

Investigating effects of climate change on biota in Cockburn Sound

Theme: Fisheries and Aquatic Resources
WAMSI Westport Marine Science Program



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ABOUT THE MARINE SCIENCE PROGRAM

The WAMSI Westport Marine Science Program (WWMSP) is a \$13.5 million body of marine research funded by the WA Government. The aims of the WWMSP are to increase knowledge of Cockburn Sound in areas that will inform the environmental impact assessment of the proposed Westport development and help to manage this important and heavily used marine area into the future. Westport is the State Government's program to move container trade from Fremantle to Kwinana, and includes a new container port and associated freight, road and rail, and logistics. The WWMSP comprises more than 30 research projects in the biological, physical and social sciences that are focused on the Cockburn Sound area. They are being delivered by more than 100 scientists from the WAMSI partnership and other organisations.

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DATA

Finalised datasets will be released as open data, and data and/or metadata will be discoverable through Data WA and the Shared Land Information Platform (SLIP).

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The WAMSI Westport Marine Science Program is a \$13.5 million body of research that is designed to fill knowledge gaps relating to the Cockburn Sound region. It was developed with the objectives of improving the capacity to avoid, mitigate and offset environmental impacts of the proposed Westport container port development and increase the WA Government’s ability to manage other pressures acting on Cockburn Sound into the future. Funding for the program has been provided by Westport (through the Department of Transport) and the science projects are being delivered by the Western Australian Marine Science Institution.

Investigating effects of climate change on biota in Cockburn Sound

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Project 4.3

Investigating effects of climate change on biota in Cockburn Sound

1 Executive Summary

The sheltered waters of Cockburn Sound and Owen Anchorage (henceforth referred to as CS) have enormous economic, social and environmental importance for the city of Perth, Western Australia. The new Westport development considered in CS has the potential to have both short-term and long-term impacts on the biota of the region, as with any port development. However, the biota in CS is not necessarily in a steady state, but rather changes because of many factors, including anthropogenic impacts, annual variability in water temperature and currents, and long-term (decadal) effects such as climate change. To understand the potential effects of the Westport development on key biota in CS, it is important to assess what effects other factors are already having on the biota, thereby enabling an assessment of the cause(s) of any future changes. These other environmental changes to the biota may have direct effects (e.g. temperature changes modifying spawning or larval phases) or indirect effects (e.g. due to loss of a preferred habitat, such as seagrass, or changes in primary productivity). The key biota assessed in this report includes important commercial and recreational fisheries species, iconic species and invasive marine species.

This desk study provides an understanding of the main factors affecting some of the key species in CS, by documenting the historic environmental and biological trends that have been observed. These are addressed by bringing together disparate time series data sources which have been collected over recent decades, to describe how CS has changed over time and, where possible, document links between the environment and key biota. Of central importance to this report is to improve the understanding of the role that climate change is having within CS and identifying the potential risks of climate change to the biota. For example, as climate change shifts the CS environment, species that cannot currently survive winter conditions may establish, resulting in local range shifts (poleward expansion) as well as novel introductions. If these long-term trends were not assessed, it would be difficult to ascertain the cause(s) of any future changes in biota abundance, should the Westport development proceed.

The major climate change trend affecting CS is an increase in water temperature. The increase has been similar to the rate of sea surface temperature (SST; $0.02^{\circ}\text{C yr}^{-1}$) warming for the wider southwest Australian coast, identified as a warming hotspot exceeding the global average rate of warming. Since records began (1887), the Fremantle mean sea level has increased at a rate of 1.76 mm yr^{-1} . However,

there has been an accelerated rate of sea level rise since the mid-1990s that may also be attributable to climate change. While not linked to climate change, the other major environmental change in CS over recent decades has been a decline in chlorophyll-*a* (as well as nitrogen and phosphorous) levels. While levels are currently stable, they are much lower than the peak industrial levels experienced in the 1990s.

