for 2022 to allow for data collection, processing and analyses. Following the next round of assessment, the RAR will be updated and expanded to include Statewide shark resources.

10. References

Barnett A, Abrantes G, Stevens JD, Bruce BD, Semmens JM. 2010. Fine-scale movements of the broadnose sevengill shark and Its main prey, the gummy shark. PloS one 5.

Borg J, McAuley R. 2004. Future management arrangements for West Australia's temperate shark fisheries. Fisheries Management Paper. Department of Fisheries, Western Australia.

Braccini M, McAuley R, Rowland F. 2013. Temperate demersal gillnet and demersal longline fisheries status report. Pages 271–284in W. J. Fletcher and K. Santoro, editors. Status reports of the fisheries and aquatic resources of Western Australia 2012/13: The State of Fisheries. Department of Fisheries, Western Australia.

Braccini M, Brooks EN, Wise B, McAuley R. 2015. Displaying uncertainty in the biological reference points of sharks. Ocean & Coastal Management 116:143–149.

Braccini M, McAuley R, Harry A. 2017a. Spatial and temporal dynamics of Western Australia's commercially important sharks. Report No. 282 Department of Fisheries, Western Australia, Perth.

Braccini M, Rensing K, Langlois T, McAuley R. 2017b. Acoustic monitoring reveals the broad-scale movements of commercially-important sharks. Marine Ecology Progress Series 577:121–129.

Braccini M, de Lestang S, McAuley R. 2018. Dusky sharks (*Carcharhinus obscurus*) undertake large-scale migrations between tropical and temperate ecosystems. Canadian Journal of Fisheries and Aquatic Sciences. doi/10.1139/cjfas-2017-0313.

Brooks EN, Powers JE, Cortes E. 2010. Analytical reference points for age-structured models: application to data-poor fisheries. ICES Journal of Marine Science 67:165–175.

Caddy JF, Mahon R. 1995. Reference points for fisheries management. FAO Fisheries Technical Paper. No. 347. Rome, FAO.

Campbell R. 2011. Assessing and managing interactions of protected and listed marine species with commercial fisheries in Western Australia. Fisheries Research Report No. 223, Department of Fisheries, Western Australia.

Chidlow J, Gaughan D, McAuley R. 2006. Identification of Western Australian Grey Nurse Shark aggregation sites. Perth. Fisheries Research Report No. 155, Department of Fisheries, Western Australia.

DoF. 2011. Resources assessment framework (RAF) for finfish resources in Western Australia. Fisheries Occasional Publication No. 85. Department of Fisheries, Perth, Western Australia.

DoF. 2012. Application to the Department of Sustainability, Environment, Water, Population and Communities on the Western Australia's Temperate Demersal Gillnet and Demersal Longline Fisheries.

DoF. 2015. Harvest strategy policy and operational guidelines for the aquatic resources of Western Australia. Fisheries Management Paper No 271, Department of Fisheries, Perth.

Donohue KJ, Hall N, Simpfendorfer C, Lenanton R. 1993. Fisheries status and stock assessment for the Southern Demersal Gillnet and Demersal Longline Fishery, October 1993.

Evans R, Molony BW. 2010. Ranked Risk Assessment for Bycatch in Multiple Fisheries : a

Bioregional Risk Assessment Method. Fisheries Research Report No 212. Department of Fisheries, Western Australia.

Evans R, Molony B. 2011. Pilot evaluation of the efficacy of electronic monitoring on a demersal gillnet vessel as an alternative to human observers. Fisheries Research Report No 221. Department of Fisheries, Western Australia.

Fairclough D, Lai E, Holts M, Nicholas T, Jones R. 2013. West Coast Demersal Scalefish Resource Report. In: Status Reports of the Fisheries and Aquatic Resources of Western Australia 2012/13: The State of the Fisheries eds. W.J. Fletcher and K. Santoro, Department of Fisheries, Western Australia, pp. 91-101.

Fletcher WJ. 2002. Policy for the implementation of ecologically sustainable development for fisheries and aquaculture within Western Australia. Fisheries Management Paper No 157, Department of Fisheries, Perth.

