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Resource Assessment Report Abrolhos Islands and Mid-West Trawl Managed Fishery Resource

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Executive Summary

- Saucer scallops, *Ylistrum balloti (*formerly *Amusium balloti*), are fished using demersal otter trawls in the Abrolhos Islands and Mid-West Trawl Managed Fishery (AIMWTMF).

- The AIMWTMF is managed according to a "constant escapement policy" designed to ensure that a minimum level of scallop spawning stock is left at the end of each fishing season. This thereby helps to ensure that fishing does not deplete the stock to a level that then impacts on recruitment. Management is generally based on limited entry, gear controls and seasonal closures

- The harvest strategy recognise that scallop recruitment is naturally highly spatially and temporally variable, however recent studies have demonstrated a spawning stock recruitment environment relationship. Thus, control rules are in place to provide the spawning stock with a very high level of protection (including fishery closure) in years when scallops are naturally low in abundance such as after a marine heatwave event.

- Broader management objectives ensure that bycatch, in particular large animals including turtles, is minimised and that the effects of fishing do not result in irreversible changes to ecological processes.

- Catches vary widely (20-1300 t meat weight) depending on the strength of recruitment, which is influenced by the spawning stock abundance, strength of the Leeuwin Current, water temperature and current and eddies. Extreme environmental events, as was observed with an extreme marine heatwave in the summer of 2010/11, had a significant impact on scallop stocks, with a fishery closure 5 years prior to recovery.

- Annual fishery-independent scallop surveys have been undertaken since 1997 and provide size and abundance information from fixed sites. These data are used to determine an index of abundance that are linked to the control rules and provides the basis for predicting the catch the following year.

- The stock status of the Abrolhos Islands and Mid-West Trawl Managed fishery in 2019 is sustainable.

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List of Abbreviations

AIMWTMF	Abrolhos Islands and Mid-West Trawl Managed Fishery
AMM	Annual Management Meeting
BOM	Bureau of Meteorology
BRD	Bycatch reduction device
CAES	Catch and Effort System
CPUE	Standardised Catch Per Unit Effort
DBCA	Department of Biodiversity, Conservation and Attractions (Western Australia, former Department of Parks and Wildlife)
DPIRD	Department of Primary Industries and Regional Development (Western Australia, former Department of Fisheries)
EBFM	Ecosystem-Based Fisheries Management
ENSO	El Niño-Southern Oscillation
EPBC	Environment Protection and Biodiversity Conservation (Act)
ESD	Ecologically Sustainable Development
ETP	Endangered, Threatened and Protected species
FHPA	Fish Habitat Protection Area
FRMA	Fish Resources Management Act
FSL	Fremantle mean Seal Level
HS	Harvest Strategy
MFL	Managed Fishery Licence
MHW	Marine Heat Wave
MSC	Marine Stewardship Council
SAFS	Status of Australian Fish Stocks
SOM	Size of Maturity
SoFAR	Status of Fisheries and Aquatic Resources Report, WA
WA	Western Australia
WCB	West Coast Bioregion

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1 Scope

This document provides a cumulative description and assessment of the Abrolhos Islands and Mid-West Trawl Managed Fishery (AIMWTMF) and all of the fishing activities (i.e. fisheries / fishing sectors) affecting this resource in Western Australia (WA). This resource comprises of a single species of scallop, *Ylistrum balloti* which occurs in inshore waters to around 40 m depth at the Abrolhos Islands. This species is captured exclusively by demersal otter trawl gear in the West Coast Bioregion.

The report contains information relevant to assist the assessment of the resource against the Marine Stewardship Council (MSC) Principles and Criteria for Sustainable Fishing, the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) export approval requirements and other reporting requirements, e.g. Status of Australian Fish Stocks (SAFS) and Status Report of Fisheries and Aquatic Resources report (SoFAR).

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 of Primary Industries and Regional Development (DPIRD, 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 (Department of Fisheries 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). Note that the effect of octopus fishing on these ecological components was examined in April 2018 as part of an EBFM risk assessment for the Octopus Interim Managed Fishery and Cockburn Sound Line and Pot Fishery.

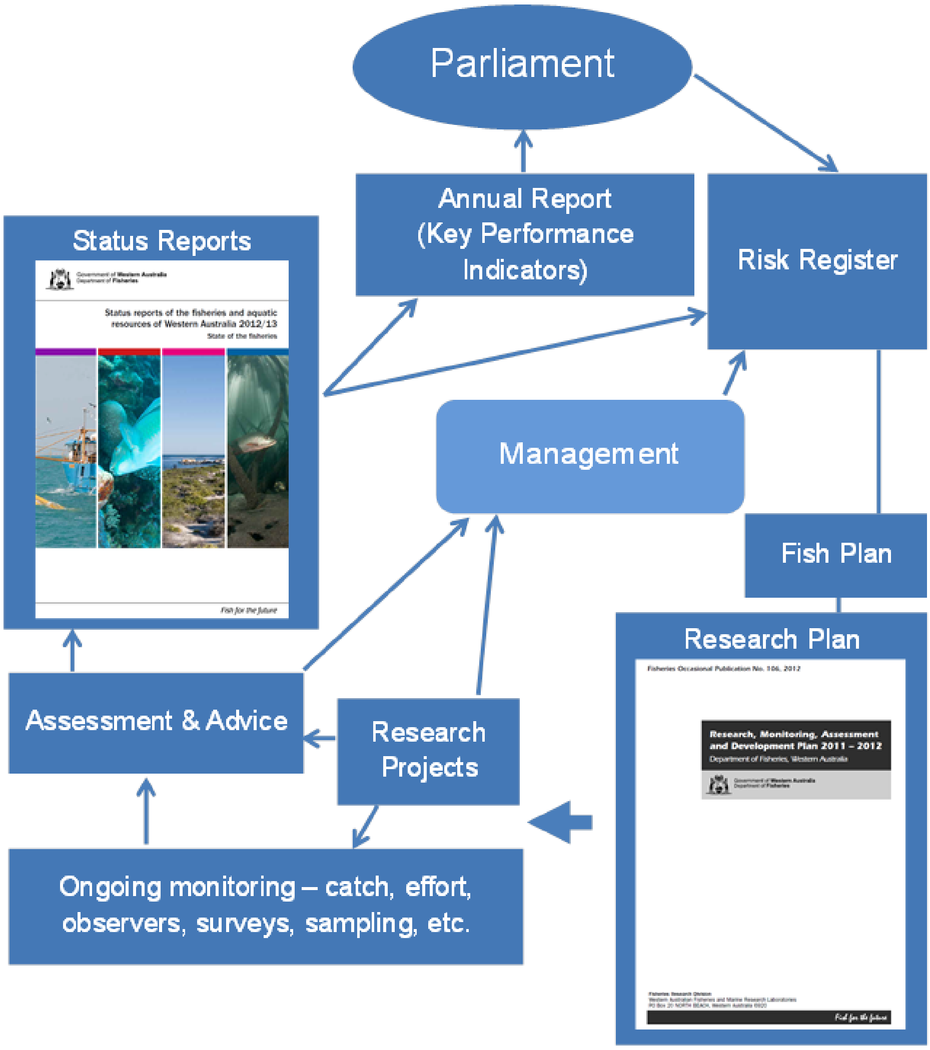


Figure 2-1. An outline of the risk-based planning cycle used for determining Departmental priorities and activities

3 Aquatic Environment

The AIMWTMF operates within the Abrolhos Islands Ecosystem off the west coast of WA (Figure 3-1). The Houtman Abrolhos Islands is located in the northern section of the west coast bioregion approx. 60 km off the coast of Geraldton. The Abrolhos Islands (Abrolhos) are a complex of 122 low-lying islands and reefs located on the edge of the continental shelf where the 50 m isobath curves around to encompass the islands (Johannes et al. 1983). There are three major island groups, the North Island-Wallabi Group, the Easter Group and the Pelsaert (Southern) Group, separated by the Middle and Zeewijk Channels, respectively (see Figure 6.4). The Abrolhos Islands are well-known for their high species diversity, coral reefs and unique mixture of temperate and tropical species. The Abrolhos are considered to be an ecological mid-point in a gradient that extends from the tropical ecosystems of Shark Bay, south along the shelf to the temperate communities at Rottnest Island (off Perth). The uniqueness and ecological value of the Abrolhos resulted in their placement on the National Estate Register (under the *Australian Heritage Act* [1975]), and were gazetted as WA's first Fish Habitat Protection Area (FHPA) under the FRMA (Webster et al. 2002).

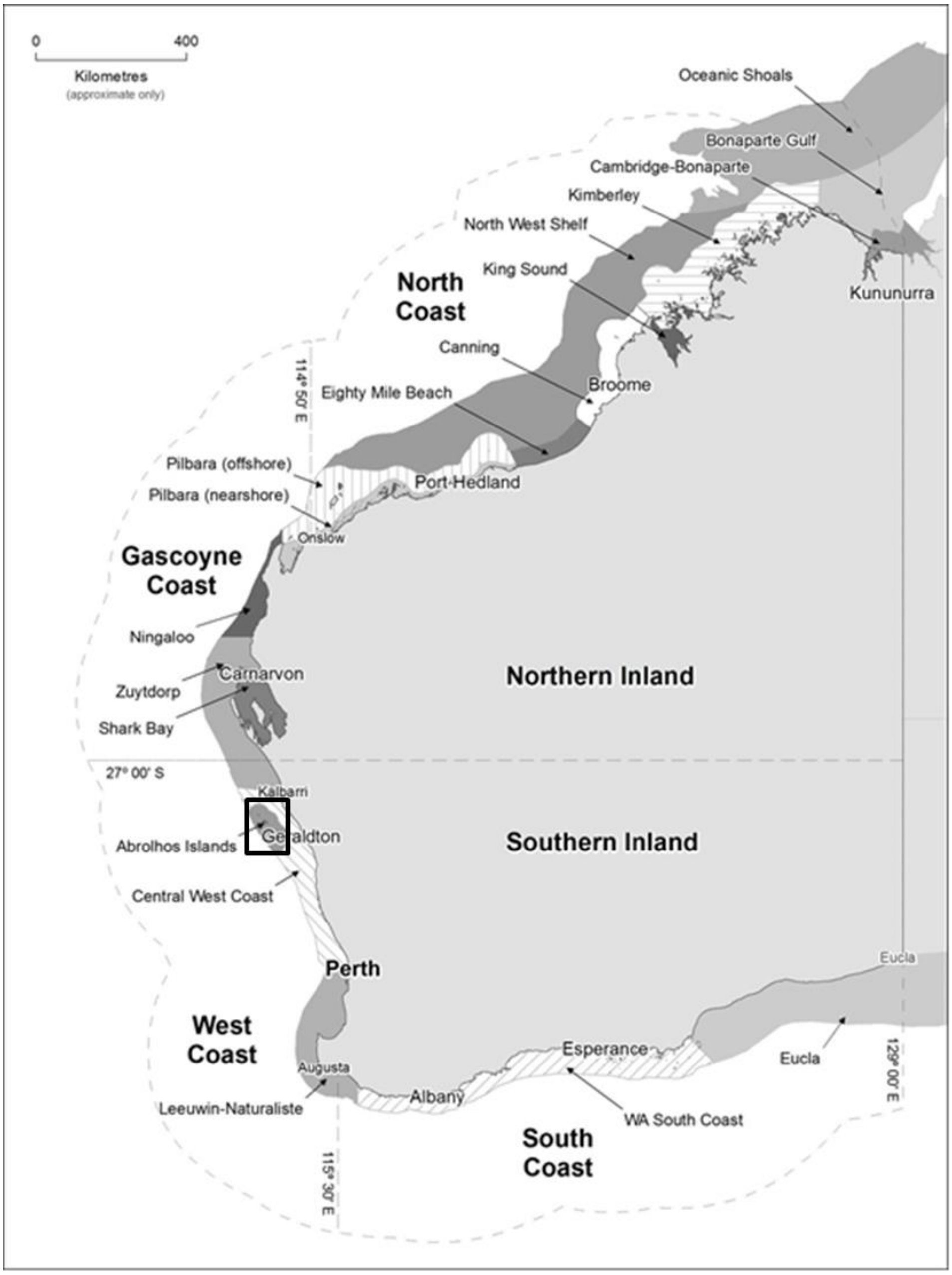


Figure 3-1. Locality of the AIMWTMF resource within the West Coast Bioregion of WA

Physical oceanographic processes off the WA coastline are highly influenced by the Leeuwin Current (LC) system which is made up of three currents: the LC, the Leeuwin Undercurrent and shelf current systems consisting of the Ningaloo, Capes and Cresswell Currents (Woo et al. 2006). The LC is a shallow and narrow (less than 300 m deep and 100 km wide) current which transports warm, low-nutrient water from the tropics southward along the shelf break and outer parts of the shelf (Church et al. 1989; Smith et al. 1991; Ridgway and Condie 2004). It is the longest boundary current in the world and extends from Exmouth to Cape Leeuwin and into the Great Australian Bight. The mean sea level at Fremantle (FSL) is commonly used as an indicator of the strength of the LC. This relationship exhibits a strong seasonality where the current flow is stronger (higher sea level and weaker winds) during the winter months (May – July) than it is during summer (October to March) when it flows against the maximum southerly winds (lower sea level) (Pearce and Phillips 1988; Feng et al. 2003). Interactions of

the LC with seafloor features also leads to the formation of meso-scale eddies, which occur in predictable locations, including the western edge of the Abrolhos Islands. Due to the strong influence of the LC, the coral reefs of the Abrolhos Islands are the most southern extensive coral community along the west coast (CoA 2008).

The Capes Current is a cooler inner shelf current, originating from the region between the Leeuwin and Naturaliste capes, which moves along the south-western Australian coast in summer towards the equator (Pearce and Pattiaratchi 1999). This current can extend as far north as the Abrolhos Islands and is characterised as being more saline (35.37–35.53 ppt) and cooler (21.0 – 21.4°C) than the LC. The Capes Current appears to be well established around November when winds in the region become predominantly southerly due to the strong sea breezes (Pattiaratchi et al. 1997) and continues until about March when the sea breezes weaken. The source water of the Capes Current arises from upwelling between Leeuwin and Naturaliste capes and is augmented by water from the south, to the east of Cape Leeuwin (Gersbach et. al. 1999).

4 Resource Description

Ylistrum balloti tends to be restricted to areas of bare sand in the more sheltered environments found in embayments and in the lee of islands and reef systems at the Abrolhos Islands. Early growth of this species is rapid and although saucer scallops have been recorded reaching 140 mm in length and living up to three to four years most appear to live no more than two years and usually attain a maximum size approximately 115 mm (Heald 1978, Dredge 1988). The timing of spawning is crucial to ensure temperatures and concentrations of phytoplankton are adequate for larval development and water temperatures between 18° and 20°C are optimal for larval survival (Cragg 2006). Larvae cannot survive temperatures above 24°C (Wang 2007). Spawning is seasonal and the timing is variable for latitudes (Chandrapavan et al. 2020) with spawning occurring up to eight to nine months in Shark Bay and only two to three (summer) months on the south coast. In the Abrolhos Islands it appears most spawning occurs between September/October and January/February with lower levels of spawning in the other months (Chandrapavan et al. 2020). Changes in environmental patterns may however, lead to different periods of the spawning cycle having a greater importance as contributors to overall recruitment (Joll and Caputi 1995a, b).

Saucer scallops are broadcast spawners, releasing their eggs and sperm into the surrounding waters for fertilisation to occur in the water column (Dredge 1981). During this period, larvae are susceptible to being passively transported by tides and currents whilst in the water column. Once settled, saucer scallops only move short distances, primarily for predator avoidance but once disturbed can lift themselves off the bottom and swim up to 23 m (Joll 1989 b) making them available for capture using demersal otter trawl nets.

5 Species Description

5.1 Saucer scallop (*Ylistrum balloti*)

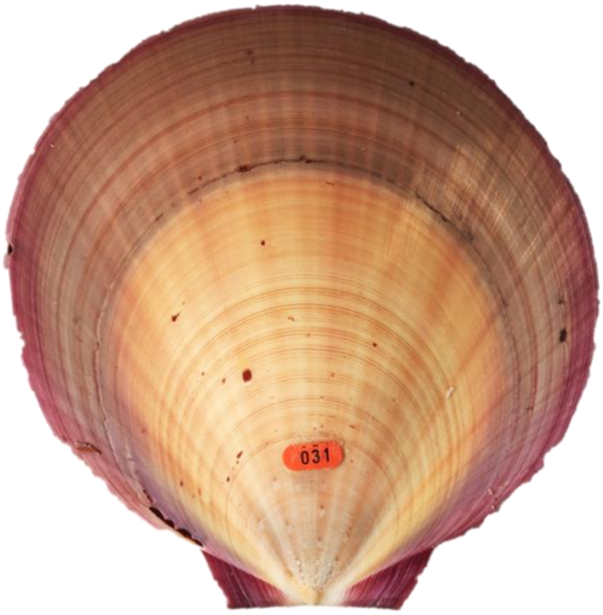


Figure 5-1. An example of a saucer scallop, *Ylistrum balloti,* that had been tagged and recaptured in the Abrolhos Islands. Note, growth post tagging and release is evident as rings and darker pigment.

5.1.1 Taxonomy and Distribution

Saucer scallops in Australian waters are now classified as *Ylistrum balloti* (formerly *Amusium balloti*) following a recent revision of the genus *Amusium* (Myrnhardt et al. 2014). This species is distributed from Israelite Bay in Western Australia, across the tropics, to the southern coast of New South Wales (fish.gov.au 2019). However, in WA, the Shark Bay population is considered to be located at the northern-extent of the distribution of the species, while the Abrolhos Islands population on the edge of the continental shelf is considered to be at the most offshore extent of the distribution of this species (Figure 3-1).

5.1.2 Life History

The sub-sections below provide an overview of the life history characteristics of the *Y. balloti* with a summary of the relevant biological parameters used in stock assessments presented in Table 5-1.

5.1.2.1 Life Cycle

Previous research has indicated that the reproductive cycle of scallops in the Abrolhos Island begins with the onset of gametogenesis from August to March/early April, with spawning occurring 4 – 8 weeks later (Joll and Caputi 1995a). More recent research (Chandrapavan et al. 2020) estimated the month of spawning from daily ring count information (Figure 5-2),

supported by the macroscopic gonadal developmental staging (Figure 5-3b) and length frequency data (Figure 5-4). Information, primarily from Shark Bay, indicated that *Y. balloti* generally mature at around 90 mm shell height at approximately one year (Joll and Caputi 1995a) although smaller scallops (~70 mm shell height) were found with maturing gonads in Queensland (Williams and Dredge 1981). The more recent study in Abrolhos Islands indicates mature individuals as small as 55 mm shell height (Figure 5-4).

With only two periods of fishery-independent sampling available from the Abrolhos Islands (November and February), it has not been possible to describe the monthly patterns of gonadal development throughout the year. Nonetheless, the ring count data indicated highest proportion recruits come from spawning scallops between October and January (Figure 5-3a). This aligns well with all scallops sampled during November being either pre-spawning or mature stage and by February 20% were mature. 15% spent and 40% immature (Figure 5-3b). Spawning appears to occur all year, however at much lower levels between March and August (Figure 5-3a).

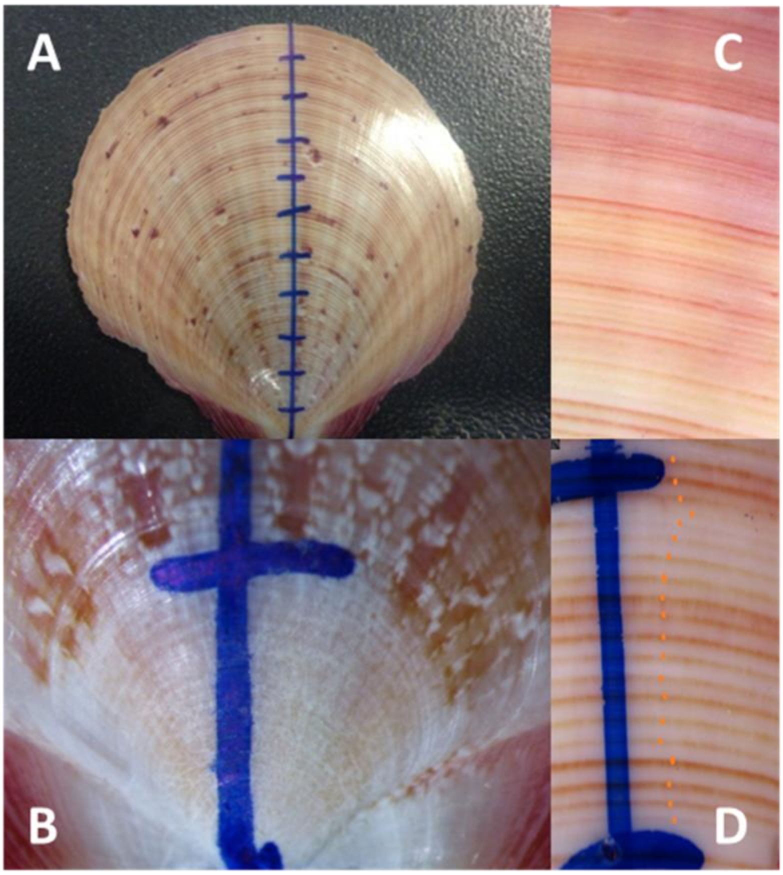


Figure 5-2. (A) Ventral valve of a scallop marked (5 mm intervals) for ring counting (B) The umbo region of a scallop shell marked to be counted (C) Growth rings on a scallop from Rottnest Island showing compacted rings closer to the shell edge (D) Abrolhos Islands. Example of ring counts (20 rings) in a 5mm interval (Chandrapavan et al. 2020).