Cockburn Sound is also affected by the La Niña phase of the ENSO climate cycle, with intensification of the Leeuwin Current and increased water temperature in southern Western Australia waters. The three most recent La Niña events (1998-2001, 2010-11 and 2020-22) resulted in elevated summer SST (up to 2-4°C anomaly) and an increase in marine heatwave (MHW) days within CS.

WAMSI Westport Marine Science Program project *Provision of multi-decadal ocean boundary conditions and field measurements* provided future climate scenarios (to 2100) under two Shared Socioeconomic Pathways (SSP) emission scenarios: (i) SSP2 represented historical patterns of development; and (ii) SSP5 assumed a 'high' emission scenario. The time series of temperature and salinity from CS over the simulation period (2000-2022) observed the 2011 extreme MHW had a maximum water temperature of 27.03°C with elevated water temperature continuing until 2014. There was also a salinity minimum (34.8 ‰) associated with this event. The minimum temperature occurred in 2016 (15.0°C) which was the start of a four-year marine cold spell. The SST predictions to 2100 indicated that the annual rate of SST increase was 0.015°C (SSP2) and 0.031°C (SSP5) per annum. However, coastal currents would expect to be relatively unchanged, as modelling predicted no major changes to salinity nor wind climate.

There was a long-term decrease in seagrass coverage in CS between 1967 (2929 ha) and 1981 (740 ha), attributed to declining water quality from the discharge of excess nutrients into CS as a result of industrial expansion along the Kwinana foreshore. Despite seagrass coverage increasing by 132 ha between 2008 and 2017 seagrass meadows, this important habitat for many species within the sound remains under threat as shoot density has declined and mass die-offs have occurred following the 2011 MHW.

Approximately 90 commercial species have been landed within CS since 1977, although only 20 have averaged >1 t per year. Commercial catches peaked during the 1980s and 1990s, but have steadily declined since. Australian sardines (*Sardinops sagax*), the most landed species caught in CS, had three years of >1000 t per year from 1991-1993, however since 2000 there have been multiple years when no Australian sardines were reported. Scaly mackerel (*Sardinella lemuru*) catches peaked in 1984-1986 at ~600 t per year, before decreasing by 90% by the mid-1990s. Blue swimmer crab (*Portunus armatus*) and southern garfish (*Hyporhamphus melanochir*) landings peaked in the late 1990s, before stocks decreased such that fishery closures were implemented to promote stock recovery. Decreasing catch for many species has been the result of management actions to reduce fishing effort, while others have been affected by changing environmental conditions. Commercial aquaculture has also declined in CS, with black mussel production decreasing from >500 t per annum between 1997 to 2007 to <100 t per annum by 2019. The major exception to these declines has been octopus, which has increased from <0.5 t per year in the mid-1990s to >50 t in 2019.

The main recreationally important species in CS are Australian herring (*Arripis georgianus*), squid and whiting. Blue swimmer crab was also an important recreational species until the stock declined in 2005 and CS south of Woodman Point has remained closed to recreational crabbing since 2014.

Case studies are provided on the historical influence of environment on key species within CS: blue swimmer crab, snapper (*Chrysophrys auratus*), southern garfish, western king prawn (*Penaeus latisulcatus*), yellowfin whiting (*Sillago schomburgkii*), sandy sprat (*Hyperlophus vittatus*), rabbitfish (*Siganus* sp.), little penguin (*Eudyptula minor*), Australian sea lion (*Neophoca cinerea*) and Indo-Pacific bottlenose dolphin (*Tursiops aduncus*).

Fishery-independent trawl surveys confirm the decline of blue swimmer crab densities from the late 1990s and early 2000s to the current levels. A stock-recruit-environment relationship (SRER) was used

to examine potential causes of the decline. The best-fit SRER contained spawning stock, water temperature and chlorophyll-*a* as significant explanatory variables. The model indicates that years with the highest recruitment also have high chlorophyll-*a* levels and above average water temperature. Even if spawning stock was high, if the environmental conditions were poor (low chlorophyll-*a* and low temperature) the recruitment was impaired. This analysis suggests that the large reduction in blue swimmer crab abundances within CS was likely due to a tightening of industry regulations, reducing anthropogenic nutrient inputs, and therefore it is unlikely blue swimmer crab stocks will return to levels of earlier decades. The analysis shows that blue swimmer crab abundances in CS are sensitive to temperature, suggesting climate change may have a role in the future, but stocks are also limited by primary productivity which has changed in CS due to the impact of tighter industrial regulations.