Fletcher WJ, Shaw J, Metcalf SJ, Gaughan DJ. 2010. An ecosystem based fisheries management framework: the efficient, regional-level planning tool for management agencies. Marine Policy 34:1226–1238.

Fletcher WJ, Santoro K. 2012. Status report of the fisheries and aquatic resources of Western Australia 2011/2012: The State of the Fisheries. Department of Fisheries, Western Australia.

Fletcher WRJ. 2015. Review and refinement of an existing qualitative risk assessment method for application within an ecosystem-based management framework. ICES Journal of Marine Science 72:1043–1056.

Fletcher WJ et al. 2016. Refinements to harvest strategies to enable effective implementation of Ecosystem Based Fisheries Management for the multi-sector, multi-species fisheries of Western Australia. Fisheries Research 183: 594-608.

Flood M et al. 2012. Status of key Australian fish stocks reports 2012, Fisheries Research and Development Corporation, Canberra.

Fournier DA, Skaug HJ, Ancheta J, Ianelli J, Magnusson A, Maunder MN, Nielsen A, Sibert J. 2012. AD Model Builder: using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. Optimization Methods and Software 27:233–249.

Francis R. 2011. Data weighting in statistical fisheries stock assessment models. Canadian Journal of Fisheries and Aquatic Sciences 1138:1124–1138.

Fuentes MMPB, Chambers L, Chin A, Dann P, Dobbs K, Marsh H, Poloczanska ES, Maison K, Turner M, Pressey RL. 2016. Adaptive management of marine mega-fauna in a changing climate. Mitigation and Adaptation Strategies for Global Change, 21: 209–224.

Gaughan DJ, Santoro K. 2018. Status reports of the fisheries and aquatic resources of Western Australia 2016/2017: the state of the fisheries. Department of Primary Industries and Regional Development, Western Australia.

Geraghty PT, Williamson JE, Macbeth WG, Blower DC, Morgan JAT, Johnson G, Ovenden JR and Gillings MR. 2014. Genetic structure and diversity of two highly vulnerable carcharhinids in Australian waters. Endangered Species Research 24: 45–60.

Hancock DA, Edmonds JS, Edinger, J. 1977. Mercury in shark in Western Australia. A preliminary report. Fishery Research Bulletin no. 18. Department of Fisheries and Wildlife. Perth, Western Australia. 22 pp.

Heald DI. 1987. The commercial shark fishery in temperate waters of Western Australia. Western Australian Marine Research Laboratories, Fisheries Department.

Hesp SA, Tweedley JR, McAuley R, Tink CJ, Campbell RA, Chuwen BM, Hall NG. 2012. Informing risk assessment through estimating interaction rates between Australian sea lions and Western Australia's temperate demersal gillnet fisheries. Fisheries Research and Development Corporation Project No. 2009/096.

Hoenig JM. 1983. Empirical use of longevity data to estimate mortality rates. Fisheries Bulletin 82:898–903.

Hobday AJ, Smith ADM, Stobutzki IC, Bulman C, Daley R, Dambacher JM, Deng RA, *et al.* 2011. Ecological risk assessment for the effects of fishing. Fisheries Research 108: 372–384.

Kirkwood GP, Walker TI. 1986. Gill net mesh selectivities for Gummy Shark, *Mustelus antarcticus* Gunther, Taken in south-eastern Australian waters. Marine and Freshwater Research 37:689–697.

Last PR, Stevens JD. 2009. Sharks and Rays of Australia (Second Edition). CSIRO Publishing, Collingwood, Victoria.

Lenanton RCJ, Heald DI, Platell M, Cliff M, Shaw J. 1990. Aspects of the reproductive biology of the gummy shark, *Mustelus antarcticus* Gunther, from waters off the south coast of Western Australia. Australian Journal of Marine and Freshwater Research 41:807–822.

Mace PM. 1994. Relationships between common biological reference points used as thresholds and targets of fisheries management strategies. Canadian Journal of Fisheries and Aquatic Sciences 51:110–122.