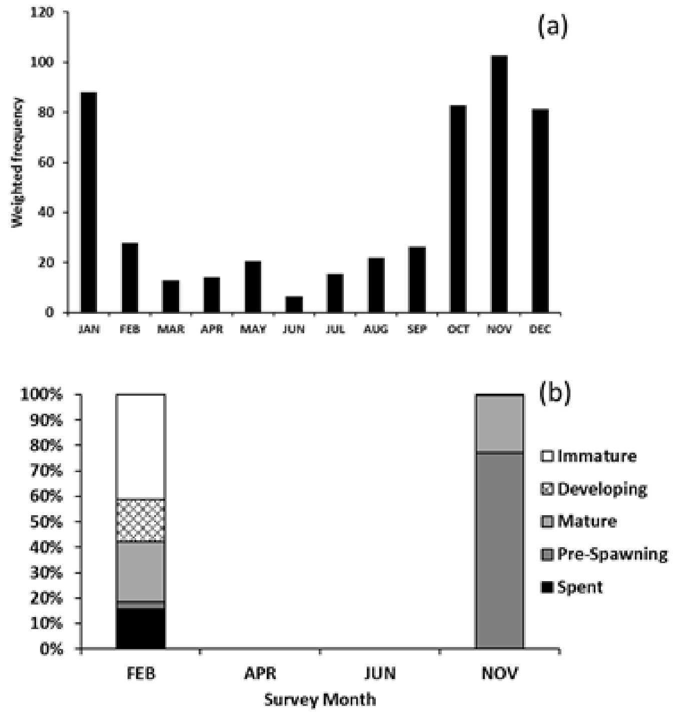


Figure 5-3. a) Estimated spawning month frequency from recruit *Y. balloti* in Abrolhos Islands (n =165), b) changes in gonad development observed from available survey data sampled in 2016 and 2017 (Chandrapavan et al. 2020).

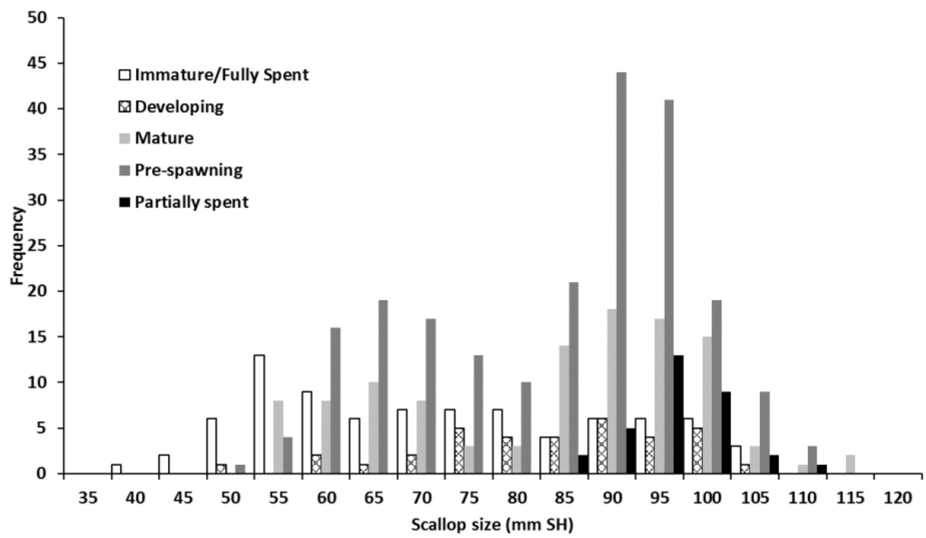


Figure 5-4. Shell height frequency and reproductive condition of female *Y. balloti* in Abrolhos Islands gonad stages combined for all the months and years sampled (Chandrapavan et al. 2020).

Revised life-cycle based on early and recent studies

The early spawning over the spring/summer months produces recruits five months later between February and May with some of the faster growing individuals capable of spawning towards April/May. These recruiting juveniles are detected during the February/March surveys (< 60 mm SH). Early spawned recruits grow rapidly and become the larger sized mature adults (>90 mm SH) (residual scallops) and are observed during the November survey and these come into spawning condition between September and January (Figure 5-5). This cohort is the larger residuals fished the following year.

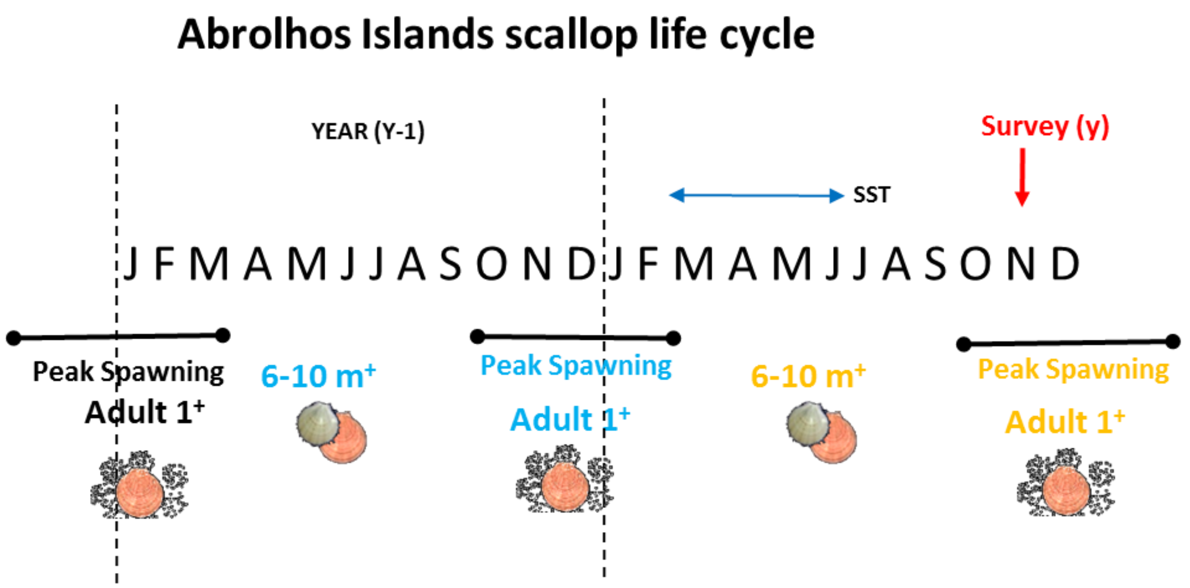


Figure 5-5. Life cycle diagram of *Y. balloti* along the Abrolhos Islands. Peak spawning between September and February gives rise to recruits that grow and mature over the following 12 months and enter their first spawning event by the following spring/summer (Chandrapavan et al. 2020).

The later spawning phase between February and May produces 0^+ recruits that are sometimes observed during the November survey at around 6-8 months of age (~60-80 mm SH) (Figure 5-5). These late spawned recruits mature over summer and become mature adults by April/May and come into spawning condition. A proportion of this cohort will also be harvested during the fishing season prior to spawning (pre-spawned scallops) and the rest will grow through to be sampled during the November survey as 1^+ residual scallops.

The commercial fishery historically operated between April and June and therefore it appears that fishers targeted the older, already spawned individuals as well as scallops at their optimal meat condition just prior to spawning. The proportion of scallops which resulted from either an early or late spawning is can vary annually and can contribute to differences in size composition of scallops during November surveys. Thus the timing of spawning between September and May and larval developmental/juvenile period in the following six/eight months are critical periods when environmental factors can substantially influence larval survival, retention, settlement and growth and survival of juveniles. Post spawned adults are then commercially targeted the following year when they are 12-18 months old.

5.1.2.2 Size of Maturity (SOM) estimate

The relationship between gonad development and size of scallops for combined sexes was explored (Figure ***5-6***) to determine if the mean size at onset of sexual maturity estimates could be determined for *Y. balloti*. The estimated length at which 50% of individuals attained maturity (L_{50}) was 54 mm SH (***Table 5-1. Summary of biological parameters for Ylistrum balloti*** Table ***5-1***). The smallest scallop in pre-spawning condition was 51 mm SH compared to Shark Bay where the smallest in northern SB was 74 mm SH and in Denham Sound was 81 mm SH. The estimated length at which 95% of individuals attained maturity (L_{95}) was 7- mm SH.

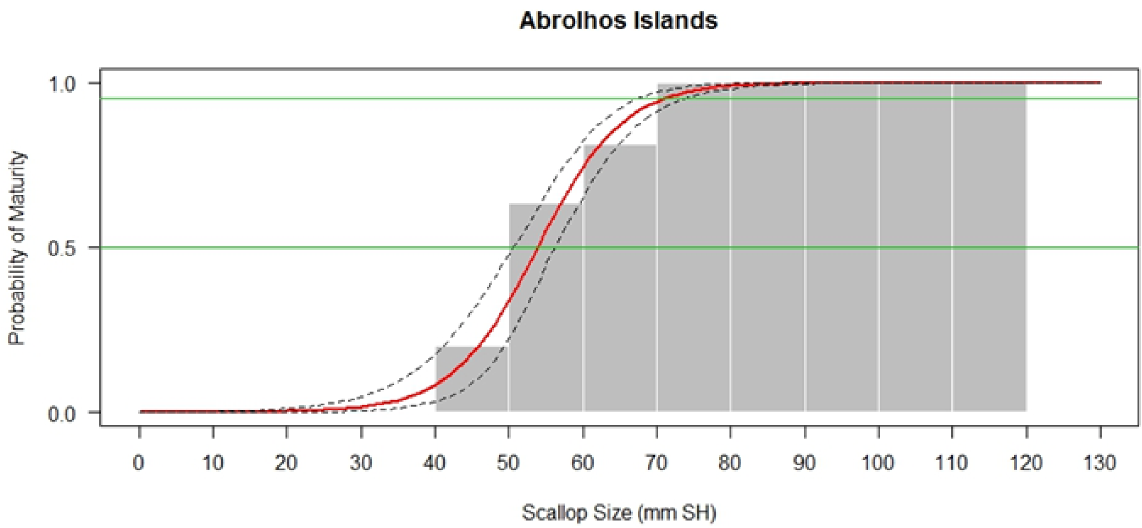


Figure 5-6. Logistic regression showing size at maturity estimates for *Ylistrum balloti* in the Abrolhos Islands (Chandrapavan et al. 2020).

Table 5-1. Summary of biological parameters for *Ylistrum balloti*

Parameter	Value(s)	Comments / Source(s)
Growth parameters	$L_t = L_\infty (1 - \exp(-K (t - t_0)))$	
L_∞ (mm)	102 - 109 mm	
K (year^{-1})	0.0515 - 0.0588	
t_0 (years)	12-24 days	Rose et al. (1988)
Maximum age (years)	4	Dredge (1988)
Maximum size (mm)	150 mm shell height SH	
Natural mortality, M (year^{-1})	1.2 year^{-1}	Dredge (1988)
Length-weight parameters (mature)	$W = a$ (SH) – b , changes seasonally with gonad development	Dredge (1981)
a	0.552	
b	32.406	
Reproduction	Generally gonochoristic, broadcast spawners but some hermaphrodites	Dredge (1981), Joll (1988)
Maturity parameters	Logistic	
A_{50} (years)	8 months	
A_{95} (years)	10 months	
L_{50} (mm)	54 mm SH	Chandrapavan et al. (2020)
L_{95} (mm)	70 mm SH	Chandrapavan et al. (2020)
Fecundity	3.20×10^5 to 2.65×10^6 (at 85 to 107 mm SH) Batch / Annual fecundity	Dredge (1981)
Size-fecundity parameters	$F = (a \text{ SH} - b)^3$	
a	0.5477	(calculated from Dredge 1981)
b	0.214	(calculated from Dredge 1981)
Spawning frequency	Potentially multiple spawners, spawning period 4-8 months	

5.1.2.3 Habitats and Movements

Ylistrum balloti tends to be restricted to areas of bare sand in the more sheltered habitats found in the lee of islands and reef systems. The species generally occurs in depths of 20-40 m in the Abrolhos Islands.

Horizontal larval advection is primarily via current and tidal movements whilst larvae may have some control over their vertical distribution (Cragg 2006). For some species, diurnal migration has been documented (Manuel et al. 1996 a, b, Kaartvedt et al. 1987, Maru 1985, Tremblay and Sinclair 1990 a and b and Raby et al. 1994). The behaviour of larval *Y. balloti* within the water column is poorly understood and collection spat of *Y. balloti* has not been successful (Sumpton et al. 1990, Robins-Troeger and Dredge 1993).

Adult scallops differ from most bivalve molluscs because of their ability to swim. This swimming ability is thought to be an adaptation from fleeing predators. The best scallop swimmers are species of the genus *Amusium/Ylistrum* which can swim up to 23 m in a single swim (Joll 1989b). When one scallop swims it often induces swimming in others nearby, setting off a chain reaction related to predator avoidance (Chapman et al. 1979, Vahl and Clausen 1980, Minchin and Mathers 1982, Howell and Fraser 1984). The sensitivity of *Y. balloti* to disturbance and its swimming ability allows it to be fished by otter trawl gear compared to other scallop species that are captured by dredges (Himmelman et al. 2009).

5.1.2.4 **Age and Growth**

Growth of the scallop shell is allometric with the height of the shell growing more rapidly than length (i.e. shell height is positively allometric to length). Scallops reach sizes around 50-60 mm in shell height around six to seven months after fertilisation. A size suitable for commercial harvest (> 90 mm shell length) is reached within approximately one year (Joll and Caputi 1995a). Saucer scallops have been recorded reaching 150 mm in length and living up to three to four years.

Daily growth rings are visible in juvenile scallops (Joll 1988) but become difficult to read in mature animals (older than eight to nine months). The fastest growth phase, in terms of shell length is in the first year of life at 8-13 mm per month with scallops attaining a size of 75 mm by seven months (Williams and Dredge 1981) and to 90-95 mm by eight to nine months (Joll 1988). At this time scallops become mature and their growth rate decreases significantly to only 1-2 mm per month. At the Abrolhos Islands, juvenile scallops in the size range of 35–45 mm SH had on average 100-150 growth rings with scallops in the size range of 60-65 mm having 250-300 rings.

Seasonal growth in bivalves, including Pectinidae, is influenced by the interaction of a number of environmental variables particularly water temperature and food supply (Broom and Mason 1978, Bayne and Newell 1983). Food availability has often been found to exert a greater influence on growth rate than temperature in temperate species (Orensanz 1984). Intraspecific variability in growth rates and tissue weight for a given shell height has most frequently been related to differences in water depth. Scallops from inshore, shallower waters typically display higher growth rates and maximum sizes than those from deeper waters associated with higher temperatures and food levels in shallow waters (MacDonald and Thompson 1985). In Shark Bay, and likely at the Abrolhos Islands, a slower growth rate is observed during the spawning months, which is likely due to energy being diverted into reproduction, although lower temperatures may also play a part.

5.1.2.5 **Natural Mortality**

There are currently no estimates of natural mortality for *Y. balloti* from WA. However, the natural mortality coefficient, M, of the saucer scallop *Y. balloti* within its central Queensland distribution has been estimated from the survival of tagged scallops to be approximately 0.025 per week (Dredge 1985). The analysis used to obtain this estimate of M incorporates a correction for tag shedding. The high natural mortality coefficient which if constant over the

scallop’s life span would mean only a 2 % survival in an unfished population after three years and 0.6 % after four years (Dredge 1985).

5.1.2.6 **Diet and Predators**

Scallops are active suspension-feeding bivalves, which rely on suspended detrital material and phytoplankton as their food source (MacDonald et al. 2006). They are non-siphonate, ciliary suspension feeders. Water enters the mantle cavity along the ventral and anterior edge and exits through the posterior exhalent openings (Hartnell 1967). The food is trapped through ciliary action within the gills and the food is transported towards the mouth.

The major predators of *Y. balloti* are believed to be large teleost species such as pink snapper (*Pagrus auratus*), large cephalopod species and crustaceans such as the slipper lobster *Thenus/Abacus* sp. as it strongly prefers scallops and its foraging behaviour appears to be adapted to hunting and ambushing scallops (Himmelman et al. 2009). Sea stars are generally considered to be key predators of scallops (Thomas and Gruffydd 1971, Wilkens 1981); however, Himmelman et al. (2009) showed that there was no response when the mantle of *Y. balloti* was touched by the sea star *Pentaceraster regulus* although several individuals showed a weak swimming response when *P. regulus* was placed on top of them.

5.1.2.7 **Parasites and Diseases**

The larval ascaridoid nematode *Sulcascaris sulcata* has been found in *Y. balloti* (Cannon 1978, Lester et al. 1980). This nematode parasite causes lesions in the muscle and reduces marketability although there are no human health implications. In addition, a small percentage of scallops sampled (Cannon 1978, Lester et al. 1980) also contained a larval gnathostome *Echynocephalus* sp. These parasites are thought to be carried via the loggerhead turtle *Caretta caretta*, which feeds on scallops.

5.1.2.8 **Factors Affecting Recruitment and Other Biological Parameters**

Scallop recruitment at the Abrolhos Islands is highly temporally and spatially variable (Chandrapavan et al. 2020). Very high recruitment was observed in the fishery in 2002, 2004, the Hummocks region in 2017 and most recently more broadly in 2019/20. Larval advection and retention, temperature, food availability and spawning stock abundance are likely to be key factors. Previous studies have suggested that cooler SSTs associated with weaker LC being necessary for good recruitment (Lenanton et al. 2009, Joll and Caputi 1995b) and Chandrapavan et al. 2020 identified mean water temperatures between March and June as a driver of recruitment as long as sufficient spawning stock was available. Increased concentration of Chlorophyll A between April and July due to the strengthening of the LC aligns with increased food source for newly settled and/or juvenile scallops.

Lenanton et al. (2010) and Caputi et al. (2010) first suggested of a weak negative correlation between recruitment strength and both water temperature (May to August) and LC strength (May to August) where a weaker LC and cooler water temperatures increased the probability of good recruitment. These earlier relationships as well as potential influences of other

environmental factors were further examined as recruitment drivers of scallop stocks in WA, including the Abrolhos Islands was completed in 2020 (Chandrapavan et al. 2020).

Generally, high sea levels corresponding to strong LC correlate with poor recruitment of scallops. Although the LC is likely to weaken over the coming century, it has experienced a strengthening trend during the past two decades, likely due to natural variability (Feng et al. 2012). Strong La Niña conditions have generally been associated with below-average scallop recruitment, and the marine heatwave event (MHW) off the WA coast (centred on the Gascoyne and Mid-West regions) in February-March 2011 contributed to the record low recruitment levels and high mortality of adult scallops in Shark Bay and the Abrolhos Islands (Pearce et al. 2011). Similar extreme events may occur more often in the future with the trend of rising ocean temperatures. On the other hand, a marine cold spell during 2016-2019 helped the recovery of the scallop stocks post the heatwave event (Feng et al. 2020).

The flow of the LC may impact larval movement dynamics as it influences the water temperatures and current strength which are critical factors for passive particles such as scallop larvae which stay in the water column two to four weeks (Rose et al. 1988). In Shark Bay, the water temperatures generally increase from ~19°C to ~24°C during the spawning period. The adverse effects of temperatures higher than the optimal range, as experienced during the 2011 MHW can result in poor spawning success due to high larval mortality. However, the impact of cooler temperatures outside of this range is not as clear, although increased stock recovery during 2016 does support a positive influence of cooler than average temperatures. After spawning, prevailing oceanographic conditions can greatly influence settlement patterns evidenced annually by varying settlement strength and locations.

The spring/summer water temperatures at the Abrolhos currently range from 20 – 24 °C and the area is protected from the peak strength of the LC which usually strengthens from March onwards after the settlement of scallops has taken place. An exception to this was the summer of 2010/11 when the LC unseasonably flowed at record strength over the summer months and meant that the Abrolhos Islands were in the direct path of the strong and warm LC. Despite the stock collapse after the 2011 MHW, no significant environmental correlations with summer months were identified (Chandrapavan et al. 2020). Spawning biomass and winter water temperatures explained 58% of the recruitment variability which did identify low recruitment in 2011 and 1999 associated with the warmest winter years from the 2011 and 1999 MHWs.

During the 2011 MHW water temperatures in the Abrolhos Islands remained below 24°C until January which may have allowed some successful early season spawning to occur. Water temperatures increased to 27°C in the following months, likely above the physiological tolerance threshold for spat and juveniles and inducing thermal stress for the remaining spawning adult scallops. Apparent low survival of larvae and juveniles resulted in the surviving adult stock being the only scallops contributing to catches in 2011 which were well below those predicted. This was confirmed by a significant stock decline observed in the November 2011 survey and subsequent low abundance in the following years (Caputi et al. 2015). The 2010-2012 La Niña event kept summer SSTs warmer than average for several years. The low spawning stock years that followed the severe decline during the MHW coincided with these

warmer summer temperatures (2011-13). Cooler conditions returned post 2013 coinciding with incremental recovery of stocks until 2016 when sufficient stock abundance was present to allow reopening of the fishery. The stock improved to full recovery during the marine cold spell of 2016-2019. See 7.3.1 for information on how climate change may affect recruitment, growth etc. of the resource.