Within the Perth region, successful recruitment of the snapper stock appears to be highly episodic, with seven years of strong year classes between 1991-2018. These strong year classes are observed in age data from recreational and commercial landings, and more recently in fisheries-independent baited remote underwater video (BRUV) and trawl data. However, analyses of conditions (temperature, salinity, and chlorophyll-*a*) within CS during the peak larval stage did not find any correlation with successful recruitment to CS and this remains an ongoing area of research.

The species range for rabbitfish is generally north of the Gascoyne Region, however, during the 2011 extreme MHW juvenile rabbitfish were observed recruiting within nearshore waters $\geq 32^{\circ}\text{S}$. The heatwave produced nearly two years of above-average SST and the rabbitfish survived consecutive winters and established a self-recruiting breeding population within CS. Rabbitfish were first recorded in fisheries-independent surveys and commercial catches in the summer of 2011/12, but have fallen since the MHW ended. Other tropical species such as sand bass (*Psammoperca* sp.) have been observed in CS commercial landings and survey data. Yellowfin whiting has been observed to benefit from increasing water temperatures within the Perth region. Following the 2011 MHW, yellowfin whiting had a particularly strong recruitment within the Peel-Harvey Estuary but not in CS.

The southern garfish (*Hyporhamphus melanochir*) fishery has experienced two decades of declines, with the fishery closed in 2017 to allow stocks to recover. Commercial catches peaked in 1999 at 38 t and then gradually declined until the fishery was closed with the most dramatic decline coinciding with the 2011 MHW. CS is on the northern edge of the species range, so any long-term rise in summer SST may be unfavourable.

Sandy sprat, an important prey for little penguins within CS, also had a gradual reduction in commercial catches since the 1990s and has not been caught within CS since 2009. However, the species is not well studied, particularly within CS, so it is not possible to determine the extent to which decreasing catches reflect any change in abundance. However, at a state level, a positive relationship between the strength of the Leeuwin Current the previous year and the relative catch of sandy sprat has been previously observed, and the relationship remains after adding a further 15 years of data to 2022.

Redmap, which compiles public sightings of out-of-range marine species, has identified 14 potential range extension species with verified sightings within CS. This includes two finfish species of commercial and recreational interest in northern waters: rankin cod (*Epinephelus multinotatus*) and spangled emperor (*Lethrinus nebulosus*).

Little penguins are commonly sighted within CS which is near breeding colonies on Garden and Penguin Islands. These colonies are at the northern extremity of their range and are most likely at the limits of the species environmental tolerance. Higher SSTs during pre-breeding, in April and May, correlates with lower breeding success, and the Penguin Island colony experienced its lowest breeding success during the 2011 MHW. The penguins' body condition and breeding success are also highly sensitive to fish availability, extending foraging ranges when prey is limited. So, climate change impacts, such as MHW, can modify fish distributions and abundance, which then effect little penguins.

The Carnac Island haulout site for Australian sea lions, which is the closest to CS, has had a decreasing trend in haulouts. Warming temperatures associated with climate change is a possible factor limiting

the recovery of the mid-west Australian sea lions. However, the trends within the Perth metropolitan populations are generally attributed to anthropogenic factors. Indo-Pacific bottlenose dolphin populations remain generally stable within CS. However, there are insufficient data to relate dolphin populations to changes in environmental conditions for the region.