Martell S, Froese R. 2013. A simple method for estimating MSY from catch and resilience. Fish Fish 14:504–514.

McAllister MK, Pikitch EK, Babcock EA. 2001. Using demographic methods to construct Bayesian priors for the intrinsic rate of increase in the Schaefer model and implications for stock rebuilding. Canadian Journal of Fisheries and Aquatic Sciences 58:1871–1890.

McAuley R, Bruce B, Keay I, Mountford S, Pinnell T. 2016. Evaluation of passive acoustic telemetry approaches for monitoring and mitigating shark hazards off the coast of Western Australia. Fisheries Research Report No. 273, Department of Fisheries, Western Australia.

McAuley RB. 2007. Demersal gillnet and demersal longline fisheries status report. Sate of the Fisheries Report 2006/07. Department of Fisheries, Perth, Western Australia.

McAuley RB, Simpfendorfer CA, Hyndes GA, Allison RR, Chidlow JA, Newman SJ, Lenanton RCJ. 2006. Validated age and growth of the sandbar shark, *Carcharhinus plumbeus* (Nardo 1827) in the waters off Western Australia. Environmental Biology of Fishes 77:385–400.

McAuley R, Simpfendorfer C, Hall N. 2007a. A method for evaluating the impacts of fishing mortality and stochastic influences on the demography of two long-lived shark stocks. ICES Journal of Marine Science 64:1710–1722.

McAuley R, Simpfendorfer C, Wright I. 2007b. Gillnet mesh selectivity of the sandbar shark (*Carcharhinus plumbeus*): implications for fisheries management. ICES Journal of Marine Science 64:1702–1709.

McAuley RB, Simpfendorfer CA, Hyndes GA, Lenanton RCJ. 2007c. Distribution and reproductive biology of the sandbar shark, *Carcharhinus plumbeus* (Nardo), in Western Australian waters. Marine and Freshwater Research 58:116–126.

McAuley R. 2005. Status report for the southern and west coast demersal gillnet and demersal longline fisheries and northern shark fisheries. Fisheries status report. Department of Fisheries.

McAuley R, Lenanton R, Chidlow J, Allison R, Heist E. 2005. Biology and stock assessment of the thickskin (sandbar) shark, *Carcharhinus plumbeus*, in Western Australia and further refinement of the dusky shark, *Carcharhinus obscurus*, stock assessment. Fisheries research report 151, Western Australian Department of Fisheries, Perth.

McAuley R, Simpfendorfer C. 2003. Catch composition of the Western Australian temperate demersal gillnet and demersal longline fisheries, 1994 to 1999. Fisheries research report 146, Western Australian Department of Fisheries, Perth.

Merson RR, Pratt Jr HL. 2001. Distribution, movements and growth of young sandbar sharks, *Carcharhinus plumbeus*, in the nursery grounds of Delaware Bay. Environmental Biology of Fishes 61: 13–24.

Molony BW, Newman SJ, Joll L, Lenanton RCJ, Wise B. 2011 Are Western Australian waters the least productive waters for finfish across two oceans? A review with a focus on finfish resources in the Kimberley region and North Coast Bioregion. Journal of the Royal Society of Western Australia 94: 323–332.

Molony B, McAuley RB, Rowland F. 2013. Northern shark fisheries status report: statistics only. In W. J. Fletcher and K. Santoro, editors. Status reports of the fisheries and aquatic resources of Western Australia 2012/13: the state of the fisheries. Department of Fisheries, Perth, Western Australia, Perth, W.A.

Moulton PL, Walker TI, Saddlier SR. 1992. Age and growth studies of Gummy Shark, *Mustelus antarcticus* Gunther, and School Shark, *Galeorhinus galeus* (Linnaeus), from Southern Australian Waters. Marine and Freshwater Research 43:1241–1267.

MSC 2014. Guidance to the MSC Certification Requirements v1.4. Marine Stewardship Council. London.