Wind dynamics and surface currents can also significantly influence larval movement and flushing. The winds are stronger during the spawning months and weaker during the post-spawned months during settlement and growth of juveniles. As the prevailing southerly winds can influence water movement and circulation, reduced wind strength may facilitate larval retention and settlement within spawning grounds. Stronger southerlies can also drive the inshore Capes Current further north and inundate the Abrolhos Islands, however, the seasonal dynamics of the Capes Current is not well understood at present.

During the summer months, the prevailing southerly winds induce a northward wind stress which in turn is forced to the left at the surface, under the influence of the Coriolis force, creating a predominantly westerly current pattern in the channels between the island groups. This creates vertical mixing and the transport of passive particles such as planktonic larvae to move down the water column. The circulation pattern near the bottom is largely channel-centric where particles are likely to be retained within the system for periods of time (Maslin 2005). The importance of these wind-driven hydrodynamics on scallop recruitment is complex however these small scale hydrodynamic processes may play a critical role in the larval settlement distribution across the islands groups that are highly variable from year to year.

5.1.3 Inherent Vulnerability

The biology and behaviour of scallops makes them low to moderately vulnerable to fishing. Depletion estimates generally indicate that their catchability is around 30-40%. with their escape response and catchability varying with size. Small individuals are less vulnerable to the demersal trawl gear as well as escaping through net mesh openings. Scallop growth is rapid with scallops attaining sexual maturity within one year, generally harvested at around one year of age and living not much beyond their second year. They are highly fecund with a short planktonic larval stage (approx. two to four weeks) usually with low to moderate dispersal. Because they are broadcast spawners, they may require a threshold density level in order to achieve spawning success.

Scallops are able to swim but they fatigue quickly (Joll 1989) and therefore generally have limited movement or mixing amongst regions. Modelling of larval advection in Shark Bay indicated low connectivity between areas with entrainment within areas due to the circulation patterns and eddies (Kangas et al. 2012). Similar processes are likely to occur in the Abrolhos Islands.

The only method of capture is by demersal trawl. There is a risk of hyper-stability in catch rates as aggregations of scallops are normally targeted. Major stock declines have occurred following extreme environmental events with recovery after management intervention (or

cessation of fishing due to uneconomic abundances) has been between three and five years in WA. The major stock declines in Shark Bay and the Abrolhos Islands indicated spawning stock abundance levels at which recruitment can be impaired, the first for this species. There is evidence however that strong recruitment can occur following significant reductions in spawning biomass indicating that the key recruitment driver in most years is environmental.

6 Fisheries / Sectors Capturing Resource

Scallops are solely fished in the AIMWTMF by dedicated scallop trawlers. All boats use low-opening demersal otter trawls and standard net size and gear configuration. No recreational or traditional fishers target saucer scallops.

In 2002, bycatch reduction device (BRD) trials commenced in the AIMWTMF to test different turtle exclusion devices (TEDs) or grids in the nets. Since 2003, all otter trawl nets, except for try nets, were fitted with a BRD when fishing for scallops. Specifically, a rigid inclined barrier (installed at an angle no greater than 60º), which comprises vertical bars spaced a minimum of 200 mm apart, must be are attached to the circumference of the net (Figure 6-1). This will guide animals and/or objects (including turtles) towards an escape opening forward of the grid, which must be at least 750 mm wide transversely across the net and 500 mm along the net from the mid-point of the width measurement.

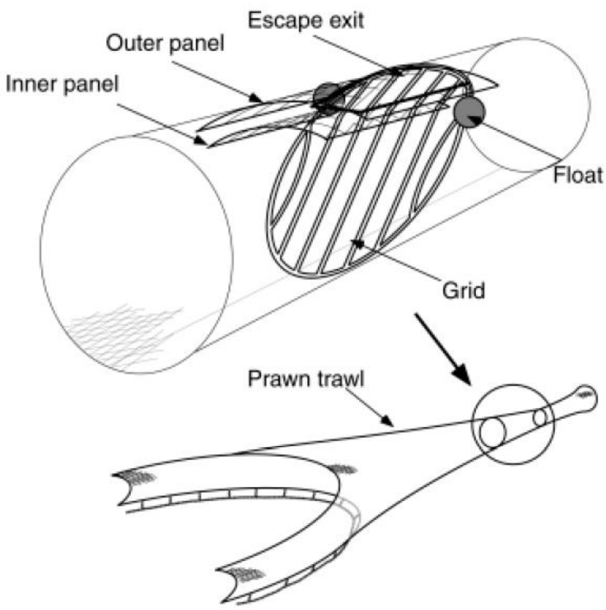


Figure 6-1. Diagrammatic representation of the type of bycatch reduction device used in the scallop trawl fisheries.

6.1 AIMWTMF

6.1.1 History of Development

The Abrolhos Islands area was first fished commercially for scallops during the late 1960; however, no fishing occurred in the region between 1969 and 1972 (Joll 1989a). The fishery

then operated intermittently over the next five years, with catches ranging from 0.3 to 6.7 t of scallop meat landed by between three and six vessels. After a poor season in 1977 (0.8 t meat weight), fishing for scallops again ceased during 1978 – 1979 (Joll 1989a) but recommenced in 1980, with just two vessels in operation. Both catches and vessel numbers increased over the next few years, primarily due to an increase in scallop price, improvements in operating efficiency, an apparent increase in scallop stocks, and a decrease in the problems associated with larval nematodes (Joll 1989a).

Following a freeze on vessel numbers in the Shark Bay fishery in 1983, a large number of operators transferred their efforts to the Abrolhos grounds causing vessel numbers to increase dramatically (Harris et al. 1999). This increase in fishing pressure greatly reduced the catch share among vessels in the fishery, causing individual profitability to become severely jeopardised. Because of this large influx of vessels, and the associated impacts on catch share and commercial viability, the entry of further vessels was restricted in 1985 (Joll 1989a). In 1986, the fishery was moved from an open-entry to a limited-entry fishery, with a maximum of 30 licences available (Joll 1989a). Following this decision, the maximum number of boats allowed to operate was gradually reduced through a two-for-one net reduction on transfer of license until there were 17 licenses operating in the Fishery.

There are currently 10 licensees in the AIMWTMF, after an industry-funded buyback in late-2010. The number of boats that actually operate depends on the likely catch for the season and in recent years has generally been between three and five boats. Scallop landings have varied dramatically over the last few decades, and are dependent on sporadic recruitment, which appears to be strongly influenced by environmental conditions (Figure 6-2). The MHW in 2010/11 resulted in a significant stock decline at the end of 2011 and the fishery was closed for five years until 2017.

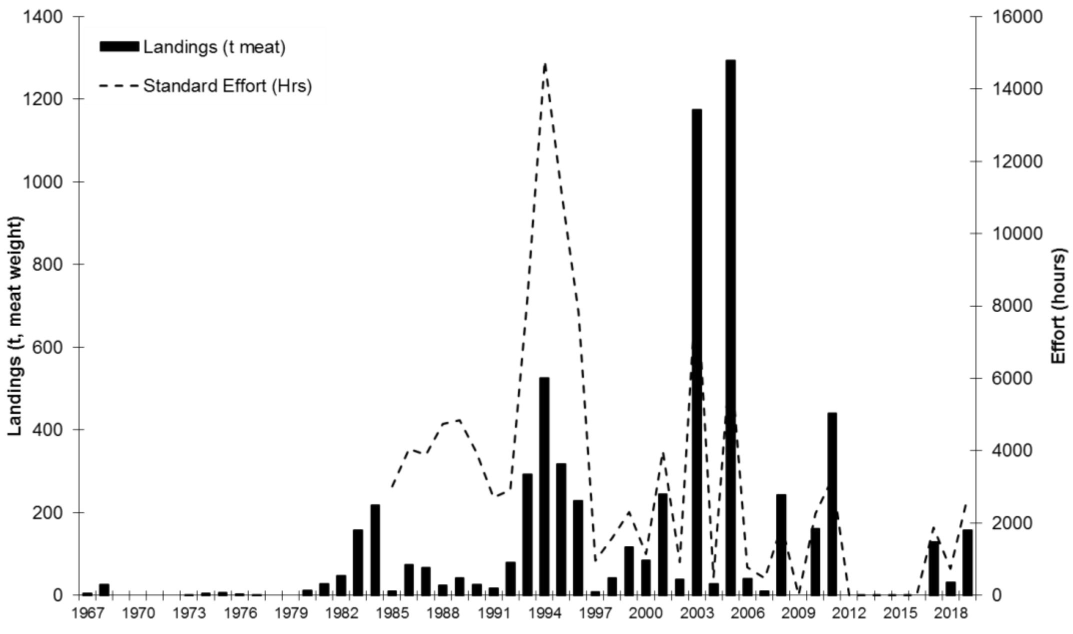


Figure 6-2. Annual total retained catches (tonnes whole weight) and fishing effort (standard hours trawled) in the commercial AIMWTMF between 1967 and 2019 (no fishing between 2012 and 2016).

6.1.2 Current Fishing Activities

A summary of key attributes of the current AIMWTMF and the fishing fleet is provided in Table 6-1.

The physical area of the Fishery includes the waters of the Indian Ocean between 27˚ 51' S and 29˚ 03' S, on the landward side of the 200 m isobath (Figure 6-3). The licenced fishery area extends out into Commonwealth waters, however, many of the principal fishing grounds are within State waters (Figure 6-3). Within the fishery boundary, historically established fishing grounds are known as traditional fishing grounds (Figure 6-4) where fishing with main gear is permitted anytime in the season whereas any other areas need to tested with 'try-gear' to determine scallop abundance prior to fishing (refer to Industry Code of Conduct in Appendix 2).

Historically the fishery operated from the second Tuesday in April (to fit in with the rock lobster fishery in the region) and generally lasted between one and eight weeks, with the length of season dependent on scallop distribution and abundance. In 2003 and 2005 the season was extended due to high scallop abundance. In 2017, the first year fishing was permitted after the severe stock decline after the MHW in 2010/11, the fishing season was set at five months (1 March to 1 August) to allow industry to optimise the meat size and quality.

Table 6-1. Summary of key attributes of the AIMWTMF

Attribute	
Fishing methods	Demersal otter trawl
Fishing capacity	256 m total headrope (140 ftm)
Number of licences	10 (40-50% active)
Number of vessels	Up to 10 (3 in 2019)
Size of vessels	22.5-24.9 m
Number of people employed	30-50
Value of fishery	Highly variable: 2019: $9 million

Figure 6-3. Boundaries and extent of the AIMWTMF. Traditional fishing areas of the fishery are detailed in Figure 6.4.

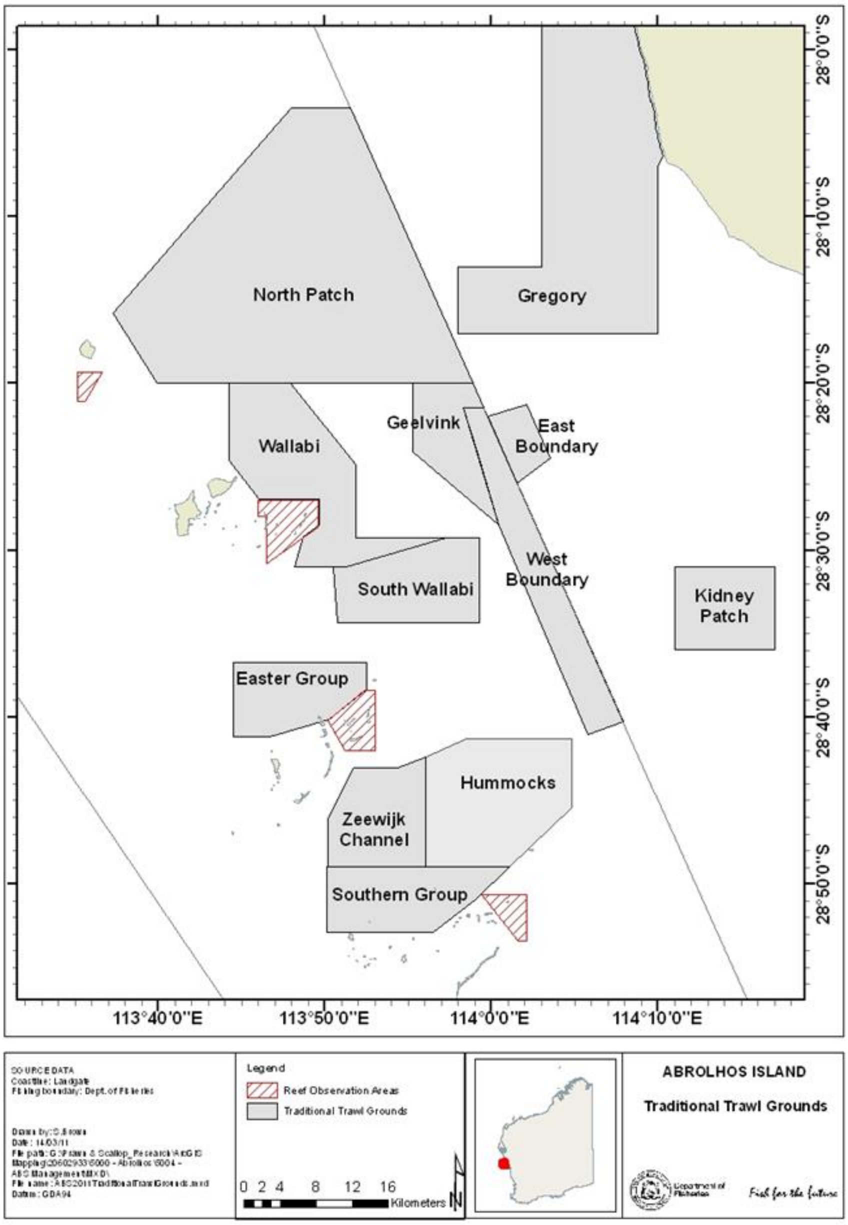


Figure 6-4. Traditional areas of the AIMWTMF, red hatched areas are permanently closed Reef Observation Areas (ROAs).

6.1.3 Fishing Methods and Gear

The fishery currently operates under a maximum total net headrope capacity restriction of 256.1 m. Recent amendments to the management plan have seen the removal of the headrope unitisation scheme in favour of a standardised net headrope allocation where each Managed Fishery Licence (MFL) has an equal allocation of net headrope length. Each licensed vessel is permitted to fish for scallops or prawns, using an otter trawl net or nets with a headrope length not exceeding 25.61 m in scallop fishing areas. This provides for each vessel to operate using two 12.8 m (7 ftm) nets in twin gear configuration. Vessels operating in the prawn fishing area (Port Gregory) are permitted to use a maximum of two otter trawl nets, with each net having a maximum headrope length of 14.62 m (8 ftm).

The boats tow two otter boards, each being no greater than 2.29 m in length and 0.91 m in breadth (DoF 2004). The mesh size of nets must not be less than 100 mm and chafers or liners may not cover more than the bottom half of the cod end. The vessels which target western king prawns in the Port Gregory area of the fishery are permitted to tow nets with mesh no less than 45 mm in the cod end, and 51 mm in the remainder of the net. The trawlers carry the skipper and up to 12 crew.

Scallop trawling is undertaken during both day and night. Trawl shots typically vary from 30 minutes up to three hours, depending on the catch rates. Trawling tow speed is around three knots. Scallops are shucked and processed at sea and frozen and the majority is exported with lesser quantities sold locally or as half shell.

6.2 Recreational Fishery

There is no recreational scallop fishery in the Abrolhos Islands.

6.3 Customary Fishing

Scallops are not a primary target of Indigenous Australians in WA (DPIRD 2020 a,b). There is no quantitative information available on catch, which is likely to be negligible relative to commercial levels.

6.4 Illegal, Unreported or Unregulated Fishing

Negligible.

7 Fishery Management

7.1 Management System

The AIMWTMF is managed to the Harvest Strategy (HS) (DPIRD 2020a) according to a “constant escapement policy”, which was designed to leave a minimum level of saucer scallop spawning stock during each breeding season to ensure that recruitment the following year is not compromised. A predicted catch based on annual fishery independent surveys is provided and a catch rate at which fishing ceases is complied with.

7.2 Harvest Strategy

The HS specifies the target and limit reference levels and associated control rules and are based on the November fishery-independent survey catch rates with regard to the opening of the fishery each year. Commercial catch rates can be monitored daily through the season and scallop fishing can cease within 48 hours if the catch rate (150 kg/day) to cease fishing is reached (see Appendix 2).

7.3 External Influences

External influences include other activities and factors that occur within the aquatic environment that may or may not impact on the productivity and sustainability of fisheries resources and their ecosystems. The relevant external influences included here are environmental factors and market influences and other industries.

7.3.1 Environmental Factors

As a short-lived, invertebrate species, environmental factors have a strong influence on the Abrolhos Islands scallop resource,

7.3.1.1 Climate Change

A risk assessment of WA's key commercial and recreational finfish and invertebrate species has demonstrated that climate change is having a major impact on some exploited stocks (Caputi et al. 2015). This is primarily occurring through changes in the frequency and intensity of El Niño/Southern Oscillation (ENSO) events, decadal variability in the LC, increase in water temperature and salinity, and change in frequency and intensity of storms and tropical cyclones affecting the state (Caputi et al. 2015). In 2010/11, a very strong LC resulted in unusually warm ocean temperatures in coastal waters of south-western WA (Pearce et al. 2011) including at the Abrolhos Islands. This MHW altered the distribution and behaviour (e.g. spawning activity and migration) of some species and caused widespread mortalities of others.

A risk screening of 35 of WA's key commercial and recreational finfish and invertebrate species revealed *Y.balloti* to be highly sensitive to climate change (Caputi et al. 2015).

7.3.2 Market Influences

Scallops are a high value commodity. Market competition for the same species exists with the Queensland and Tasmanian scallop fisheries and with imported scallops (i.e. Canada). The majority of the annual catch is destined for export as frozen scallop meat to Asia, principally via Hong Kong markets. Very small quantities of scallops are left, in the shell or in the half-shell to supply the local gourmet seafood markets. Size and condition of the meat is essential in obtaining high market value for scallop meat, and consequently these factors greatly influence selection of appropriate seasonal opening dates as meat size and condition vary significantly through the year (Joll and Caputi 1995b). Higher prices are usually paid for larger scallops, so it is desirable to open the scallop fisheries when meats may reasonably be expected to be in the range of 20 to 40 pieces per pound (454 grams) criterion, as this size is preferred on the export market.

In 2020, the markets have been highly volatile due to COVID-19 and initial loss of the lucrative Hong Kong markets. Finding other markets and requirements for alternative size packaging of product has required an adaptive scallop industry which has also impacted the amount of scallops that industry desired to catch (in a high scallop abundance year in the Abrolhos) that will be reflected in the total annual landings.

7.3.3 Other industries/tourism/recreational fishing

There has been a long-standing working relationship with the Western Australian Rock Lobster Industry who have fished the region well before the commencement of scallop trawling, however the two fisheries fish over different habitats for their respective target species.

More recently, the establishment of dedicated Aquaculture Zones within the Abrolhos contributes to resources sharing issues as one of these Zones overlap historical scallop trawling grounds. As of 2020, there has been no activity in either zone permitting trawlers to fish in these areas unimpeded.

Tourism in the Abrolhos Islands is becoming increasingly valuable and more recreational fishers are visiting the islands due to changes in the recreational rock lobster rules and increased charter boats available for hire. This will result in a higher visibility of scallop trawlers by other stakeholders even though the trawl grounds are well distanced from areas of tourism and recreational fishing interests.

8 Information and Monitoring

8.1 Range of Information

There is a range of information available to support stock assessment and the HS for the AIMWTMF (see Table 8-1). Both fishery-independent (recruitment and adult catch rates and size during surveys) and fishery-dependent (daily shot-by-shot logbook catch and effort information) and processor unloads make up the information used.

Table 8-1. Summary of information available for assessing the AIMWTMF

Data type	Fishery-dependent or independent	Purpose /Use	Area of collection	Frequency of collection	History of collection
CAES	Dependent	Monthly catch and effort by blocks	Fishery	Monthly	1967 to 1990
Daily scallop logbook data	Dependent	Annual catches and catch rates as indicators of abundance	Detailed shot latitude and longitude	Daily Shot by shot (since 1998)	Logbook since 1991
Processor unloads	Dependent	Validates the estimated catches			Since 1991
Pre-season surveys	Independent	Catch prediction and abundance of recruits (0+) and residuals (1+)	Common sites throughout traditional fishing grounds	November Feb/Mar	Since 1998 Since 2014
VMS data	Dependent	Verify boat locations for logbook analysis		Every fishing season	2001
Environmental (SST, LC, ENSO)	N/A	Correlations between environmental variables and stock abundance	Selected sites within fishing grounds,	Monthly and seasonal and during surveys	Since 1980s, salinity and temperature logger on net during surveys 2019.2020

8.2 Monitoring

8.2.1 Commercial Catch and Effort

Compulsory monthly catch and effort (CAES) returns were required to be submitted by fishers when fishing within the AIMWTMF. From 1991, fishery removals are monitored with a high degree of certainty through daily logbooks which are validated through processor unloads. The monitoring information is comprehensive with regard to fisheries removals as the information is available for all operating vessels. These data are complemented by the fishery-independent surveys. Additional, depletion analysis of fishery-dependent catch and effort on daily catch rates and cumulative catch are conducted if appropriate. This is combined with daily catch monitoring to ensure that fishing ceases around the limit level. The moderate uncertainty around the initial catch prediction is understood and accounted for through comparisons early in the season with fishery-dependent catch rate information and fisher observations.