Climate change risk assessments using a traits-based assessment methodology was applied to 14 fisheries species and five species iconic to the Perth region (little penguins, Australian sea lions, Indo-Pacific bottlenose dolphins and two commonly occurring syngnathids). The species identified as potentially the most sensitive to a warming climate (Severe risk) include sandy sprat, little penguin, Australian sardine and southern garfish. Snapper and King George whiting (*Sillaginodes punctata*) were identified as High risk, while Australian herring, blue swimmer crab, West Australian seahorse (*Hippocampus subelongatus*), spotted pipefish (*Stigmatopora argus*), southern calamari (*Sepioteuthis australis*), Australian sea lion and western king prawn were identified as Medium risk. The species identified as Low risk were tailor (*Pomatomus saltatrix*), sea mullet (*Mugil cephalus*) and Indo-Pacific bottlenose dolphin. Species which were identified as Negligible risk or may benefit from a warming climate include scaly mackerel, western rock octopus (*Octopus djinda*) and yellowfin whiting. The risk assessment identified potential physiological benefits of warmer SSTs to certain species such as blue swimmer crab and western king prawn. However, the overall risk of these species was assessed as Medium, as these species are strongly associated with seagrass habitats in CS, and these habitats are known to be sensitive to MHWs and climate change impacts.

The climate change risk assessment methodology was also applied to four Invasive marine species (IMS) which may be a threat to the Perth region. The Asian green mussel (*Perna viridis*), charru mussel (*Mytella strigata*), Asian paddle crab (*Charybdis japonica*), and carpet sea squirt (*Didemnum vexillum*), all have the potential to pose an increased risk in CS as warmer water temperatures may be more suitable for tropical species to establish. While many IMS have been innocuous or failed to establish significant populations and impacts in CS, several IMS were identified as potential marine pest species of concern due to recent detections (*Didemnum vexillum*) and adaptive potential to regime shifts in the CS environment (*Perna viridis*, *Mytella strigata*, *Charybdis japonica*).

This study has highlighted warming water temperatures as the main climate change effect in CS, and the WAMSI Westport Marine Science Program project *Provision of multi-decadal ocean boundary conditions and field measurements* indicated further warming will occur. It has also indicated possible regime shifts having occurred with a major loss of seagrass and a major reduction in productivity (reduced chlorophyll, nitrogen and phosphorus). The warming trend could have a negative effect on species near the northern end of their range, such as southern garfish and little penguins, but may benefit some tropical species to varying degrees (e.g. rabbitfish and blue swimmer crab). The limited number of long-term datasets for key species within CS, and the challenges of predicting climate change impacts highlight the need for an expanded environmental and biological monitoring program within CS. This would be particularly important in the context of additional stressors on CS, such as the planned Westport development, which may have other associated impacts.

2 Introduction

The sheltered waters of Cockburn Sound and Owen Anchorage (henceforth referred to as CS) have enormous economic, social and environmental importance for the city of Perth, Western Australia (WA) (Gartner et al. 2018). For decades this sheltered marine embayment has provided safe access for ships which support a range of heavy industry and a naval base. The highly diverse biota within CS is also highly valued by the Perth community for both aesthetic and cultural reasons (Gartner et al. 2018), supporting substantial recreational and commercial fishing activities, and until recently, aquaculture facilities. With the proposal for the new Westport development in CS being considered, any port development has the potential to have both short-term and long-term impacts on the biota of the region. It is important to note that the biota in CS is not necessarily in a steady state, but rather changes because of many factors, including annual variability in water temperature and currents, and long-term (decadal) effects such as climate change as well as extreme events such as marine heatwaves. To understand the potential effects of the Westport development on the CS biota, it is important to assess how other factors are already influencing the biota, thereby enabling an assessment of the cause(s) of any future changes observed. These other environmental changes to the biota may have direct effects (e.g. temperature changes modifying spawning or larval phases) or indirect effects (e.g. due to loss of a preferred habitat, such as seagrass, or changes in primary productivity).