Newman SJ and 12 co-authors. 2018. A risk assessment and prioritisation approach to the selection of indicator species for the assessment of multi-species, multi-gear, multi-sector fishery resources. Marine Policy 88:11–22.

Ovenden J, Kashiwagi T, Broderick D, Giles J, Salini J. 2009. The extent of population genetic subdivision differs among four co-distributed shark species in the Indo-Australian archipelago. BMC Evolutionary Biology 9, 40.

Portnoy DS, McDowell JR, Heist EJ, Musick JA and Graves JE. 2010. World phylogeography and male-mediated gene flow in the sandbar shark, *Carcharhinus plumbeus*. Molecular Ecology 19: 1994–2010.

Prince J. 2005. Gauntlet fisheries for elasmobranchs–the secret of sustainable shark fisheries. Journal of Northwest Atlantic Fishery Science 35:407–416.

Prince J. 2011. Developing a robust new empirically based harvest strategy for gummy shark. FRDC Project 2009/066. Biospherics. 69pp.

Roberts C, McClean C, Veron J, Hawkins J, Allen G, McAllister D, Werner T. 2002. Marine biodiversity hotspots and conservation priorities for tropical reefs. Science 295:1280–1284.

Rogers P, Huveneers C, Goldsworthy SD, Mitchell JG and Seuront L. 2013. Broad-scale movements and pelagic habitat of the dusky shark *Carcharhinus obscurus* off Southern Australia determined using pop-up satellite archival tags. Fisheries and Oceanography 22: 102–112.

Ryan KL, Wise BS, Hall NG, Ollock EH, Sulin EH, Gaughan DJ. 2013. An integrated system to survey boat-based recreational fishing in Western Australia 2011-12. Fisheries Research Report No. 249, Department of Primary Industries and Regional Development, Western Australia.

Ryan KL, Hall NG, Lai EK, Smallwood CB, Taylor SM, Wise BS 2015. Statewide survey of boat-based recreational fishing in Western Australia 2013-14. Fisheries Research Report No. 287, Department of Primary Industries and Regional Development, Western Australia.

Ryan KL, Hall NG, Lai EK, Smallwood CB, Taylor SM, Wise BS 2017. Statewide survey of boat-based recreational fishing in Western Australia 2015/16. Fisheries Research Report No. 287, Department of Primary Industries and Regional Development, Western Australia.

Sadovy Y, Punt A, Cheung W, Vasconcellos M, Suharti S, Mapstone B. 2007. Stock assessment approach for the Napoleon fish, *Cheilinus undulatus*, in Indonesia. A tool for quota setting for data-poor fisheries under CITES Appendix II Non-Detriment Finding requirements. FAO Fisheries Circular 1023, Rome.

Salini J, McAuley R, Blaber S, Buckworth R, Chidlow J, Gribble N, Ovenden J, Peverell S, Pillans R, Stevens J, Stobutzki I, Tarca C, Walker T. 2007. Northern Australian sharks and rays: the sustainability of target and bycatch species, phase 2. FRDC Project No. 2002/064. Fisheries Research and Development Corporation and CSIRO Marine and Atmospheric Research 2006

Schnute JT, Haigh R. 2007. Compositional analysis of catch curve data, with an application to Sebastes maliger. ICES Journal of Marine Science 64:218–233.

Simpfendorfer CA, Lenanton RCJ, Unsworth P. 1996a. Stock assessment of large coastal and demersal sharks. Final Report to the Fisheries Research and Development Corporation for Project 93/067.

Simpfendorfer C, Lenanton R, Unsworth P. 1996b. Stock Assessment of large coastal and demersal sharks. Final report for FRDC Project 93/067. Fisheries Department of Western Australia and The Fisheries Research and Development Corporation.

Simpfendorfer C, Donohue KJ. 1998. Keeping the fish in "fish and chips': research and management of the Western Australian shark fishery. Marine and Freshwater Research 49:593–600.

Simpfendorfer CA, Unsworth P. 1998a. Gill-net mesh selectivity of dusky sharks (*Carcharhinus obscurus*) and whiskery sharks (*Furgaleus macki*) from south-western Australia. Marine and Freshwater Research 49:713–718.