8.2.1.1 Daily logbooks

Daily logbooks have been completed by commercial scallop fishers since 1991. Daily catch and effort were recorded as shot by shot. The spatial information was initially recorded in a 10

x 10 nautical mile block or fishing ground format. The daily catch and effort information was then summarised by day commencing at 0600 hrs each day and by block up to 1997. Since 1998, spatial information has been collected on a shot-by-shot basis with latitude and longitude co-ordinates (Figure 8-1) for the start of the trawl. The majority of scallops are shucked at sea and most weights recorded as meat weight (meat weight is on average approximately 20 % of the whole weight). For catch, the skippers record the estimated number of baskets of shell (i.e. whole animal) and what the estimated meat weight for that basket of shell is. By comparing the recorded nightly meat weight and the number of baskets of whole shell, the estimated meat weight can be weighted up or down as appropriate. Since 2017 some operators have landed whole shell (and lesser quantities of half shell) and this weight has been recorded and converted into meat weight by a standard formula (whole weight = 5 x meat weight). This is an average and does not take into account any seasonal variability in adductor muscle size/weight due to reproduction.

The data quality (completeness, shot by shot detail for location, trawl start time and duration and water depth and catch amount) from individual skippers is variable but has improved since 2000 (i.e. more accurate estimate when compared to processor unloads). In addition, fishers need to report interactions with ETP species.

The daily logbooks are checked, entered and validated by the trawl science staff on a monthly basis and any possibly erroneous entries or gaps are checked directly with skippers or the fishing company. Annual spatial data validation is undertaken using GIS and random checks of data entry is made through using VMS location records for all fisheries.

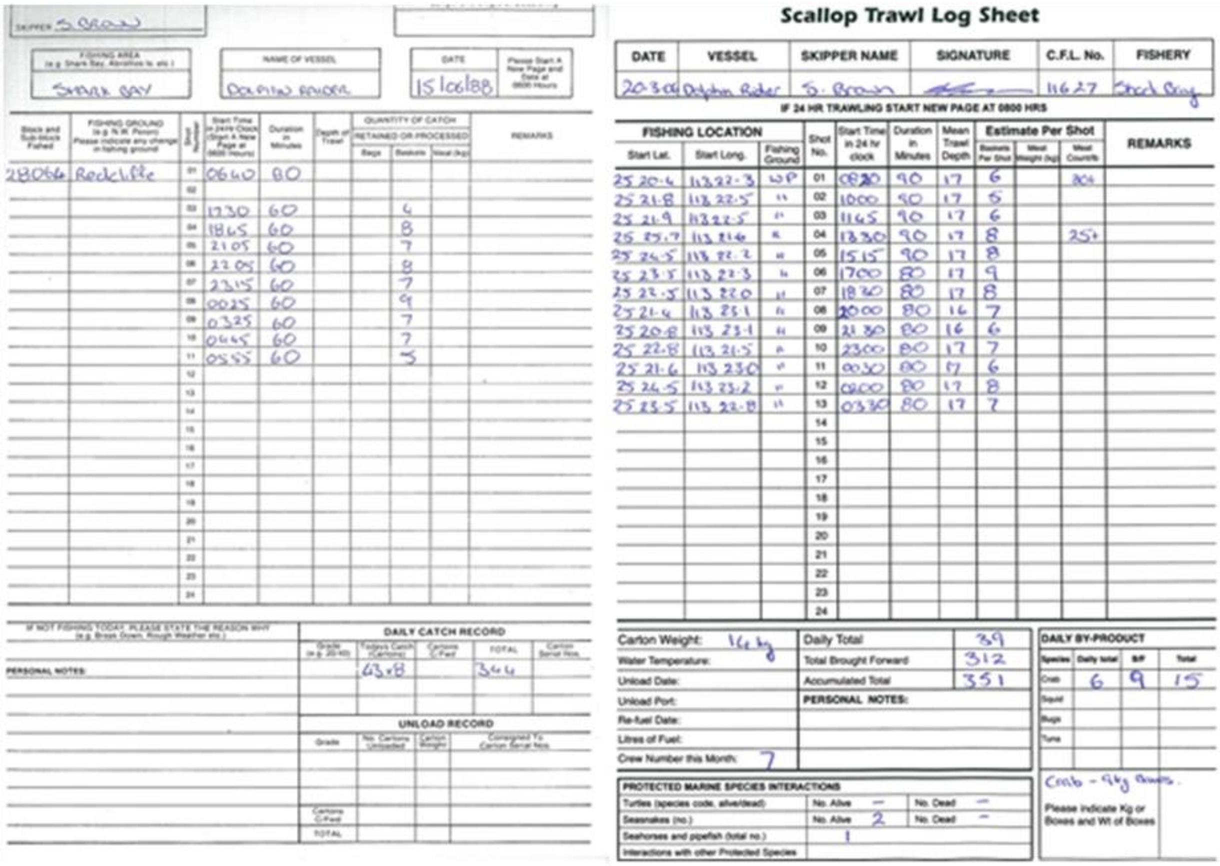


Figure 8-1. Example of a hypothetical completed scallop daily log sheet. Left: historical version, Right: current version including requirement to report interactions with ETP species

8.2.1.2 Processor returns

Catch unload information has been provided by processors since 1991 and is used to validate the logbook data. Licensee catch landings (processor returns) are collected generally on a monthly basis and are used to adjust the daily logbook catch estimates. Licensee catch landings are considered to provide an accurate representation of actual landings because there is a high degree of consistency between these records and daily logbook records. Note that there is no evidence of substantial illegal catches of scallops in any of the fisheries that could affect the accuracy of licensee catch landings data.

8.2.2 Fishery-Independent Monitoring

Since 1997, regular fishery independent surveys have been undertaken in the Abrolhos Islands in November, although the location of sampling sites have been modified since the earlier years. Surveys have also been undertaken in February since 2014 with the November survey providing the long-term data series to enable catch prediction at this stage.

8.2.2.1 Surveys

Scallop surveys have been undertaken annually in their current form (larger number of trawls within designated fishing grounds) since 1997 and are used to estimate scallop abundance (mainly 1+ residuals) and size composition and data on meat size and quality. Typically, 20 – 25 sites are sampled within the key fishing grounds, the locations of which were based on fisher

knowledge and some earlier research surveys (conducted in 1980s) (Figure 8-2). Within the fishing grounds there are designated ‘boxes’ which are approximately 1x1 nm (except the main ground in the Hummocks fishing area which is 2 x 2 nm) and within which trawls need to be undertaken. Up to five sites/trawls occur within a fishing ground, with a minimum of two.

Within the ‘site boxes’ there will be variation annually around the actual trawl paths given the weather and sea state (swell and wave height) but only one trawl is done in one box. The industry sometimes seeks to do further sampling to investigate areas outside the survey boxes such as areas that they caught scallops in the previous fishing year to see if they still contain scallops at reasonable abundances. These additional sites are not included in the survey index but are used by industry to guide their fishing strategies. If a large abundance of scallop is found outside traditional survey sites, they are noted in the Status of Fisheries and Aquatic Resources Report (SoFAR) and considered as part of the weight-of-evidence information for stock assessment. The number of research trawls undertaken within a fishing ground are largely consistent among years particularly for the more southern fishing grounds where traditionally scallops are more abundant. In the northern fishing grounds, sometimes only one trawl is undertaken if the abundance is very low. This means the total index may not provide an accurate reflection of the ‘average’ stock abundance for the whole fishery but leads to a more reliable catch prediction as fishers’ target areas of higher abundances.

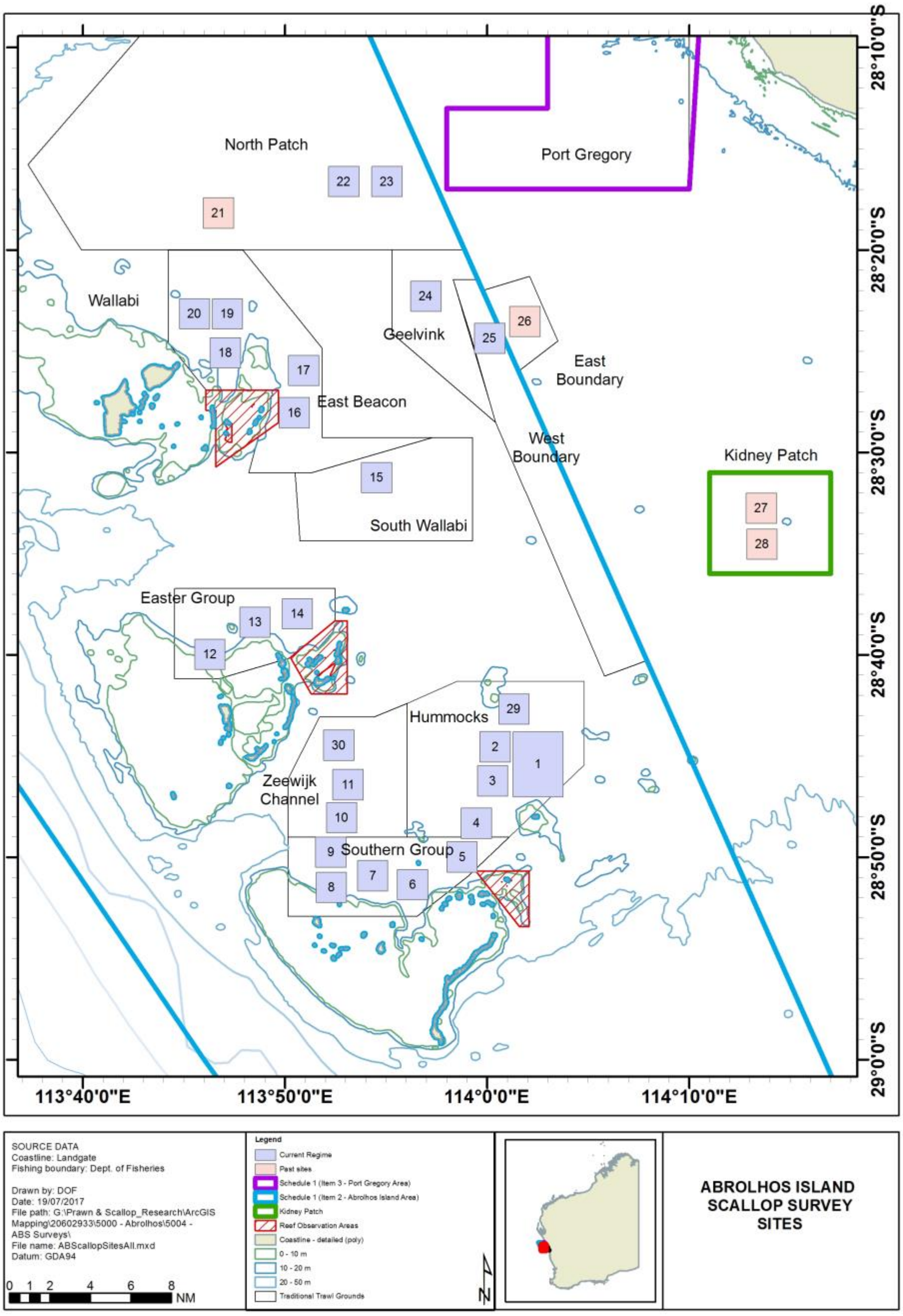


Figure 8-2. Survey sites conducted in November 2017 in the Abrolhos Islands.

The November/December fishery independent survey is generally conducted over two days/nights. Sampling was conducted by industry boats up to 2013 (under direction of Departmental staff on-board), the RV Naturaliste undertook sampling (using the same nets/gear) from 2014 through the closure period of the fishery. Since re-opening the fishery in 2017, an additional survey in February (two nights) has been incorporated into the survey regime with the RV Naturaliste doing the February survey with an industry boat undertaking the November survey with both using the same sampling gear.

Twin six-fathom headrope length flat nets with 50 mm mesh in the panels and 45 mm in the cod-end are used for all surveys. This configuration does not change from year to year although both the RV Naturaliste and commercial boats now use bison boards compared to wooden boards used historically. The duration of each trawl is 20 minutes (trawl period begins when the trawl gear started to fish (winches cease paying out until the commencement of retrieving the trawl gear) and the start and end latitude and longitude is recorded to calculate distance trawled. Processing each shot involves recording numbers of scallops (if the catch is in excess of two baskets, only one basket is counted and the total number of scallops obtained by multiplying the number of scallops in one basket for the total number of baskets). To obtain dorso-ventral length (SH) frequency measurements, a sample of 100 to 150 scallops is taken from one net from each site and if low numbers, both sides are combined.

The survey provides data on the abundance of recruits (0+) and residual (1+) scallops (number per nautical mile) and shell height frequency data for scallops from each sampling site, trawl duration, distance trawled and environmental (depth, water temperature, sea conditions) information for each site. A data logger attached to the trawl gear has been used since 2019 to record salinity and temperature information during each trawl. All of these data are entered (with manual checking) into an Access database.

8.2.2.2 **Adjustment of abundance data**

As the speed at which trawling takes place influences the efficiency of the trawl gear (Figure 8-3, L. Joll, unpublished data, Department of Fisheries) the catch (by recruit, residual and total) is standardised according to:

$$c_{st} = \frac{c}{3.2331 - 0.6485v}$$

where v denotes the trawl speed in knots and c and c_{st} the catch and the standardised catch respectively (see also Mueller et al. 2008) i.e. the equivalent catch at a speed of 3.4 knots. The standardised number of residuals, recruits and total number of scallops were further converted to densities, d, taking into account the distance trawled and the number of nets and their spread,

$$d = \frac{c_{st}}{2Tw}$$

Here, T and w denote the shot distance and the width per net in nautical miles, assuming a width of six fathoms (10.97 m) head rope for each net.

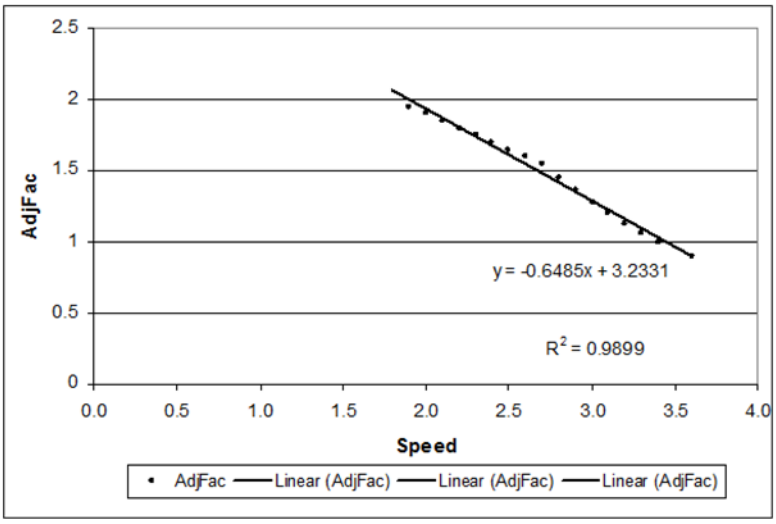


Figure 8-3. Adjustment factor in relation to trawl efficiency with speed compared to a standard 3.4 knot.

8.2.2.3 **Spatial Extent of the Fishery**

The spatial extent of fishing (referred to as the trawl footprint) is calculated by combining the compulsory fishery-dependent logbook data and fishery-independent satellite (VMS) data from 2010 to 2019 (noting 2012 to 2016 were closed to fishing). For each trawl shot, the logbook data includes a start location (latitude and longitude), date and time (AWST) and duration of each trawl on a given fishing day. The VMS collects spatial information for each vessel, including vessel call signs, location (latitude and longitude), date and time (UTC), speed and bearing, and stored securely at DPIRD.

The dates and times provided by the VMS data was converted to AWST (UTC + 8 hours) and the two datasets were combined using a unique identifier, which included vessel name, date and time. Any logbook data that did not have a start time but had a trawl duration and was the first shot of the fishing-day, was assigned an estimated start time of 12:00 midday. An end time was assigned to each individual trawl, based on the trawl start time and trawl duration. A subset of the VMS data was derived, given the start and (assigned) end time of each trawl, as per the fishery-dependent logbook data (hereafter referred to as VMSLB data). The VMSLB dataset increases the spatial accuracy of the trawl footprint by collating additional, fishery independent, information on vessel/s spatial location when fishing. All data manipulations were performed using R (Version 3.5.2), and subsequent analyses of the trawl footprint were conducted using ESRI ArcMap (Version 10.6).

To estimate the spatial extent of the trawl footprint per fishing season, a 500 m^2 grid was created incorporating the entire AIMWTMF excluding areas that are permanently closed to fishing (e.g. Reef Observation Areas). The cell size was based on the fishing patterns, including average speed and direction. VMSLB data from all vessels operating within the AIMWTMF for the season was aggregated into this spatial grid, and each grid cell that contained VMSLB data was considered to be fished (Figure 8-4a for 2019). Therefore, an entire grid cell was considered to be fished if a single VMSLB data detection point occurred within it,

acknowledging that this method will overestimate the trawled area, but enables standardisation for different gear sizes, spread-ratios and tow speeds within the fishery. Finally, the spatial extent of the trawl footprint for an extended period was estimated by combining the sum of effort for all VMSLB data (i.e. cumulative effort) when the fishery was operational between 2010 and 2019, inclusive, and is based on the presence or absence of VMS detections within the 500 m^2 cells (Figure 8-4b).

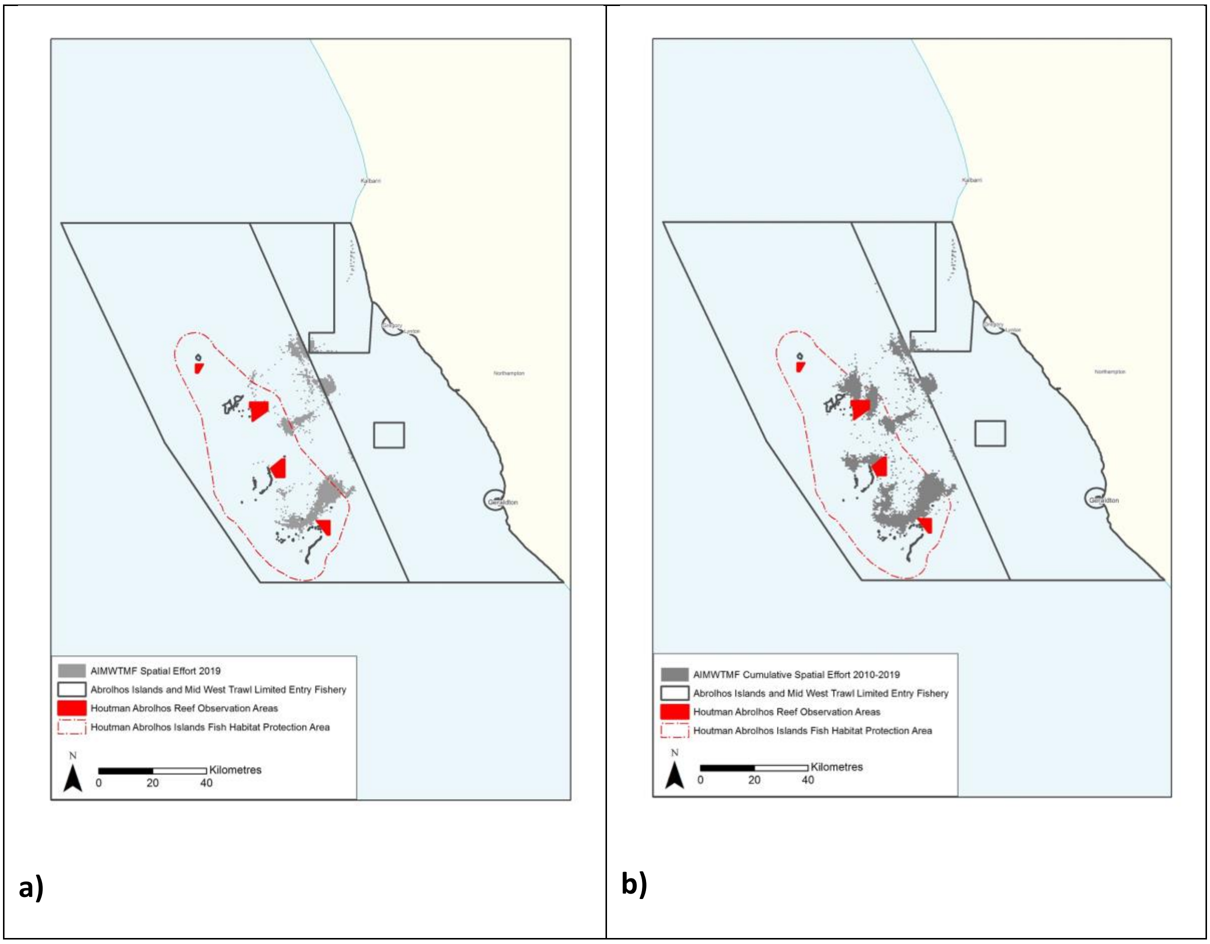


Figure 8-4. a. AIMWTMF 2019 spatial effort (grey shaded). Individual blocks are representative of a 500 m^2 area. b). AIMWTMF 2010-2019 cumulative spatial effort (grey shaded). Individual blocks are representative of a 500 m^2 area. Note that in 2012 to 2016 fishery was closed.