Early in the development of infrastructure around CS, there was little effort to monitor the state of the environment. However, there was public concern over the impact on CS of the solid rock-filled causeway built during the development of HMAS Stirling on Garden Island in the 1970s, resulting in several baseline studies at the time (Chiffings 1979, DCE 1979, Dybdahl 1979). In the decades since these initial studies, various survey programs have been established that capture time series data within CS. Nevertheless, these have generally been piecemeal, based on the priorities of the different government departments collecting the data. This current project brings these disparate data sources together to describe how CS has changed over time and, where possible, document links between the environment and key biota in CS.

This desk study project provides an understanding of the main factors affecting some of the key species in CS, by documenting the historic environmental and biological trends that have been observed. The key biota assessed in this report include important commercial and recreational species, iconic species and invasive marine species. Of central importance to this report is to improve the understanding of the role that climate change is having on the CS biota and identify the potential risks of climate change to key species present in CS, particularly their abundance, over the coming decades. If these environmental factors were not assessed, it would be difficult to ascertain the cause(s) of any future changes in the biota abundance in the future, should the Westport development proceed.

The key objectives of this project were:

- To document historical environmental data trends in CS,
- To construct time series data trends of abundance of key biota,
- To assess biological and environmental effects on key biota,
- To document climate change modelling projections downscaled to the coastal environment,
- To undertake a risk assessment of the effects of climate change on key biota,
- To undertake a risk assessment of the effects of climate change on potential invasive marine species.

This project uses environmental and biological data from other WAMSI Westport Marine Science Program (WWMSP) themes such as:

- *Benthic communities and habitats,*

- *Water and sediment quality,*
- *Fisheries and aquatic resources,*
- *Hydrodynamic modelling, and*
- *Apex predators and iconic species.*

Assessment of the environmental factors affecting forage species such as sandy sprat, blue sprat and anchovy are also relevant information for the WWMSF projects in the *Apex predators and iconic species* theme. While the results from this project are also relevant to the WWMSF *Ecological modelling* theme, including the *Using conceptual, qualitative and quantitative ecosystem models to characterise the trophic structure, ecosystem attributes and functioning of Cockburn Sound* project.

3 Methods

The methods are broken down by the objectives of this project:

3.1 Historical environmental data for CS

Historic time series data were available for several environmental variables within CS or the wider Perth metropolitan region (Table 1). These datasets were compiled from various sources including: state and national government agencies, the Cockburn Sound Management Council (CSMC) and internet sources. The environmental variables from these databases were used in analyses of correlations with biological parameters in the fisheries case studies. These environmental data also enabled an examination of long-term trends within CS. Where possible, environmental datasets were sourced at a spatial scale and location that was representative of CS. If no such data existed for a relevant variable, then datasets from adjacent locations, such as Warnbro Sound or the wider Perth metropolitan region, were included as a proxy. Where available, data from stand-alone studies were included to infill or extend the time-series datasets.

Table 1. Environmental data from internet sources and measurements by the Department of Primary Industries and Regional Development (DPIRD), other government agencies and the Cockburn Sound Management Council (CSMC).

Variable	Data Source	Sampling Interval	Period of data
Fremantle sea level	Permanent Service for Mean Sea Levels – Station 111 (https://psmsl.org/)	Monthly	1897-ongoing
Chlorophyll- <i>a</i>	CSMC	Weekly from Dec-Mar	1982–ongoing ¹
Total nitrogen	CSMC	Weekly from Dec-Mar	1982-ongoing ¹
Total phosphorus	CSMC	Weekly from Dec-Mar	1982-ongoing ¹
Salinity at the surface	CSMC	Weekly from Dec-Mar	1985-ongoing ¹
Sea surface temperature	CSMC	Weekly from Dec-Mar	1985-ongoing ¹
Dissolved oxygen at surface	CSMC	Weekly from Dec-Mar	1985-ongoing ¹
pH at surface	CSMC	Weekly from Dec-Mar	2004-ongoing ¹
Sea surface temperature	DPIRD – Warnbro Sound lobster puerulus monitoring site	Monthly	1984-2021
Sea surface temperature	NOAA OI SST V2 High Resolution Dataset (https://psl.noaa.gov/ , Huang et al. 2021a). Mean of datapoints at 31.125°S, 115.625°E, and 31.375°S 115.625°E	Daily	1981-2022
Seagrass coverage	Kendrick et al. (2002), Hovey et al. (2013), Hovey and Fraser (2018)	7 seagrass maps over 50-year period	1967-2017
Rainfall	Armadale and Perth Airport weather stations (BoM, 2022)	Monthly	1901-ongoing
River flow	Swan River – Walyunga, site 616011 (DWER, 2022)	Monthly	1970-ongoing