Simpfendorfer CA, Unsworth P. 1998b. Reproductive biology of the whiskery shark, *Furgaleus macki*, off south-western Australia. Marine and Freshwater Research 49:687–693.

Simpfendorfer C. 1999. Management of shark fisheries in Western Australia. In R. Shotton, editor. Case studies of the management of elasmobranch fisheries 378/1. FAO, Rome.

Simpfendorfer CA, McAuley R, Chidlow JA, Lenanton R, Hall N, Bastow T. 1999. Biology and stock assessment of Western Australia's commercially important shark species. Project 96/130 Fisheries Research and Development Corporation.

Simpfendorfer C, Chidlow J. 2000. Age and growth of the whiskery shark, *Furgaleus macki*, from southwestern Australia. Environmental Biology of Fishes:335–343.

Simpfendorfer CA, Childlow J, McAuley RB, Unsworth P. 2000a. Age and growth of the whiskery shark, *Furgaleus macki*, from southwestern Australia. Environmental Biology of Fishes 58:335–343.

Simpfendorfer C, Donohue K, Hall N. 2000b. Stock assessment and risk analysis for the whiskery shark (*Furgaleus macki* (Whitey)) in south-western Australia. Fisheries Research 47:1–18.

Simpfendorfer CA, Goodreid A, McAuley RB. 2001. Diet of three commercially important shark species from Western Australian waters. Marine and Freshwater Research 52:975–985.

Simpfendorfer CA, McAuley RB, Chidlow JA, Unsworth P. 2002. Validated Age and Growth of the Dusky Shark, *Carcharhinus obscurus*, from Western Australian Waters. Marine and Freshwater Research 53:567–573.

Stevens JD, West GJ. 1997. Investigation of school and gummy shark nursery areas in southeastern Australia (p. 76). CSIRO Marine Research.

Stevens J. 1999. Management of shark fisheries in Northern Australia. In R. Shotton, editor. Case studies of the management of elasmobranch fisheries 378/1. FAO, Rome.

Sumner, NR, Williamson, PC. 1999. A 12-month survey of coastal recreational boat fishing between Augusta and Kalbarri on the west coast of Western Australia during 1996-97. Fisheries Research Report No. 117, Department of Fisheries, Western Australia.

Sumner, NR, Williamson, PC, Blight, SJ, Gaughan, DJ. 2008. A 12-month survey of recreational boat-based fishing between Augusta and Kalbarri on the West Coast of Western Australia during 2005-06. Fisheries Research Report No. 177, Department of

Fisheries, Western Australia.

Walker T, Brown L, Taylor B. 2000. Southern shark tag database project. Marine and Freshwater Resources Institute, Queenscliff, Victoria.

Walker, TI, Brown L, Clement JG. 2001. Age validation from tagged school and gummy sharks injected with oxytetracycline. FRDC Project No. 97/110, Final Report to Fisheries Research and Development Corporation. Marine and Freshwater Resources Institute: Queenscliff, Victoria, Australia.

Walker TI. 2007. Spatial and temporal variation in the reproductive biology of gummy shark *Mustelus antarcticus* (Chondrichthyes: Triakidae) harvested off southern Australia. Marine and Freshwater Research 58:67–97.

Western Australian Food Monitoring Program. 1993. Mercury in sharks. Department of Minerals and Energy of Western Australia and Health Department of Western Australia

Whitley GP. 1943. Preliminary report on the long line fishery at Bunbury, W.A. Unpublished report, 9 pp (available from Western Australian Marine Research Laboratories: North Beach.).

11. Appendix 1. Justification for Harvest Strategy Reference Levels

Currently, there is a single biological Reference Point (RP) for whiskery, gummy and dusky sharks. The biological RP is 40% of the unfished biomass and was considered a target level as an overall management objective: 'to maintain the biomass of the fisheries' for the three traditional target stocks at or above 40% of their unfished levels by 2010 for gummy and whiskery sharks and by 2040 for dusky shark'. Currently, there is no specific biological RP for sandbar sharks and no economic or social RPs for the fisheries. As a result, and similar to assessments for other WA finfish resources, the current assessment sets the target, threshold and limit RPs at 40%, 30% and 20% of the unfished biomass, respectively.