Based on the VMSLB data, cumulatively, between 2010 and 2019, the trawl footprint of the AIMWTMF was 573 km^2, which accounts for 4.35% of the AIMWTMF (Figure 8.4b). Of this spatial effort, 380 km^2 occurs within the Houtman Abrolhos Islands (Abrolhos) Fish Habitat Protection Area (FHPA), which equates to ~15% of the total area of the FHPA. For the 2019 individual season, the AIMWTMF trawl footprint covers an area of 333 km^2, which is ~2.5% of the total area of the AIMWTMF (13165 km^2) (Table 8-2, Figure 8-4a). Of the 2019 effort, 156 km^2 occurs within the Abrolhos FHPA, which equates to ~6.25% of the total area of the FHPA (Table 8-2, Figure 8-4a).

Table 8-2. *Total annual AIMWTMF spatial effort and spatial effort within the Abrolhos FHPA (km²) since 2001.*

Year	Total Spatial Effort of Fishery (km^2)	Spatial Effort within FHPA (km^2)	Vessels Operating
2001	189	96	16
2004	93	66	16
2005	416	291	17
2006	79	71	14
2007	47	40	14
2008	210	190	15
2010	188	170	15
2011	237	229	8
2017	139	120	4
2018	107	95	4
2019	333	156	5

8.2.2.4 **AIMWTMF Fishing and Habitat Association**

AIMWTMF and habitat associations was undertaken on the most recent broad-scale mapping that could be obtained for areas of the fishery. Two of the maps used hydro-acoustic mapping techniques, Radford et al. 2008 (Marine Futures) and DoF, 2016 (Midwest Aquaculture Development Zone), and the other satellite remote sensing (Evans et al. 2012) (Figure 8.5). The Marine Futures and Midwest Aquaculture Development Zone (MWADZ) maps provide the most comprehensive spatial extent of broad habitats in relation to AIMWTMF fishing effort. Overlaying the 2010-19 AIMWTMF effort data on the Marine Futures Project habitat map (Radford et al. 2008) (available habitat data shown in Figure 8-5), shows that the AIMWTMF predominantly occurs on sand (57.9 %), with mixed reef and sand (38.1 %) and reef habitat (3.3 %). This is comparable to the effort observed within the MWADZ habitat (Figure 8-5) (DPIRD unpublished data 2015), of which 91.9 % targets sand, 1.4 % sparse mixed assemblage, 1 % mixed assemblage, 0.2 % reef and 0.2 % sand/mixed assemblage. An additional 5.3 % defined as “none modelled with confidence”.

The area fished within the Abrolhos FHPA is relatively low, on average ~6.7 % of the total area per year between 2010 and 2019 and cumulatively ~15 % of the total Abrolhos FHPA for 2010-2019. Where habitat data is available within the Abrolhos FHPA, it confirms AIMWTMF fishing also occurs primarily on sand substrate.

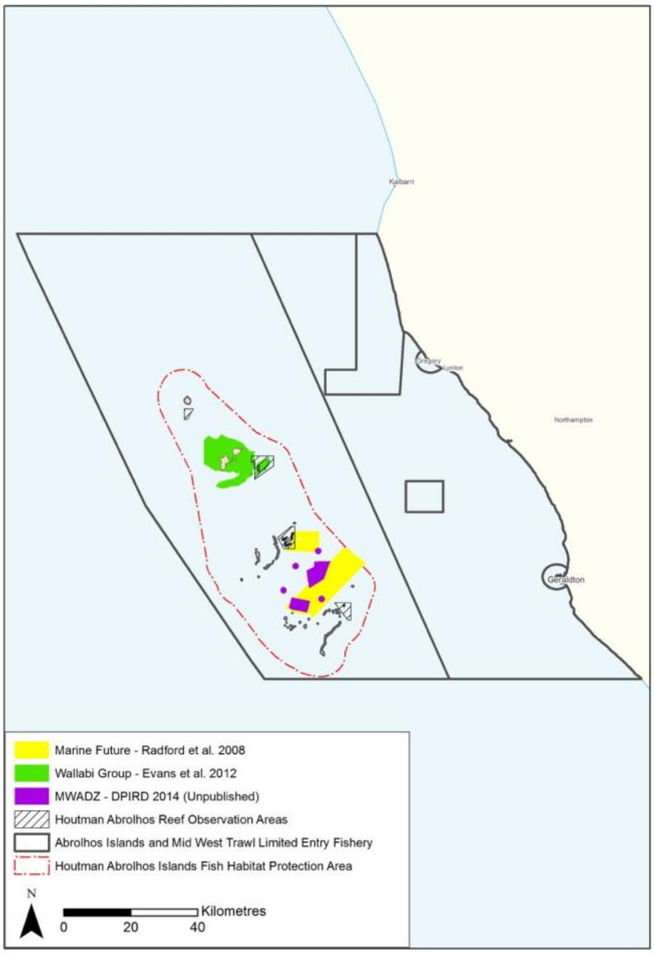


Figure 8-5. Recent examples of the spatial distribution of habitat mapping available for AIMWTMF

8.2.2.5 Habitat Management

Long-term management plans are embedded in both the AIMWTMF and the Houtman Abrolhos Islands Management Plans and includes management of the AIMWTMF following an Ecosystem Based Fisheries Management (EBFM) approach. This includes management measures such as, gear restrictions, permanent closures and the development of technology to reduce impacts of fishing activity on the habitats. Ongoing assessments of the impacts of fishing on habitat types, will include annual monitoring of the spatial extent of the trawl footprint, on-board observers during by-catch surveys and ongoing video assessment and predictive mapping of habitats.

8.2.2.6 Environmental monitoring

Databases with environmental variables (e.g. water temperature, wind and sea level) are continuously updated and extended as new data become available from collections by the Department, internet sources and from other agencies (see Caputi et al. 2015 a, b, Chandrapavan et al. 2020). These data are used to explore the extent to which these factors affect recruitment strength (Lenanton et al. 1991, 2009, Chandrapavan et al. 2020) and whether the environmental conditions are likely to be conducive for good recruitment which can influence harvesting strategies. The MHW (Caputi et al. 2015, Caputi et al. 2016) significantly impacted scallop stocks in the Abrolhos Islands and therefore extreme events and climate change continues to be a key focus for this fishery. The environmental data is also used to assess the stock-recruitment-environmental relationship (Caputi et al. submitted).

9 Stock Assessment

9.1 Assessment 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 catch rates, through to the application of more sophisticated analyses and models that involve estimation of fishing mortality and biomass. 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 risk-based, weight-of-evidence 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 inherent vulnerability of the species to fishing. For each species, all of the lines of evidence are then combined within the Department’s ISO 31000-based risk assessment framework (see Fletcher 2015; Appendix 2) to determine the most appropriate combinations of consequence and likelihood to determine the overall current risk status.

9.2 Assessment Overview

A range of fishery-dependent and independent indices are used to assess the Abrolhos Islands scallop stock.

9.2.1 Peer Review of Assessment

Annual internal reviews are undertaken as part of the process for completing (and updating) the Departments annual SoFAR and as part of the Status of Australian Fish Stock Reports (fish.gov.au).

The Department of the Environment for the Australian Government assessed the fishery in 2015 as being sustainable under the provisions of the Environment Protection and Biodiversity Conservation (EPBC) Act 1999. This has provided the export accreditation for the fishery for a period of ten years until May 2025. An external review by Professor Malcolm Haddon was conducted for Shark Bay prawn and scallop fisheries in 2019 and the science and stock assessment methodology for scallops in the AIMWTMF reflect that conducted in Shark Bay (Haddon, unpublished).

The fishery has commenced a third party Accreditation process with the Marine Stewardship Council in late 2020.

9.3 Analyses and Assessments

9.3.1 Data Used in Assessment

Logbook / Processor returns / VMS data Economic data Environmental data Fishery-dependent data Fishery-independent survey data

9.3.2 Catch and Effort Trends

9.3.2.1 Commercial Catches

Scallop landings from the AIMWMTF have fluctuated markedly from <20 tonnes (meat weight) to up to 1300 tonnes (meat weight) (Figure 6-2, Table 9.1). The fishery has also been closed to fishing due to low abundances of scallops (2009 and 2012-2016). Fluctuating landings are largely a reflection of high recruitment variability, including recruitment impairment post-2010/11 MHW.

The daily catch (kg per 24 hours trawled) is used in the HS with a reference level of 150 kg/24 hours trawled to cease fishing (2019 in

Figure 9-1).

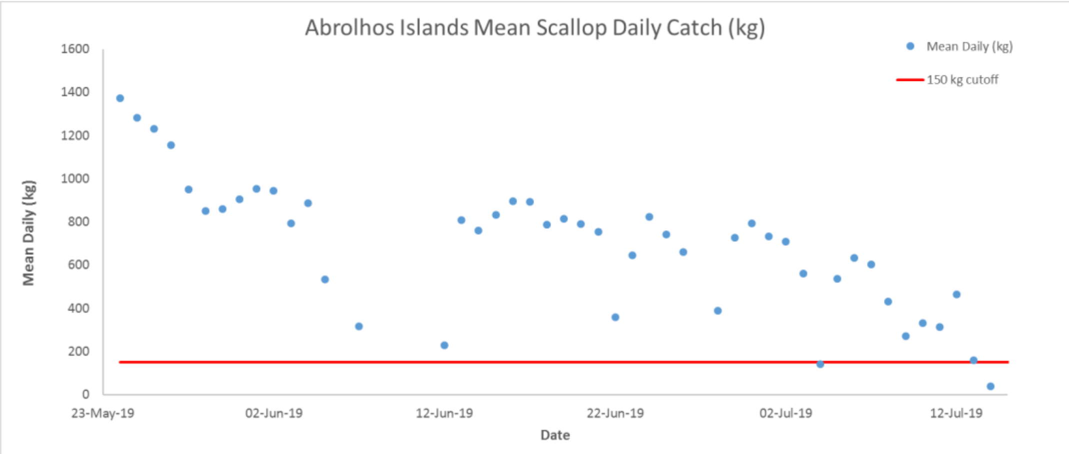


Figure 9-1. Mean daily fleet catch for the first two weeks of the fishing season in the AIMWTMF for 2019 indicating the 150 kg/24-hour reference level for cessation of fishing.

9.3.2.2 Commercial Effort

Fishing effort is generally commensurate with the abundance of scallop stocks with fishers ceasing to fish when catches become uneconomic. Higher costs of fishing and variable market prices for scallops influence level of fishing effort. Due to the high variability in annual stock abundance, the amount of total effort in this fishery since 1985 has been between 468 and 14782 trawl hours. Currently there are 10 licenses in this fishery where historically there were 15 (Figure 6.2, Table 9.1). In 2019 five boats actually operated for a total of 77 days fishing and 2728 trawl hours (standardised effort to 14-fathom headrope). This was a threefold increase in effort compared to 2018 and this increase in effort was expected due to the higher scallop abundance indicated by surveys and exploration of alternative fishing grounds.

9.3.2.3 Spatial Effort Distribution

The spatial effort distribution is dependent of the abundance within each traditional fishing ground and if/when skippers locate abundances of scallops in areas not surveyed. In high scallop settlement years when the distribution of scallops is widely dispersed (i.e. in 2003 and 2005, Figure 9-2a) fishing can occur in all main trawl grounds, whereas in some years it is primarily directed at only one of two fishing grounds (i.e. 2017, in the Hummocks, Figure 9-2b).

Table 9.1 **S**callop landings (t meat weight), number of boats fishing, nominal and standardised effort (hrs), swept area and standardised catch rate (meat weight kg/h), days fished and total boat days in the AIMWTMF, 1985-2019. N/A- no fishing

Year	Total Landings (t meat wt)	Total Landings (t whole wt)	Boats Fishing	Nominal Effort (Hrs)	Standard Effort (Hrs)	Swept Area (nm2)3	Standardised catch rate (kg meat/hr)	Days Fished	Boat Days
1967	4.6	23	3						
1968	25.9	129.5	8						
1969	0	0	0						
1970	0	0	0						
1971	0	0	0						
1972	0	0	0						
1973	0.3	1.5	3						
1974	4.2	21	4						
1975	6.7	33.5	6						
1976	2.9	14.5	4						
1977	0.8	4	3						
1978	0	0	0						
1979	0	0	0						
1980	12.3	61.5	2						
1981	28.5	142.5	6						
1982	47	235	9						
1983	158.2	791	22						
1984	219.1	1095.5	40						
1985	10	50	27	3566	3011		3		
1986	74.2	371	28	4799	4052		18		
1987	67.6	338	16	4612	3894		17		
1988	23.6	118	20	5615	4741		5		
1989	43.1	215.5	14	5737	4844		9		
1990	25.8	129	20	4670	3943		7		
1991	17.5	87.5	12	3214	2713		6		
1992	80.2	401	8	3449	2912		28		
1993	292.2	1461	12	9635	8135		36		
1994	526.7	2633.5	19	17508	14782		36		
1995	317.4	1587	19	13185	11132		29		
1996	228.7	1143.5	17	9280	7835		29		
1997	8.8	44	7	1138	961		9		
1998	42.3	211.5	16	1915	1600	39.8	26.4		
1999	117.7	588.7	16	2865	2307	57.4	51		
2000	85.7	428.5	14	1281	1134	25.3	75.6		
2001	244.1	1220.6	16	4773	3998	86.2	61.1	21	89
2002	38.9	194.7	15	1048	912	20	42.7	10	93
2003	1174.8	5874.0	16	10382	8765		134	92	544
2004	28.8	144.1	16	811	498		58	26	69
2005	1294.0	6470.0	17	8691	6654	173.7	195	86	1130
2006	40.7	203.3	14	878	783	22.5	52	10	105
2007	9.6	48.0	14	521	468	12	21	3	39
2008	243.2	1216.0	15	2348	1946	48	125	21	296
2009	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2010	161.3	806.5	15	2751	2269	60	71	22	294
2011	440.6	2202.9	8	3240	3240	85.9	136	69	513
2012	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2013	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2014	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2015	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2016	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2017	130.2	650.9	4	1878	1878	49.8	69	52	163
2018	31.0	154.8	4	731	731	19.4	42	29	61
2019	159.1	795.6	5	2728	2728	67.9	58	77	236

* The fishery did not open in 2009 / 2012 / 2013 / 2014 / 2015 /2016 due to low abundance of scallop

1. **Nominal Effort**: Total number of hours fished by the whole fleet, regardless of net headrope length.
2. **Standard Effort (effective effort)**: Total number of hours fished with each vessel standardised as if towing nets with 14 fathoms of headrope length. ie. for each vessel: std hrs= total hours fished x (headrope length (fthm)/14)
3. **Swept Area**: $\frac{\text{standard effort (hrs) x speed (kts) x headrope length (fthms) x net 'inefficiency' factor}}{\text{No. fathoms in a nautical mile}}$

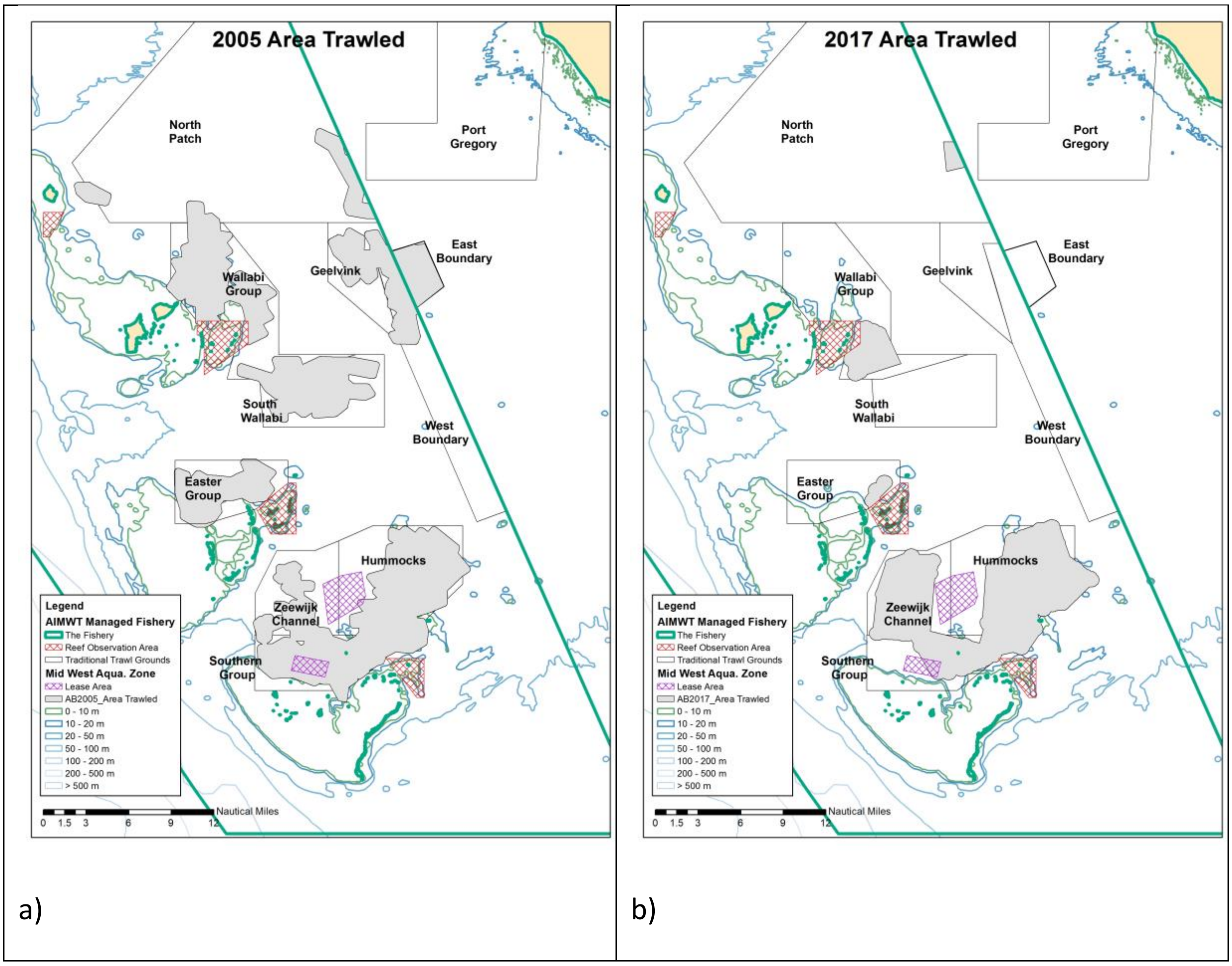


Figure 9-2. Examples of the spatial distribution of fishing effort within the AIMWTMF a) high abundance years 2005 b) post heatwave primarily within Hummocks area in Southern Group in 2017. The grey shading indicates the areas trawled.

9.3.3 Fishery-Dependent Catch Rate Analyses

Daily logbooks provide information on catch (meat weight) and time trawled for each trawl conducted in the fishery. This allows for catch rate analyses by season (Figure 9-3), month, boat, fleet (all boats), day and location. Due to the patchy nature of scallop aggregations and settlement annual catch rates are highly variable.

Since the early 1990's the fishery dependent catch rates have ranged between 10 and 195 kg meat/hour (Figure 9-3). Exceptionally high catch rates (kg meat/hr) of scallops have been observed in 2003, 2005, 2008 and 2011 due to very high and/or widespread recruitment in the preceding year. The relatively high catch rate observed in 2011 was in part due to a restructure in the fleet, reducing number of boats operating and thereby maintaining higher catch rates. The catch rates in that year, could have been even higher, however, the scallop stocks were negatively impacted by the MHW. Since the re-opening of the fishery in 2017 the scallop fleet mean annual commercial catch rates have been between 40 and 70 kg meat/hour.