12. Appendix 2. Productivity Susceptibility Analysis (PSA) Scoring Tables

Productivity attribute	High productivity Low risk Score = 1	Medium productivity Medium risk Score = 2	Low productivity High risk Score = 3)
Average maximum age	<10 years	10-25 years	>25 years
Average age at maturity	<5 years	5-15 years	>15 years
Average maximum size (not to be used when scoring invertebrates)	<1000 mm	1000-3000 mm	>3000 mm
Average size at maturity	<400 mm	400-2000 mm	>2000 mm

(not to be used when scoring invertebrates)			
Reproductive strategy	Broadcast spawner	Demersal egg layer	Live bearer
Fecundity	>20,000 eggs per year	100-20,000 eggs per year	<100 eggs per year
Trophic level	<2.75	2.75-3.25	>3.25
Density dependence (only to be used when scoring invertebrates)	Compensatory dynamics at low population size demonstrated or likely	No depensatory or compensatory dynamics demonstrated or likely	Depensatory dynamics at low population sizes (Allele effects) demonstrated or likely

Susceptibility attribute	**Low susceptibility** **Low risk** **Score = 1**	**Medium susceptibility** **Medium risk** **Score = 2**	**High susceptibility** **High risk** **Score = 3)**
Areal overlap (availability) i.e. overlap of fishing effort with stock distribution	<10% overlap	10-30% overlap	>30% overlap
Encounterability i.e. the position of the species / stock within the water column / habitat relative to the position of the fishing gear	Low encounterability / overlap with fishing gear	Medium overlap with fishing gear	High encounterability / overlap with fishing gear (Default score for target species in a fishery)
Selectivity of gear type i.e. potential of gear to retain species	a) Individual smaller than the size at maturity are rarely caught b) Individual smaller than the size can escape or avoid gear	a) Individual smaller than the size at maturity are regularly caught b) Individual smaller than half the size can escape or avoid gear	a) Individual smaller than the size at maturity are frequently caught b) Individual smaller than half the size are retained by gear
Post-capture mortality i.e. the chance that, if captured, a species would be released and that it would be in a condition permitting subsequent survival	Evidence of majority released post-capture and survival	Evidence of some released post-capture and survival	Retained species or majority dead when released

13. Appendix 3. Consequence, Likelihood and Risk Levels (based on AS 4360 / ISO 31000) modified from Fletcher et al. (2011) and Fletcher (2015)

CONSEQUENCE LEVELS

As defined for major target species

1. Minor – Fishing impacts either not detectable against background variability for this population; or if detectable, minimal impact on population size and none on dynamics

   Spawning biomass > Target level (B_{MEY})

2. Moderate – Fishery operating at maximum acceptable level of depletion

   Spawning biomass < Target level (B_{MEY}) but > Threshold level (B_{MSY})

3. High – Level of depletion unacceptable but still not affecting recruitment levels of stock

   Spawning biomass < Threshold level (B_{MEY}) but > Limit level (B_{REC})

4. Major – Level of depletion is already affecting (or will definitely affect) future recruitment potential/ levels of the stock

   Spawning biomass < Limit level (B_{REC})

LIKELIHOOD LEVELS

These are defined as the likelihood of a particular consequence level actually occurring within the assessment period (5 years was used)

1. Remote – The consequence has never been heard of in these circumstances, but it is not impossible within the time frame (Probability of <5%)
2. Unlikely – The consequence is not expected to occur in the timeframe but it has been known to occur elsewhere under special circumstances (Probability of 5 - <20%)
3. Possible – Evidence to suggest this consequence level is possible and may occur in some circumstances within the timeframe. (Probability of 20 - <50%)
4. Likely – A particular consequence level is expected to occur in the timeframe (Probability of >50%)

Consequence × Likelihood Risk Matrix		Likelihood			
		Remote (1)	Unlikely (2)	Possible (3)	Likely (4)
Consequence	Minor (1)	Negligible	Negligible	Low	Low
	Moderate (2)	Negligible	Low	Medium	Medium
	High (3)	Low	Medium	High	High

	Major (4)	Low	Medium	Severe	Severe

Risk Levels	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; If not already introduced, major changes required to management in immediate future	Recovery strategy and detailed monitoring	Increased management activities needed urgently

14. Appendix 4. Equations

The code developed for implementing the age-structured and size-structured models is stored in https://github.com/JuanMatiasBraccini/Git_Repository_of_tpl

14.1 Age-structured model

The Excel model constructed by Simpfendorfer et al. (1996, 2000b) was coded in ADMB and used in the S2 scenario. For future applications and to add modelling flexibility, the original model of Simpfendorfer et al. (1996, 2000b) was extended by incorporating a maturity ogive, a fecundity relationship, spatial structure and movement among spatial zones. For the current assessment, only the original model developed by Simpfendorfer et al. (1996, 2000b) was used.

Below is a description of the population dynamics implemented and the objective function used.

14.1.1 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_r , estimated in *14.2.4 Population dynamics* (see below) 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.

14.1.2 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 the base case, which assumes movement among zones, the initialisation of the model required the cycling of the model to allow for movement among the zones and attain equilibrium conditions before entering the dynamic phase.

14.1.3 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 catch rate data from Zone 2 only was used (see *9.3.3 Fishery-Dependent Catch Rate Analyses* for a justification). For the spatial models of gummy sharks, R^*_{WC} and R^*_{ZN1} could not be estimated because the SCR series is only available for ZN2. Hence, these two parameters were set at the mean proportion of the annual catch in those zones relative to the annual catch in Zone2 (3.5% and 9% for WC and Zone1, respectively).

14.2 Size-based model

In the past, quantitative assessments of whiskery and gummy shark stocks in WA had been done using an age- and sex-structured population dynamics model fitted only to 'effective' CPUE (Simpfendorfer et al. 1996b, 2000b). Since the application of this model, additional information useful for calibrating population dynamics model has become available. Hence, to incorporate this information in the assessment process, an integrated stock assessment model was developed. A series of sensitivity tests were also done to illustrate the effect of incorporating new data and making different assumptions about key quantities, and to test uncertainty in model structure.

Below is a description of the integrated size-base, sex-structured model proposed as the base case. A size-based model is appropriate because the available biological (e.g. fecundity, maturity) and fishery (e.g. gillnet selectivity) relationships are functions 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 the age-structured model where a growth curve is required for converting at-size information to at-age information. Also, an integrated approach makes used of all available information, in addition to 'effective' CPUE.

14.2.1 Growth

Growth parameter values are required for estimating the size transition matrix, $\Psi_{j',j,g}$, which represents the fraction of individuals in size-class j' that grows into size-class *j* during the modelled time step.

Following (Simpfendorfer et al. 2000a), growth is modelled using a modified version of the von Bertalanffy equation

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

where $L_{a,g}$ is the predicted length at age *a* for individuals of sex *g*; L_0 is the mean total length at birth; and $L_{\infty,g}$ and K_g are growth parameters for individuals of sex *g*. This parametrisation of the growth curve ensures that the curve passes through the known size at birth.

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

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

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

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.

14.2.2 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_SD} is the standard deviation of L_0 .

14.2.3 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*; $P_j^{"}$ is the proportion of mature females in size class *j*; and $N_{0,j,g=f}$ is the initial numbers of females per recruit in size class *j*, calculated as

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

where $Surv_{j,g=f}$ is the survival probability of female individuals in size class *j*, calculated as

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

where P_g''' is the proportion embryos of sex *g*; $N_{a,j,g}$ 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*; $Sel_{j,\text{init}}$ is the overall gillnet selectivity of individuals in size class *j* prior to 1975 (as this information was not available, it was assumed to be the same as in 1975); 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 F_{init}, which is the fishing mortality rate prior to 1975. Finally, to loop over enough years A_{f_size} is set at double the maximum age, A_f .