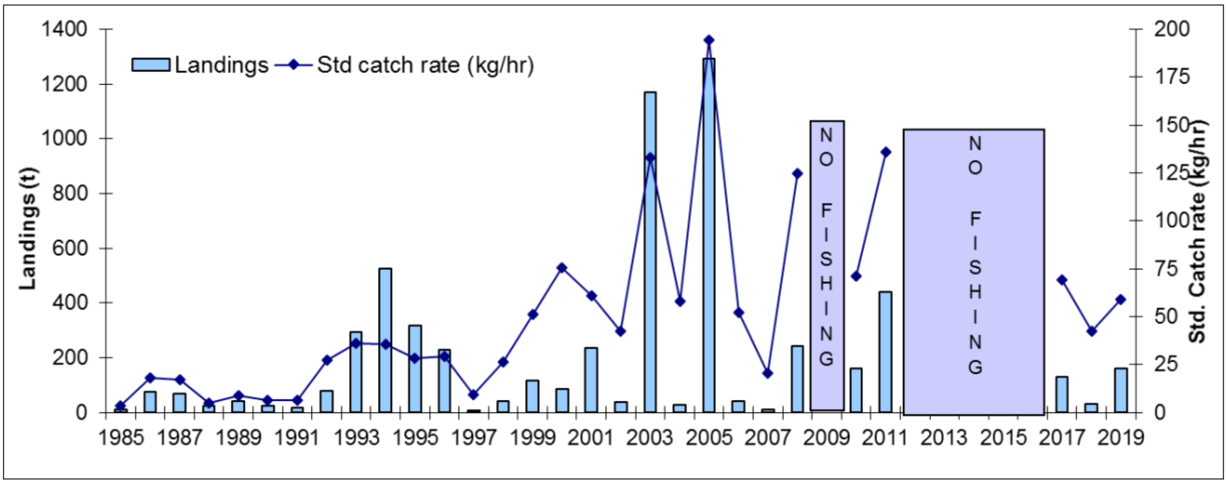
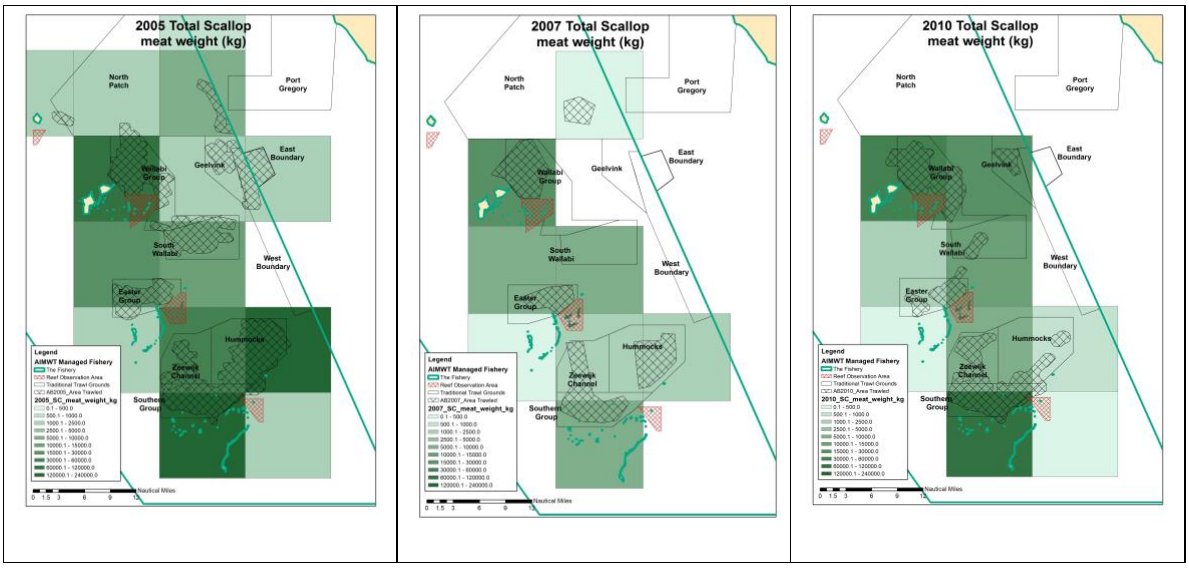


Figure 9-3. Fishery dependent commercial annual fleet landings and catch rates (kg meat/hr trawled) for the AIMWTMF between 1985 and 2019. The was no fishing in 2009 and the fishery was closed 2012 to 2016.



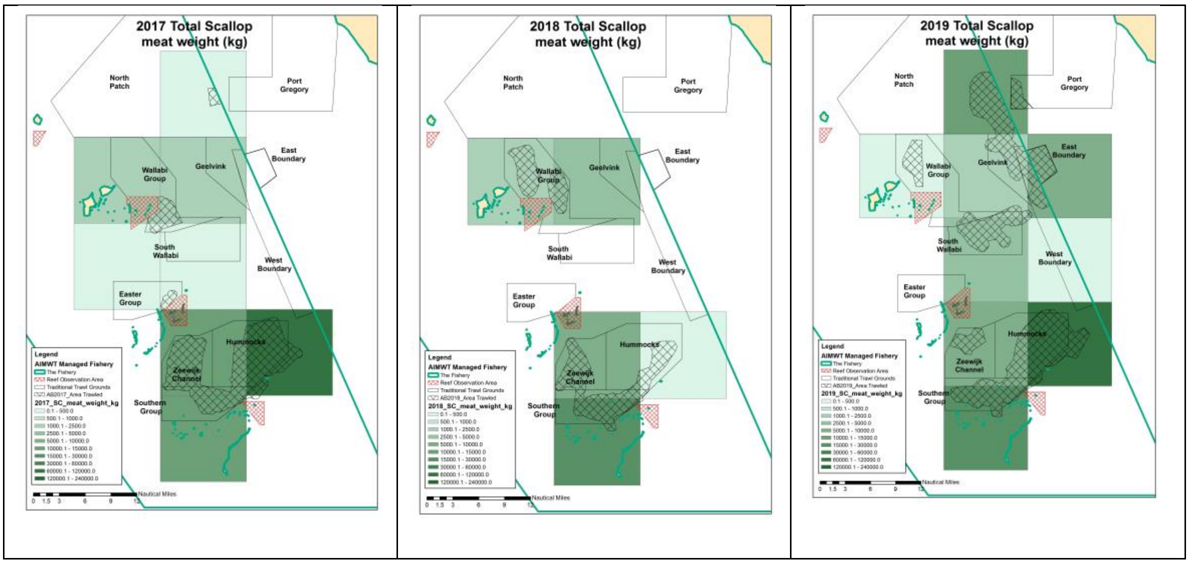


Figure 9-4. Fishery dependent commercial annual fleet catch rates (kg meat/hr trawled) for the key fishing grounds in the AIMWTMF in 2005, 2007, 2010 2017, 2018 and 2019.

Depletion analyses

The daily logbook catch rate data can be used in depletion analyses to estimate i) exploitation rates and ii) the biomass of the scallop stock at the beginning of the fishing season. This information can be used to complement the catch prediction estimate using the fishery-independent survey indices (see 9.3.4.3).

Using the Leslie method (Ricker 1975), the catch per unit of effort (CPUE at time t) is linearly related to the cumulative catch up to that time-1 (days);

$$CPUE_t = qN_0 - qK_{t-1}$$

where K_{t-1} is the cumulative catch up to the previous day, q is the catchability coefficient (the magnitude of the slope), and qN_0 is the intercept which is used to determine initial biomass i.e. by dividing the estimated intercept by $\hat{q}$. Note that until present, the analyses have differed from the above description as the catch rate was regressed against cumulative catch at time t instead of t-1. However, impact of this has been explored and shows almost negligible effect on the biomass estimate. In the future the analysis will be based not just on the description given but also using an alternative method including the Ricker adjustment (Ricker 1975). Hilborn and Walters (1992) note that the index of abundance for the Leslie method can be either catch or CPUE. Furthermore, they note that the data used as an index of abundance in the Leslie method can be independent of the data used to measure cumulative catch.

The Leslie method for estimating the initial biomass is built upon six assumptions:

1. The population is closed (i.e. closed to sources of animals such as recruitment and immigration and losses of animals due to natural mortality and emigration). As scallops in Shark Bay constitute a functionally separate stock (see Section 4.2), scallops are sedentary and the fishing season is short (less than two months), this assumption is likely to be true. There is also an assumption that the area fished by the fleet is relatively consistent.

2. Catchability is constant over the period of removals. For the short period of fishing there are no major seasonal environmental effects on catchability. Some reduced catch rates have been observed during the season because of strong swell conditions.

3. Enough fish must be removed to substantially reduce the catch-per-unit-effort. The historical catch data clearly demonstrate for this to be true.

4. The catches remove more than 2 % of the population. As above.

5. All fish are equally vulnerable to the method of capture. The net mesh size that is permitted by scallop (and prawn) fishers is of a size that ensures that the scallops are fully vulnerable to the fishing gear. Changes in the spatial distribution of effort can affect this assumption; however, the fleet would generally focus on the area

6. The units of effort are independent. The catch rates are based on the scallop fleet only and the fishers are assumed to operate relatively independently of each other and thus the individual units of effort (for each boat) are assumed to be independent. Because the prawn fleet do not directly target scallop effort from this sector is excluded from the analysis. In addition, the usual assumptions of simple linear regression also apply.

The daily scallop fishing within a small spatial area within the Hummocks fishing grounds in the Abrolhos Islands in 2017 (Figure 9-5. Daily cumulative catch and catch rate for four boats fishing within the Hummocks area of the Abrolhos islands during 2017. Red line indicated approximate limit for cessation of fishing as indicated in the Harvest Strategy.), by four boats, provided an opportunity to determine a weekly harvest rate ((CPUEinitial-CPUEfinal)/CPUEinitial)/ (days fished/7) for this region of 0.17. This is within the range observed in Denham Sound (between 0.15 and 0.39 wk^{-1}) and 0.16 and 0.31 wk^{-1} in northern Shark Bay. Dredge (1985) determined that Z (total mortality) for a given statistical fishing block in central Queensland did not exceed 0.16 wk^{-1}.

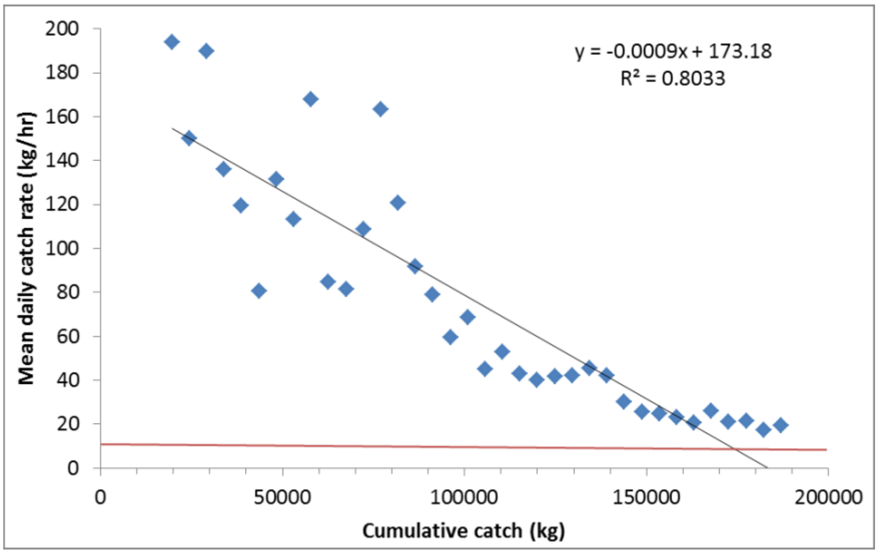


Figure 9-5. Daily cumulative catch and catch rate for four boats fishing within the Hummocks area of the Abrolhos islands during 2017. Red line indicated approximate limit for cessation of fishing as indicated in the Harvest Strategy.

9.3.4 Fishery Independent Data Analyses

9.3.4.1 Annual indices of abundance

The annual mean abundance index within Abrolhos Islands is highly variable (Figure 9-6), depending of scallop abundance. The index is calculated as the mean abundance of all scallops sampled in the November survey, due to primarily one cohort being evident at this time of year in the majority of years (Figure 9-7).

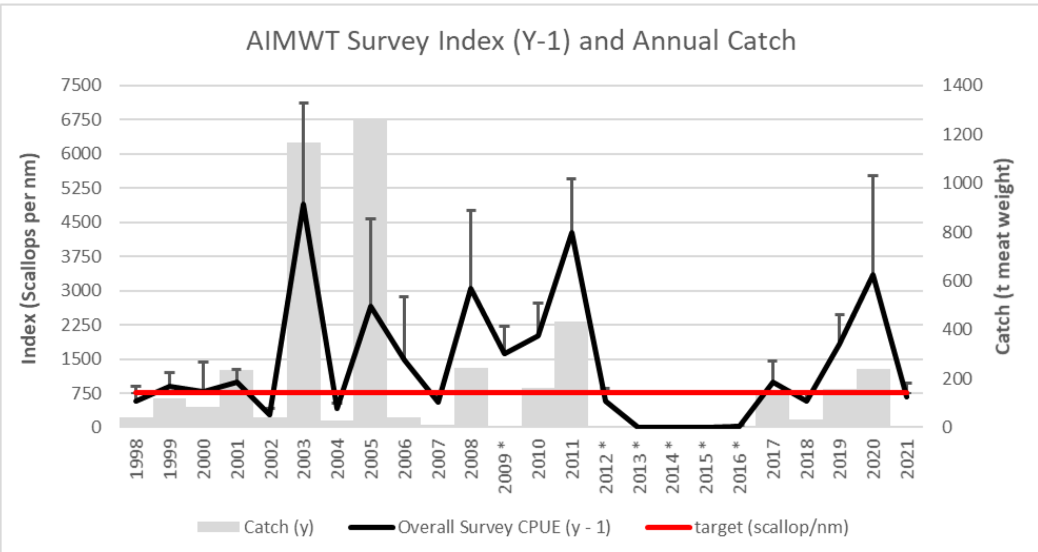


Figure 9-6. Annual pre-season scallop abundance (no/nm + s.e.) in November (Y) for the AIMWTMF between 1998 and 2020 and commercial landings (t meat weight). The red line indicates the target reference level for scallop abundance (no/nm trawled) for November. * No fishing.

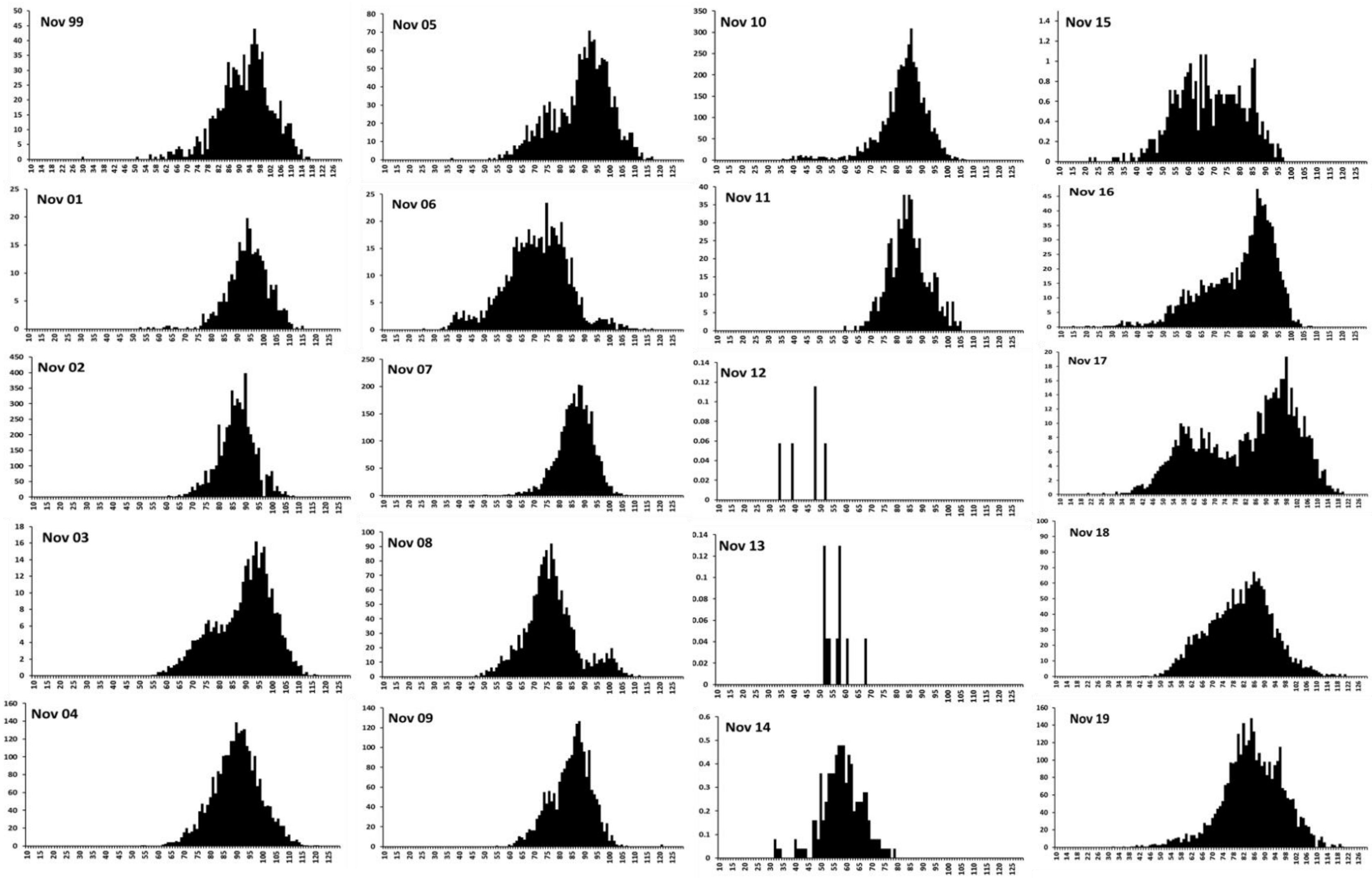


Figure 9-7. Shell height frequencies of *Ylistrum balloti* in November surveys between 1999 and 2019 (Y-axis is CPUE, numbers/nm, note different scales for MHW years).

Since 2014, annual surveys have been additionally conducted in February/March. Extremely low scallop abundances were evident in 2014 and 2015 with a moderate increase in 2016 (allowing fishing to commence in 2017). During February/March, two cohorts are observed showing clear recruit (0+) and residual (1+) individuals (Figure 9-8). The value of these surveys are to indicate areas of small scallops to avoid during the upcoming commercial surveys (commence in March/April) and may be incorporated into future stock assessments once more years of data are available.

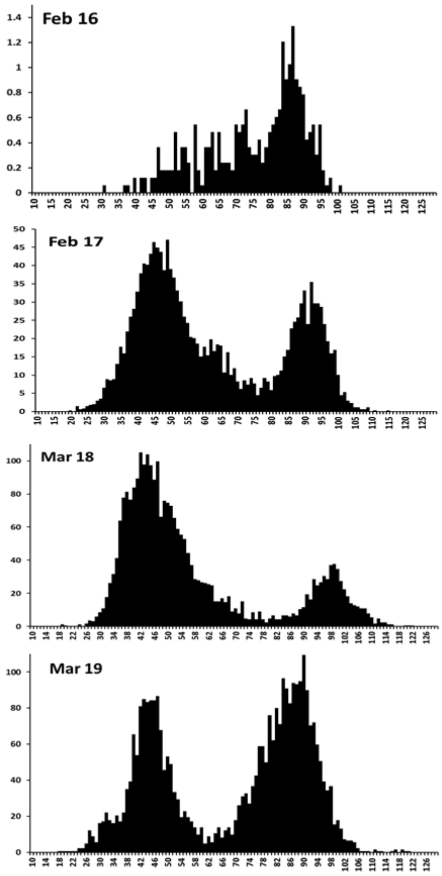


Figure 9-8. Shell height frequencies of *Ylistrum balloti* in February/March 2016 to 2019. Note different Y-scales for 2016 and 2017 due to lower abundance.

9.3.4.2 Trends in Age and Size Structures

Saucer scallops are short-lived (maximum of 3-4 years) with relatively fast growth in the first year until maturity and then growth slowing considerably. Annual variability in the relative abundance of recruits and residuals are evident as a result of; variable recruitment success, fishing and variable survival of residual stock. In some years several recruiting cohorts are evident reflecting settlement pulses.

Due to key spawning period being September to March, the older age classes (1+) tend to merge resulting in one cohort in November (Figure 9-7) in most years. For November surveys, nine of the 20 surveys indicate one cohort at around 80-90 mm SH (Figure 9-7) with most of these nine years being pre-MHW. Scallops at this size in November are likely to be 8 months or older During the years of scallop recovery post MHW, once scallop abundance had improved, two cohorts are evident, one around 55-60 mm SH and the other 85 to 95 mm SH which may imply a more protracted spawning period post MHW with larger individuals derived from spawning at the start of the spawning period and the smaller scallops from spawning towards the end of the period. The size composition in November 2019 however appears to be more similar to years prior to the MHW. This may be due to cooler water temperatures experienced in the last two years (marine cold spell, Feng et al. in press) potentially reducing the length of the spawning period. In contrast, for February, 0+ individuals around 45 mm SH are seen in the annual surveys with the 1+ individuals ranging between 80 and 95 mm SH (Figure 9-8).

9.3.4.3 Catch Predictions

The November (Y) survey data have been used to determine an index of abundance (proxy for recruitment although the individuals can be 1+) i.e. individuals derived from spawning September (Y-1) to March (Y). These data provide the basis for predicting the catch the following fishing season (Y+1). A relatively good correlation between the survey index and annual commercial catch is evident (

Figure 9-9) although areas of scallop abundance can be located by fishers outside of the standard survey sites which can add to total landings in some years.

The November fishery independent survey indices provide a mean abundance index and the survey index-annual catch relationship informs, with some uncertainty the likely catches in the following fishing season. Following the restructure of the fleet in 2011 and resumption of fishing in 2017, the fishing season has been extended to enable the reduced fleet to harvest the available catch. Supplementary information is available from an additional survey conducted in February and are yet to be formally incorporated into stock assessment.