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

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

14.2.4 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

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

where $Sel_{j,t,z}$ is the selectivity of individuals in size class *j* at time *t* in zone *z*; $FSF_{g,t,z}$ 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 a movement transition matrix, representing the probability of moving from one zone to another zone in a year, defined 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, respectively. Note that each row sums to one.

In the dynamic model, Θ had a time step of one year, which was calculated as the product matrix of compounding, Θ_d, 365 times. However, a daily transition matrix was required because the conventional and acoustic tagging data have a daily time step (i.e. days at liberty). Hence, based on Θ_d and *t* (days at liberty for conventional tags and days between detections for acoustic tags) for an individual *n*, $\mathbf{P}_n$ was calculated as the product matrix of compounding Θ t-times. Next, $\hat{p}_{ij}$, the predicted probability of moving from zone *i* to zone *j* after time *t* for an individual *n*, was extracted from the $\mathbf{P}_n$ row and column that corresponded to the observed release and recapture zone for that individual.

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 CPUE at time *t* in zone *z*, $U_{t,z}$, is calculated as

$$U_{t,z} = q_p Be_{t,z}$$

where q_p is the model-estimated catchability coefficient for period *p*.

$P_{g,t,z,j}$, the predicted proportion of the catch of sex *g* at time *t* in zone *z*, and size class *j* is calculated as

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

14.2.5 Objective function

To estimate K_g, $L_{\infty,g}$, σ_G (the standard deviation of the growth data), R^*, pR_z (spatial models only), q_p, τ (the standard deviation of the CPUE data), and the p_{ij} parameters (spatial models with movement only), the model is fitted to the CPUE, catch size composition, age and growth, and conventional and acoustic tagging (spatial models with movement only) data by minimizing an overall objective function, λ, which contains seven terms

$$\lambda = \lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5 + Catch_{pen} + Tag_{pen}$$

where λ_1, λ_2, λ_3, λ_4, and λ_5 are the negative log-likelihoods for the CPUE, catch size composition, growth data, conventional tagging, and acoustic tagging data, respectively;

$Catch_{pen}$ is a penalty to maintain $FSF_{g,t,z}$ below a maximum value of 3 y^{-1}; Tag_{pen} is a penalty used to maintain all p_{ij} parameters between 0 and 1. F_{init} could not be estimated so it was fixed at a range of values given that the commercial exploitation of sharks in WA commenced in the early 1940s (Whitley 1943) (see Table 9.11 and Table 9.12).

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

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

where $U_{t,z}$ is the observed CPUE 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 CPUE at time *t* in zone *z* (derived from the CPUE standardisation process).

λ_2 is calculated following (Schnute & Haigh 2007) based on the Dirichlet distribution as

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

where $P_{g,t,z,j}$ is the observed proportion of the catch of sex *g*, time *t*, zone *z* and size class *j* and $\eta_{g,t,z,j}$ is

$$\eta_{g,t,z,j} \approx \frac{\delta_{g,t,z} - 1}{2} \left(\sum_{first}^{last} P_{g,t,z,j} \log\left(\frac{P_{g,t,z,j}}{P_{g,t,z,j}}\right) \right)$$

where $\delta_{g,t,z}$ is the number of size classes with size composition information for sex *g*, time *t* and zone *z*, and *first* and *last* are the first and last size class with size composition information.

λ_3 is calculated using a normal likelihood with standard deviation σ_G .

Finally, λ_4 and λ_5 are calculated as

$$\lambda_4 = -\sum_n \log(\hat{p}_{conv,ij})$$

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

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

14.2.6 Future projections

Population were projected into the future for 5 years assuming a constant catch set at the average catch of the last 5 years of available data. Uncertainty was incorporated in the form of recruitment variability where the model predicted recruitment in future years, $Rf_{t,z}$, is calculated as

$$Rf_{t,z} = R_{t,z} e^{\xi_t}$$

where ξ_t is a random number sampled from a lognormal distribution with mean of 1 and standard deviation of 0.05.