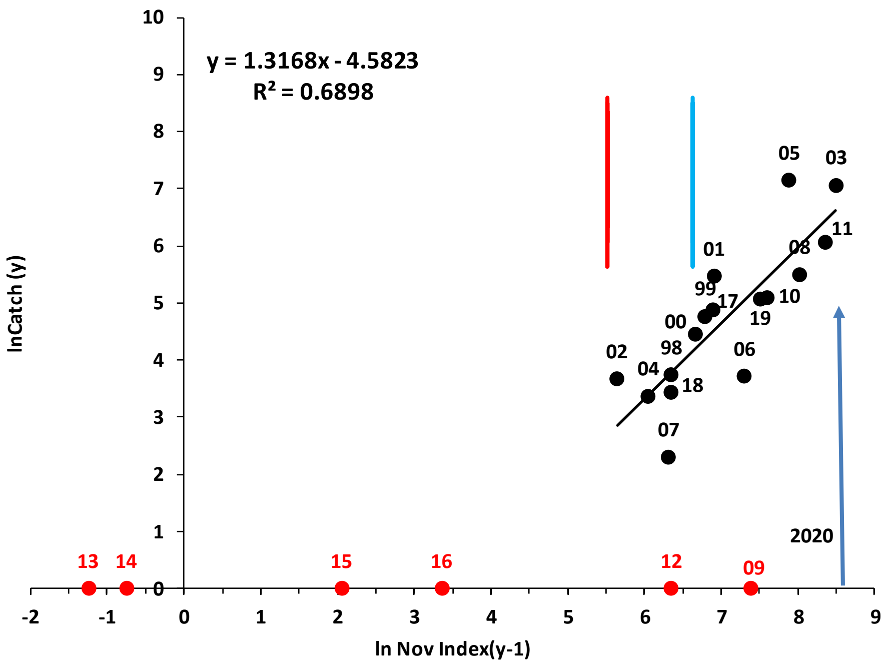


Figure 9-9. Relationship between the annual mean scallop abundance index (ln total scallops/nm trawled (Y-1)) in November with the annual landings (ln Catch Y, t meat weight). Years when no fishing occurred are in red. The red vertical line represents the limit reference level and turquoise line the threshold level. The years shown are the catch years and 2020 catch prediction from the 2019 survey index is indicated by the blue arrow.

9.3.4.4 **Stock-Recruitment-Environment Relationships**

Environmental conditions have also been identified as a driver of recruitment variability of the scallop stocks in the Abrolhos Is. with SST (which is influenced by the Leeuwin Current) having a negative relationship with recruitment (Caputi et al. 2016). The 2011 heatwave followed by two years of above-average SST, resulted in record-low recruitment over 2011-2015 and subsequently low spawning stock which resulted in the fishery being closed for these five years. However, a small improvement in recruitment occurred in 2016 and the fishery was classified as fully recovered after further good recruitment in 2018 (Figure 9.10).

There is a significant spawning stock recruitment relationship (SRR) for *Y. balloti* in the Abrolhos Islands (Caputi et al. submitted). Spawning stock (SS) was estimated to be the scallop abundance in the fishery independent survey in November (Y) and the recruitment (Rec) was the stock abundance from fishery independent surveys the following year (Y+1); lnRec = 0.65lnSS + 2.15, R^2 = 0.412, p = 0.0013. Given the significant decline in scallop stocks in Abrolhos Islands after the 2010/11 MHW, the effect of SST between March and June (post spawning period for settlement of juvenile scallops) on recruitment was also examined which was not significant at p=0.05. However, combining SS and the environment in a stock-recruitment-environment relationship (SRER) indicated a relatively strong relationship; lnRec = 0.71lnSS -1.62SST + 39.7211 (bSS, p= 0.0017) (bSST, p = 0.0118), R^2 = 0.58, p = 0.00026.

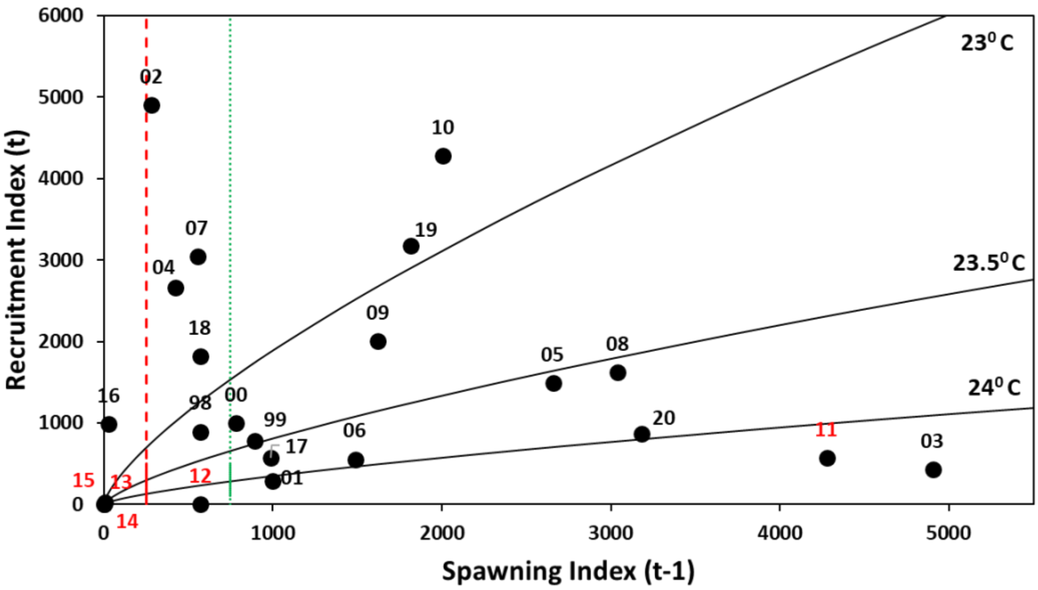


Figure 9-10. Relationship between the annual mean scallop abundance index (In total scallops/nm trawled (Y-1)) in November with the annual mean scallop abundance index (in total scallops/nm trawled in Y) between 2000 and 2019. The year of recruitment is indicated on the graph with the SST (ºC) in March to June lines shown. The dashed red line is the current limit spawning stock reference level and the dotted green line is the threshold reference level.

This SRER provided a biological basis for proposing the limit reference point using the survey abundance of 1-year old scallops (DPIRD 2020), noting that levels of spawning stock below this limit reference level are likely to be having a negative impact on recruitment (as observed with the recruitment during 2013-2015). A threshold reference level has also been proposed to provide an indication of when the spawning stock is getting close to the limit reference level and hence some management action will be required to further protect the stock. The spawning stock levels above the threshold can be regarded as the target for the sustainable management of the stock. When spawning stocks remain above this target level, the environmental conditions can be expected to be the dominant factor affecting recruitment (Figure 9-10).

9.3.5 Productivity Susceptibility Analysis

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.

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. 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.

9.3.5.1 PSA Scores

Updated scores: Average age at maturity (1), Average maximum age (1), Fecundity (1), Reproductive strategy (1), trophic level (1), density-dependence (2), Availability (3), Encounterability (3), Selectivity (3) Post-capture mortality (2), MSC PSA-derived score (98), Risk category (Low –>80).

The scores, in part, reflect this species being short-lived (maximum age ~2-3 years), highly fecund, broadcast spawning strategy, medium trophic level, but being highly-selected by the fishing gear and exhibiting low to moderate post-capture mortality.

9.3.6 Ecological Risk Assessment

Ecological risk assessments (ERAs) are undertaken periodically to assess the impacts of fisheries on all the different components of the aquatic environments in which they operate. An ERA was undertaken for the AIMWTMF in 2019 (DPIRD 2020b). The assessment focused on evaluating the ecological impact of the scallop trawl component of this fishery (i.e.

excluding the Port Gregory prawn fishery) on all retained species, bycatch, endangered, threatened and protected (ETP) species, habitats, and the broader ecosystem.

The risk assessment methodology utilised for the 2019 ERA is based on the global standard for risk assessment and risk management (AS/NZS ISO 31000). This methodology applied a consequence-likelihood analysis, which involves the examination of the magnitude of potential consequences from fishing activities and the likelihood that those consequences will occur given current management controls. All of the risk issues were assessed using a consultative and structured workshop held at the Western Australian Fisheries and Marine Research Laboratories in Hillarys on 13 September 2019.

All issues were scored medium, low or negligible risk using the adopted methodology. Risk rankings of medium or less are considered acceptable risks for a well-managed fishery, subject to ongoing management practices and performance monitoring.

9.3.7 Accounting for Uncertainty

A range of measures are taken to account and reduce uncertainty in assessment information.

These include:

- The catch prediction has a moderate to high level of uncertainty as abundances of scallops can be located in areas not regularly surveyed and that the fleet operations and market conditions have changed. Monitoring the achievement (or not) of the expected harvest levels and the reasons for not achieving these over the next three years will allow an assessment of the level of uncertainty in this measure.
- Very high scallop abundance areas that have been identified in surveys may not be as productive as expected due to crowding, stunting and poor meat quality that has been observed previously. To reduce uncertainty, within season commercial catch and catch rates are used to evaluate stock abundance and stock status.
- In the HS the mean November survey catch rates are used to assess whether fishing should commence or not i.e. that the stock is above or below the limit. The robustness of this measure is yet to be fully evaluated as it has only recently been adopted (DPIRD 2020).
- The survey in Feb/March will provide a basis for comparison with the longer term November survey in terms of scallop abundance, size composition and subsequent annual landings.
- Fishery-dependent information is used by fishers within season to cease fishing at or above the target catch rate level. This data is verified by the Department at the end of the season. Due to highly patchy and variable nature of scallop cessation of fishing at a pre-determined catch rate (and in practise above the limit) ensures breeding stock protection.
- The level of uncertainty in the catch prediction and requirement to protect breeding stock is further assisted by identification of areas of small scallops (either from surveys or by

fishers whilst fishing) and subsequently implementing small-scale spatial closures for the rest of the season.

- Accounting for uncertainty in fishery dependent data is by validating catch information against processor returns and regular communication with fishers.

9.4 Stock Status Summary – 2019 Abrolhos Islands, *Saucer Scallop Ylistrum balloti*

A summary of each line of evidence considered in the overall weight of evidence assessment of the AIMWTMF scallop resource is presented below, followed by the management advice and recommendations for future monitoring of the species.

9.4.1 Weight of Evidence Risk Assessment

Category	Lines of evidence
Commercial Annual catch	Annual scallop landings have fluctuated markedly from <20 tonnes (meat weight) to up to 1300 tonnes (meat weight) during the history of the fishery with landings in most years being between 30 and 300 tonnes meat weight (see Table 9.1). The fishery has also been closed to fishing due to low abundance of scallops in 2009 and 2012 to 2016. Fluctuating landings are largely a reflection of high recruitment variability and more recently with recruitment impairment post-2010/11 MHW event. The fishery had recovered by 2017 (as indicated by the mean scallop abundance in November 2016 survey) and landings since the re-opening of the fishery has been between 30 and 160 tonnes meat weight in the lower end of the historical catch range. **This line of evidence suggests the annual landings, since the re-opening of the fishery in 2017 are within the range of landings observed historically. The evidence does not indicate that currently there is any stock depletion.**
Annual commercial fishing effort	Fishing effort is generally commensurate with the abundance of scallop stocks. The gear towed by boats were unitised until 2011 after which remaining operators agreed to tow standardised size gear (twin 7-fathom (12.8 m) nets) with a reduction in the fishing fleet from 14 to 10 licenses. The historical fishing effort in this fishery has varied between 468 and 14782 trawl hours. Five boats fished in 2019 for a 2728 trawl hours, which is in the lower end of the historical effort range.

	This line of evidence indicates that the level of fishing effort should not cause stock depletion.
Catch distribution	The spatial effort distribution is dependent on the abundance within each traditional fishing ground and if/when skippers locate abundances of scallops in areas not surveyed. In 2019 scallops were caught within the traditional scallop grounds. The logbook information indicates that most scallops were retained from areas that were identified as higher scallop catch rates during the November 2018 survey and fishing effort occurred in primarily three traditional fishing grounds (see Figure 9.4). **This line of evidence indicates that effort distribution reflected the abundance and distribution of scallops within the Abrolhos Islands that were identified through fishery independent surveys. There is no evidence to indicate that the fishery exploited aggregations of scallops in areas not identified by surveys.**
Annual fishery-dependent catch rates	The annual commercial catch rate of 58 kg meat/hr in 2019 was in the mid-range of overall catch rates (30-75 kg meat/hr) seen historically in the fishery apart from very high catch rate years of 2003, 2005 and 2008 where catch rates were 125 to 195 kg meat/hr (see Table 9.1). **Annual scallop fleet trawl catch rates in 2019 are in the mid-range of the historical catch rates and do not indicate any stock depletion.**
Fishery independent spawning stock indices Fishery independent recruitment indices	The November fishery-independent survey index in year Y-1 is used to represent the spawning stock abundance whilst the abundance in Y is used for recruitment. These 'recruiting scallops' are fished in Y+1. The spawning stock in 2018 at 1815 scallops/nm was above the target level (750 scallops/nm) and with cooler than average temperatures successful recruitment was expected to occur in 2019. **The line of evidence indicate that the spawning stock is adequate.** The November 2019 survey confirmed a very high recruitment with the scallop abundance at 5346 scallops/nm, the highest observed survey abundance since surveys began in 1997 and the catch prediction for 2020 was 350-540 t meat weight. The February 2020 survey confirmed high scallop abundance levels **The lines of evidence indicate that the recruitment is very good with above average landings expected.**

Size composition data	In November 2018 and 2019 one broad cohort is observed with a mean size of scallops between 80 and 95 mm SH. In March 2019 two cohorts were evident at 40-50 mm SH and 80-90 mm SH with similar abundances of both size classes indicating further recruitment. **This line of evidence indicates good recruitment in 2019 and the presence of a larger cohort of scallops does not indicate a heavy depletion of spawning stock.**
Stock-recruitment analysis (SRR and SRER)	A stock recruitment relationship (SRR) is evident for scallops in Abrolhos Islands and SST impacts are also significant. Water temperatures greater than 24°C during the scallop larval and settlement time has a significant negative impact on scallop recruitment. These relationships were used to set the limit and target reference levels in the harvest strategy. In 2018 and 2019, the spawning index was above the target reference level (750 scallops/nm). **These lines of evidence indicate that the spawning stock level in the Abrolhos Islands is adequate. Water temperature conditions in 2019 was favourable for scallop recruitment.**
PSA analysis	The PSA score is Low for this species. The score reflects this species being short-lived (maximum age ~3-4 years), highly fecund, broadcast spawning strategy, medium trophic level, but being highly selected by the fishing gear and exhibiting low to moderate post-capture mortality and negative impacts of increasing water temperatures. **This line of evidence indicates that this species would be susceptible to overfishing/unacceptable depletion if appropriate management was not in place and can be adversely impacted by environmental conditions even within the current management framework.**
Ecological Risk Assessment	A consequence-likelihood analysis was conducted in 2019 with participation by industry, universities and other key stakeholders, which involved the examination of the magnitude of potential consequences from fishing activities and the likelihood that those consequences will occur given current management controls. All of the risk issues were assessed using a consultative and structured workshop. All issues were scored medium, low or negligible risk using the adopted methodology. **This line of evidence indicates that fishing activities in this fishery are acceptable.**
Environmental factors	Abrolhos Islands experienced the hottest summer SSTs on record in 2010/11 and 2011/12, which is considered to have led to a significant

Climate change	effect on recruitment over 2011-13 resulting in very low spawning stock. Water temperatures have since returned to within historical ranges. Scallops are ranked "high risk" under the current climate change scenario impacting the WA coastline. Longer-term impacts of climate change (increasing water temperatures) may negatively impact scallops within the Abrolhos Islands. **Recruitment levels in the Abrolhos are expected to improve with the current SST conditions but may be negatively impacted through medium to longer term climate change trends in Western Australia.**
Catch-MSY Stock assessment	A Catch-MSY model (Martell and Froese, 2013), implemented within the "simpleSA" R package (Haddon et al. 2018) was attempted for the saucer scallop stock in the Abrolhos Islands. The Catch-MSY model is a "data-poor" stock assessment method that can be used to estimate biomass and fishing mortality trends based on a catch history and inputs relating to the assumed productivity of the stock. Note that the method makes some strong assumptions and biomass estimates typically exhibit large uncertainty (variation) but the high variability in annual scallop catches precludes this method being suitable. **The Catch-MSY model was not suitable for scallop annual catch data.**

9.4.1.1 Current Risk Status

In assessing the overall the risk to stock recovery in the Abrolhos Islands the lines of evidence indicate a **Moderate risk level** (maximum score of 8) due to vulnerability of stocks to environmental impacts.

Risk assessment:

Consequence (Stock Depletion) Level	Likelihood				Risk Score
	L1 Remote (<5%)	L2 Unlikely (5- <20%)	L3 Possible (20- <50%)	L4 Likely (≥50%)	
C1 Minor		X			2
C2 Moderate				X	8
C3 High		X			6
C4 Major		NA			0

C1, 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})

C1 (Minimal stock depletion): **L2** – All the lines of evidence support that there has been an unlikely likelihood of minimal scallop stock depletion during 2019 because 159 t meat weight (796 t whole weight) was caught and the landings were around expectations in relation to the fishery independent survey index in November 2018.

C2 (Maximum Acceptable Depletion): **L4** – Lines of evidence indicate that a maximum acceptable depletion occurred as there was no evidence of recruitment impairment during the November 2019 survey.

C3 (Unacceptable Depletion): **L2** – The lines of evidence indicate that it is an unlikely likelihood that unacceptable stock depletion has occurred as commercial daily catch rates remained above the target level (150 kg/24 hours).

C4 (Unacceptable): **L1**– All the lines of evidence support that is a remote likelihood that fishing has caused a major risk to recruitment impairment with good scallop abundance observed in 2019/20.

C5 (Catastrophic) – Not plausible under current circumstances.

Overall risk score: Medium

Monitoring/management requirements:

Full Performance Report – regular monitoring	Specific management and/or monitoring required

9.4.1.2 Future Monitoring

- Continue regular monitor of the environmental conditions to inform on potential negative impacts on breeding stock and recruitment.
- Identify what is causing stunting and poor meat quality in areas of very high scallop abundance.
- Conduct pilot-investigations into the potential to translocate scallops from very high density areas into known productive scallop beds that have naturally low abundance levels in the same year.
- Assess selectivity of alternative gear (T90/square mesh) if/when adopted by industry to reduce interactions with small scallops.

10 References

Cannon, L.R.G., (1978) A larval ascaridoid nematode from Queensland scallops. *International Journal for Parasitolog.y* 8: 75-80

Caputi, N., Feng, M., Pearce, A., Benthuysen, J., Denham, A., Hetzel, Y., Matear, R., Jackson, G., Molony, B., Joll, L. and Chandrapavan, A. (2015). Management implications of climate change effect on fisheries in Western Australia. Part 1. Environmental change and risk assessment. Department of Fisheries, WA.

Caputi, N., M. Kangas, A. Denham, M. Feng, A. Pearce Y. Hetzel, and A. Chandrapavan (2016). Management adaptation of invertebrate fisheries to an extreme marine heat wave event at a global warming hotspot. *Ecol Evol* 6 (11): 3583-3593.

Caputi N., Chandrapavan, A., Kangas, M., de Lestang, S., Hart, A., Johnston, D. and Penn, JW. 2020 (submitted) Stock-recruitment-environment relationship of invertebrate resources in Western Australia and their link to pro-active management harvest strategies.

Chapman, C.J., Main, J., Howell, T. and Sangster, G.I, (1979). The swimming speed and endurance of the queen scallop Chlamys opercularis in relation to trawling. In: J.C. Gamble and J.D. George (Eds.). Progress in Underwater Science, Volume 4. Pentech Press, London. Pp. 57-72.

Chandrapavan A, Kangas M, Caputi N. 2020. Understanding recruitment variation (including the collapse) of Ballot's saucer scallop stocks in Western Australia and assessing the feasibility of assisted recovery measures for improved management in a changing environment. Fisheries Research Report No. 308 Department of Primary Industries and Regional Development, Western Australia. 76pp.

Church, J.A., G.R. Cresswell, and J.S. Godfrey (1989). The Leeuwin Current. In: Neshyba, N.K.M.S., Smith, R.L. (Eds.), Poleward Flows Along Eastern Ocean Boundaries. *Coast Estuar. Stud.* 34: 230-52.

Commonwealth of Australia [CoA] (2008). The South-West Marine Bioregional Plan: Bioregional Profile. Canberra: Department of Environment, Water, Heritage and the Arts.

Cragg S.M. (2006) Chapter 2: Development, physiology, behaviour and ecology of scallop larvae. Developments in Aquaculture and Fisheries Science, Volume 35: 45-122

Department of Fisheries (DoF). (2011). Resource Assessment Framework (RAF) for finfish resources in Western Australia. Fisheries Occasional Publication No. 85. Department of Fisheries, WA.

Department of Fisheries (DoF) (2015). Harvest Strategy Policy and Operational Guidelines for the Aquatic Resources of Western Australia. Fisheries Management Paper No. 271. Department of Fisheries, WA.

Department of Fisheries (DoF) (2016) Midwest Aquaculture Development Zone Public Environmental Review. Fisheries Occasional Paper No. 130. Department of Fisheries, WA

Department of Primary Industries and Regional Development (DPIRD 2020a) Saucer scallop resource of the Abrolhos Islands Harvest Strategy 2020-2025 Version 1.0. Fisheries Management Paper No. 299, DPIRD, Western Australia.

Department of Primary Industries and Regional Development (DPIRD) (2020b). Western Australian Marine Stewardship Council Report Series No. 15: Ecological Risk Assessment of the Abrolhos Islands and Mid-West Trawl Managed Fishery. DPIRD, Western Australia.

Dredge, M.C.L. (1981). Reproductive biology of the Ballot's saucer scallop *Amusium japonicum balloti* (Bernardi) in central Queensland waters. *Aust J Mar Fresh Res* 32: 755-87.

Dredge, M.C.L., 1985. Estimates of natural mortality and yield-per-recruit for *Amusium japonicum balloti* Bernardi (Pectinidae) based on tag recoveries. *J. Shellfish Res*. 5, 103–109.

Dredge, M. C. L. 1988. Recruitment overfishing in a tropical scallop fishery? *Journal of Shellfish Research* **7**(2): 223-239.

Evans, S., Bellchambers, L., & Murray, K. (2012). Mapping shallow water habitats of the Wallabi Group, Houtman Abrolhos Islands, using remote sensing techniques. Fisheries Research Report No. 237. Department of Fisheries WA

Feng, M., G. Meyers, A. Pearce, and S. Wijffels (2003). Annual and interannual variations of the Leeuwin Current at 32°C. *J Geophys Res*. 108 (C11): 3355.

Feng M., N. Caputi, and A. Pearce (2012) Leeuwin Current. In A Marine Climate Change Impacts and Adaptation Report Card for Australia 2012 (Eds. E.S. Poloczanska, A.J. Hobday and A.J. Richardson).

Feng M., N. Caputi, Chandrapavan, Al, Chen, M., Hart, A and Kangas, M. (in press) Multi-year marine cold-spells off the west coast of Australia and effects on fisheries. *Journal of Marine Systems.*

Fletcher, W.J. (2002). Policy for the implementation of ecologically sustainable development for fisheries and aquaculture within Western Australia. Fisheries Management Paper No. 157. Department of Fisheries, WA.

Fletcher, W.J (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(3): 1043-1056.

Fletcher, W.J., Shaw, J., Metcalf, S.J. and Gaughan, D.J. 2010. An Ecosystem Based Fisheries Management framework: the efficient, regional-level planning tool for management agencies. *Marine Policy* 34: 1226-1238.

Fletcher, W.J., Shaw, J., Gaughan, D.J. and Metcalf, S.J. (2011). Ecosystem Based Fisheries Management case study report – West Coast Bioregion. Fisheries Research Report No. 225. Department of Fisheries, Western Australia. 116 pp.

Fletcher, W.J. and Santoro, K. (eds.) (2015). Status reports of the fisheries and aquatic resources of Western Australia 2014/15: State of the fisheries. Department of Fisheries, WA. 91

Fletcher, W.J., Wise, B.S., Joll, L.M., Hall, N.G., Fisher, E.A., Harry, A.V., Fairclough, D.V., Gaughan, D.J., Travaille, K., Molony, B.W. and Kangas, M. (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.

Howell, T.R.W. and Fraser, D.I., (1984). Observations on the dispersal and mortality of the scallop, *Pecten maximus* (L.). International Council for the Exploration of the Sea, Shellfish Committee, CM1984, Doc No K:35. 13pp.

Gersbach, G. H., C. B. Pattiaratchi, G. N. Ivey, and G. R. Cresswell (1999). Upwelling on the southwest coast of Australia - source of the Capes Current? *Cont. Shelf Res.* 19: 363-400.

Haddon, M, Burch, P, Dowling, N, and Little, R 2018, Reducing the Number of Undefined Species in Future Status of Australian Fish Stocks Reports: Phase Two - training in the assessment of data-poor stocks. CSIRO. FRDC Final Report 2017/102. Hobart. 125 p.

Harris, D.C., Joll, L.M. and Watson, R.A. (1999). The Western Australian Scallop Industry. *Fisheries Research Report* **114:** 30pp.

Hartnoll, R.G., 1967. An investigation of the movement of the scallop, *Pecten maximus*. Helgo. Wiss. Meeresunters. 16, 523–533.

Heald, D. (1978). A successful marking method for the saucer scallop, *Amusium balloti* (Bernardi). *Australian Journal of Marine and Freshwater Research* 29: 845-851.

Hilborn, R. and Walters, C.J. (1992) Quantitative fisheries stock assessment, choice, dynamics and uncertainty. Chapman and Hall, London.

Himmelman, J.H., Guderley, H.E., P.F. Duncan (2009). Responses of the saucer scallop *Amusium balloti* to potential predators. *J Exp. Mar. Bio. Eco.* 378: 58-61.

Hobday, A.J., Smith, A.D.M., Stobutzki, I.C., Bulman, C., Daley, R., Dambacher, J.M.,Deng, R.A., Dowdney, J., Fuller, M., Furlani, D., Griffiths, S.P., Johnson, D., Kenyon,R., Knuckey, I.A., Ling, S.D., Pitcher, R., Sainsbury, K.J., Sporcic, M., Smith, T., Turnbull, C., Walker, T.I., Wayte, S.E., Webb, H., Williams, A., Wise, B.S. and Zhou, S. (2011). Ecological risk assessment for the effects of fishing. *Fisheries Research* 108: 372-384.

Johannes, R. E., W. J. Wiebe, C. J. Crossland, D. W. Rimmer, and S. V. Smith (1983). Latitudinal limits of coral reef growth. *Mar Ecol Prog Ser* 11(2): 105– 111.

Joll, L.M. (1988). Daily growth rings in juvenile Ballot's saucer scallops, *Amusium balloti* (Bernardi). *J. Shell. Res*. 7(1):73-76.

Joll, L.M. (1989 a). History, biology and management of the Western Australian stocks of the saucer scallop *Amusium balloti*. *In:* Proceedings of the Australian scallop workshop, Dredge, M.L.C., Zacharin, W.F. and Joll, L.M (eds.), pp. 30-41, Hobart, Tasmania.

Joll, L.M., (1989 b). Swimming behaviour of the saucer scallop *Amusium balloti* (Mollusca: Pectinidae). *Mar. Biol.* 102, 299–305.

Joll, L.M. and N. Caputi (1995 a). Environmental influences on recruitment in the Ballot's saucer scallop (*Amusium balloti*) fishery of Shark Bay, Western Australia. ICES Mar Sci Symposia (Actes du symposium) 199: 47-53.

Joll, L. and N. Caputi (1995 b). Geographic variation in the reproductive cycle of the Ballot's saucer scallop, *Amusium balloti* (Bernardi, 1861) (Mollusca: Pectinidae) along the Western Australian coast. *Mar Fresh Res* 46: 779-792

Kaartvedt, S. Aksnes, D.L., Egge, J.K. (1987). Effect of light on vertical distribution of Pecten maximus larve. *Mar. Ecol. Prog. Ser*. 40:195-197.

Kangas, M.I., Chandrpavan, A., Hetzel, Y.L. and Sporer E.C. 2012. Minimising gear conflict and resource sharing issues in the Shark Bay trawl fisheries and promotion of scallop recruitment. *Fisheries Research Report* 229: 136 pp. Department of Fisheries WA.

Lenanton, R., Fletcher, R. and Gaughan, D. (2006). Integrated fisheries management in Western Australia – a significant challenge for fisheries scientists. *In* Phelan, M.J. and Bajhau, H. (eds.), A guide to monitoring fish stocks and aquatic ecosystems. Australian Society for Fish Biology Workshop Proceedings, Darwin, Northern Territory, 11-15 July 2005. Fisheries Incidental Publication No. 25. Northern Territory Department of Primary Industry, Fisheries and Mines, Darwin, pp. 37-43.

Lester, R.J.G., Blair, D. and Heald, D. (1980) Nematodes from scallops and turtles from Shark Bay, Western Australia. *Marine and Freshwater Research* **31**, 713-717.

MacDonald, B., & Thompson, R. (1985). Influence of temperature and food availability on the ecological energetics of the giant scallop *Placopecten magellanicus*. I. Growth rates of shell and somatic tissue. *Mar. Eco. Prog. Ser.*, *25*(3), 279-294.

MacDonald, B. A., Bricelj, M. V., Shumway, S. E., 2006. Physiology: Energy acquisition and utilisation. In Scallops: Biology, Ecology and Aquaculture. Vol. 35. Elsevier, Developments in Aquaculture and Fisheries Science, Ch. 7, pp. 417–492.

Marine Stewardship Council (MSC). (2014). MSC Guidance for the Fisheries Certification Requirements, V2.0, 1st October 2014.

Martell, S. and Froese, R. (2013). A simple method for estimating MSY from catch and resilience. *Fish and Fisheries* 14: 504-514.

Manuel, J.L., Burbridge, S., Kenchington, E.L., Ball, M. and O'Dor, R.K. 1996 a. Veligers from two populations of sea scallop *Placopecten magellanicus* exhibit different vertical distributions in the same mesocosm. *J. Shellfish Res*. 15:251-257.

Manuel, J.L., Gallagher, S.M., Pearce, C.M., Manning, D.A. and O'Dor, R.k. 1996 b. Veligers from different populations of sea scallop *Placopecten magellanicus* have different vertical migration patterns. *Mar. Ecol. Progr. Ser.* 142:147-163.

Maru K (1985) Ecological studies on the seed production of scallop, *Patinopecten yessoensis* (Jay). Sci Rep Hokk Fish Exp Stud 27:1–55.

Maslin, M (2005). Analysis of early life history stages of the Ballot's saucer scallop *Amusium balloti* (Bernardi 1861): Impacts on the development of hatchery practices. PhD thesis. University of Queensland.

Minchin, D. and Mathers, N.F., (1982). The escallop, *Pecten maximus*. *Journal of the Marine Biological Association of the United Kingdom* 72:807-819

Mueller, U., Dickson, J., Kangas, M. and Caputi N (2008) Geostatistical modelling of the scallop density distribution in Shark Bay. *Geostatistics*, 2008: 971-980.

Mynhardt, G, Alejandrino, A, Puslednik, L, Corrales, J and Serb, JM 2014, Shell shape convergence masks biological diversity in gliding scallops: description of *Ylistrum* n. gen. (Pectinidae) from the Indo-Pacific Ocean, *Journal of Molluscan Studies*, 80: 400–411.

Orensanz, J.M., 1984. Size, environment, and density: the regulation of a scallop stock and its management implications. In: G.S. Jamieson and N. Bourne (Ed.). North Pacific Workshop on Stock Assessment and Management of Invertebrates. *Can. Sp. Publ. Fish. Aquat. Sci* 92:195-227.

Pattiaratchi, C. B, B. Hegge, J. Gould, and I. Eliot (1997). Impact of sea-breeze activity on near shore and foreshore processes in south-western Australia. *Cont Shelf Res* 17(13): 1539–1560.

Pearce, A. and C. Pattiaratchi (1999). The Capes Current: a summer counter current flowing past Cape Leeuwin and Cape Naturaliste, Western Australia. *Cont Shelf Res* 19: 401–420.

Pearce, A.F. and B.F. Phillips (1988). ENSO events, the Leeuwin Current, and larval recruitment of western rock lobster. *J Conseil* 45:13-21.

Pearce, A., Lenanton, R., Jackson, G., Moore, J., Feng, M. and Gaughan, D. (2011). The "marine heat wave" off Western Australia during the summer of 2010/11. Fisheries Research Report No. 222. Department of Fisheries, WA.

Raby, D., Lagadeuc, Y., Dodson, J.J. and M. Mingelbier, (1994) Relationship between feeding and vertical distribution of bivalve larvae in stratified and mixed waters*. Marine Ecology Progress Series. 103:275-284.

Radford, B., van Niel, K., Holmes, K. (2008). WA Marine Futures: Benthic modelling and mapping- Final report. University of Western Australia.

Ricker, W. E. 1975. Computation and interpretation of biological statistics of fish populations. *Fish. Res. Board Can., Bull*. 191: 382 p.

Ridgway, K.R., and S.A. Condie (2004). The 5500-km-long boundary flow off western and southern Australia. *J Geophys Res*, 109: C04017

Robins-Troeger, J.B., Dredge, M.C.L. (1993). Seasonal and depth characteristics of scallop spatfall in an Australian subtropical embayment. *Journal of Shellfish Research*, Vol. 12 (2), pp. 285-290.

Rose, R. A., Campbell, G. B. and Sanders, S. G. 1988. Larval development of the saucer scallop *Amusium balloti*, Bernadi (Mollusca: Pectinidae. *Australian Journal of Marine and Freshwater Research* **39**: 153-160.

Ryan, K.L., Wise, B.S., Hall, N.G., Pollock, K.H., Sulin, E.H. and Gaughan, D.J. (2013). An integrated system to survey boat-based recreational fishing in Western Australia 2011/12. Fisheries Research Report No. 249. Department of Fisheries, WA.

Ryan, K.L., Hall, N.G., Lai, E.K., Smallwood, C.B., Taylor, S.M. and Wise, B.S. (2015). Statewide survey of boat-based recreational fishing in Western Australia 2013/14. Fisheries Research Report No. 268. Department of Fisheries, WA. 92

Smith, R. L., A. Huyer, J.S. Godfrey, and J.A. Church (1991). The Leeuwin Current off Western Australia, 1986–1987. *J Phys Ocean* 21: 323–345.

Sumpton, W.D., Brown, I.W., Dredge, M.C.L. (1990). Settlement of bivalve spat on artificial collectors in a subtropical embayment in Queensland, Australia. *Journal of Shellfish Research,* Vol. 9 (1) pp. 227-231.

Thomas, G.E. and Gruffydd, L.D., 1971. The types of escape reactions elicited in the scallop Pecten maximus by selected sea star species. *Mar. Biol.* 10:87-93

Tremblay. M.J. and Sinclair, M.M. (1990 a). Diel vertical migration of sea scallop larvae *Placopecten magellanicus* in a shallow embayment. *Mar. Ecol. Prog. Ser*. 67:19-25.

Tremblay, M.J., Sinclair, M.M., (1990 b). Sea scallop larvae *Placopecten magellanicus* on Georges Bank: vertical distribution in relation to water column stratification and food. *Mar. Ecol. Prog. Ser.* 61, 1–15.

Vahl, O. and Clausen, B., (1980). Frequency of swimming and energy cost of byssus production in *Chlamys islandica* (O.F. Müller). *Journal du Conseil International pour l'Exploration de la Mer.* 39:101-103.

Wang, S (2007). Analysis of early life history stages of the Ballot's saucer scallop *Amusium balloti* (Bernardi 1861): Impacts on the development of hatchery practices. PhD thesis. University of Queensland.

Webster, F.J., Dibden, C.J., Weir, K.E. and Chubb, C.F. 2002. Toward an assessment of the natural and human use impacts on the marine environment of the Abrolhos islands, vol.1. Fisheries Research Report 134: 120 pp. Department of Fisheries, WA.

Wilkens, L.A., 1981. Neurobiology of the scallop. I. Starfish-mediated escape behaviours. *Proc. R. Soc. Lond. B* 211:341-372

Williams M.J. and M.C.L. Dredge (1981). Growth of the saucer scallop *Amusium japonicum balloti* (Habe) in Central Eastern Queensland. *Aust. J. Mar. Freshwater Res*. 32, 657-66.

Woo, M., C. B. Pattiaratchi, and W. Schroeder (2006), Dynamics of the Ningaloo current off Point Cloates, Western Australia, *Mar. Freshwater Res.*, 57, 291–301.

11 Appendix 1

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_{MSY}) 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

12 Appendix 2

West Coast Trawl Association

RESPONSIBLE FISHING

A Code of Conduct to Reduce the Impact of Trawling on the Rock Lobster Industry for Operators Working in the Abrolhos Islands and Mid-West Trawl Managed Fishery.

This Code of Conduct sets out some basic guidelines and principles for the operators of trawlers fishing for scallops in the Abrolhos Islands and Mid-West Trawl Managed Fishery (AIMWTF).

The owners of the 8 trawlers licensed to operate in the AIMWTF endorse this code of conduct and undertake to communicate to trawler operators the importance of abiding by the principles and guidelines set out in the code.

Owners, skippers and crew need to be aware that the Scallop industry shares the waters of the Abrolhos Islands with Rock Lobster fishermen. Rock Lobster fishermen have been operating in the waters of the Abrolhos Islands for over 50 years and they too earn their living from the sea. The Scallop industry needs to be aware that unless appropriate care is taken by trawler operators there is potential to impact on the operations of Rock Lobster fishermen and to ultimately affect their ability to successfully fish.

This Code of Conduct specifically seeks to reduce the impact that trawling can potentially have on Rock Lobster fishermen and is a considered attempt to foster better relations between the two industries.

You need to be aware that your actions and willingness to observe the Code of Conduct can make a difference.

1. Dividing the Fishery into 'Traditional' and 'Unknown' Areas.

The centerpiece of this Code of Conduct is an understanding that the Abrolhos Islands Scallop Fishery can be effectively split into:

a) Traditional Trawl Areas

These are the areas of the Fishery that contain known scallop grounds and are the areas historically fished by the scallop fleet.

These nine Traditional Trawl Areas are clearly marked and labeled on the charts contained in this Code of Conduct.

The co-ordinates that mark the boundaries for each of these Traditional Trawl Areas are also contained in this Code of Conduct.

b) Non-Traditional or Unknown Areas

These are the areas of the Fishery that are not traditionally fished by the scallop fleet.

While some of these areas may contain bottom suitable for trawling, they also contain ground important to the Rock Lobster industry that is unsuitable for trawling.

The Non-Traditional or Unknown Areas are effectively all other areas of the Scallop Fishery outside of the nine Traditional Trawl Areas.

2. Skippers must plot the co-ordinates of the Traditional Trawl Areas.

It is expected that skippers will put the co-ordinates for the Traditional Trawl Areas into their plotters and strictly observe the Code of Conduct when they fish outside of these Traditional Trawl Areas.

3. Protocol for Working in Traditional Trawl Areas.

When working in Traditional Trawl Areas, standard fishing procedures apply and the use of both main and try gear is entirely at the skipper's discretion.

Skippers should, however, exercise their professional judgement as to the appropriateness of fishing ground within the Traditional Trawl Areas.

If skippers are working in ground unknown to them, but still within a Traditional Trawl Area, they should observe the protocol for exploring new or unknown ground.

4. Protocol for Exploring Non-Traditional Areas or Unknown Ground.

Skippers should take every precaution to know and understand the ground they are working on before they commence fishing. The following protocol should be observed when exploring new or unknown ground:

a) Call other skippers who may know the ground or area.

b) Survey the area by running a grid pattern with echo sounder and plotter.

c) If the surveyed area is sand bottom, then use try gear in the surveyed area to look for scallops.

d) Use winching time to 'fill in' the grid pattern with echo sounder and plotter.

e) If scallops are found, use echo sounder and plotter to map the extent of the sand bottom.

f) If scallops are found and the ground is well plotted, commence fishing in the surveyed area.

g) If no scallops are found, let others skippers know.

h) If the ground is not suitable for trawling, let other skippers know.

5. Protocol for Reducing Trawler Interaction with Cray Pots.

While no one intentionally hooks-up cray pots, it is important to respect that cray pots are the property and the principal means by which Rock Lobster fisherman earn their livelihood. Skippers must recognize that trawler interaction with cray pots presents major problems for Rock Lobster fisherman. Skippers should consider the following repercussions of hooking up a cray pot:

a) the Rock Lobster fisherman's effort of setting the pot is wasted,

b) a hooked-up pot will not provide any catch for the fisherman,

c) if the pot is lost, they are expensive to replace

d) the fisherman may lose further catch while waiting for a replacement pot

Skippers can minimize the interaction with cray pots, by observing the following procedures:

a) Where it is possible, avoid steaming through known areas of Rock Lobster habitat.

b) If you have to steam through a known area of Rock Lobster habitat, bring in your stabilizers.

c) If you do hook-up cray pots, make sure that you observe the following procedures for handling and returning cray pots:

- Place the cray pot close to other pots
- If possible, contact the skipper of the cray boat

6. Protocol for Anchoring and the Disposal of Shell.

Areas of hard bottom are the type of ground principally targeted by Rock Lobster fishermen. Skippers should respect the importance of these bottom types to the Rock Lobster Fishery and observe the following procedures:

a) Unless the safety of the vessel is a concern, do not anchor in areas of garden or hard bottom.

b) Do not anchor and shuck (that is, do not deposit shell) in areas of garden or hard bottom. There is potential for discarded scallop shell to damage coral. Additionally, discarded scallop roe and guts can reduce the effectiveness of baited pots.

7. Protocol for the Disposal of Rubbish and Waste.

It is an offence to dispose of solid wastes and rubbish at sea. Skippers should ensure that there is sufficient capacity to store solid wastes and rubbish on the vessel so that it can be disposed of correctly upon returning to port.