¹ Incomplete time series with no measurements in some years.

While the frequency and location of water quality samples collected on behalf of the CSMC have changed multiple times over the last four decades, water quality measurements were generally sampled in weekly intervals from December-March each year. Standardised annual summer indices of chlorophyll-*a*, total nitrogen, total phosphorus, salinity, temperature, dissolved oxygen and pH were calculated using Generalised Additive Models (GAMs; Appendix 1).

Being adjacent to a major metropolitan area, CS has experienced various changes due to urbanization and industrialization over the last 50 years (Gartner et al. 2018), including the establishment and/or expansion of major industrial facilities (e.g. cement works, water extraction for industrial cooling and desalination and port developments). Over the same time, increasing water management practices have also improved the existing domestic and industrial uses through rerouting wastewater pipelines

and managing the nearby Swan-Canning Estuary. As such, this current project considers a range of environmental parameters, such as water quality metrics, whose change in CS would not be primary driven by climate change.

3.1.1 Seagrass trend

Changes in seagrass coverage within CS were assessed using estimates from previous studies. As CS is adjacent to the Kwinana industrial area there have been multiple studies mapping the seabed habitats that document change in seagrass habitat extent within CS (Kendrick et al. 2002, Hovey et al. 2013, Hovey & Fraser 2018). Maps of seagrass coverage are available for 1967, 1972, 1982, 1994, 1999, 2012 and 2017. Although the studies all focused on CS south of Woodman Point, the study area extent varied slightly.

3.1.2 Rainfall and freshwater inputs

Data on freshwater inputs to CS were derived from two sources: flow rates of the Swan River and rainfall measurements. Monthly rainfall data were derived from the Armadale weather station (number 9001) since 1901 (the oldest and most continuous weather station in Perth). Where months were missing, data were infilled from the Perth Airport weather station (number 9201). Despite there being no natural surface freshwater inputs directly into CS, outflow from the Swan River regularly influences the water quality within CS, particularly the waters north of Woodman Point. In particular, following heavy rainfall and flooding events, plumes of turbid freshwater have been visible from satellite imagery extending into CS (Gartner et al. 2018). As the Swan-Canning catchment is managed at multiple locations throughout the system (in particular the Canning River – Kent Street Weir), the Walyunga site (number 616011) provides a measurement of unregulated flow and is a reasonable approximation for Swan River flow (Johnston et al. 2021). However, no data exists for total discharge from the Swan and Canning River systems. Further data on surface and groundwater fluxes into CS are expected to be delivered by WWMSP project *Elements of the groundwater/surface water flux into Cockburn Sound*.

3.2 Time series of data on the abundance of the key biota

The abundance of different species within CS are presented from a range of fishery-independent and fishery-dependent sources. Below is a brief description of each data source and any processing steps required to create a standardized annual time-series for each species.

3.2.1 Fisheries-independent survey data

DPIRD have undertaken several repeat surveys as part of its fisheries research and monitoring activities within CS which provide time-series datasets using consistent methodologies.

Large otter-trawl

In 1971/72 an area in the north central basin of CS, commonly referred to as the 'Research Area' (Figure 1; Johnston et al. 2020), was repeatedly trawled to study various aspects of western king prawn (*Penaeus latisulcatus*) biology (Penn 1975, 1976). These trawls were conducted monthly for 18-months and consisted of 4-6 trawls each lasting 30-minutes aboard the Fisheries Research trawler RV *Flinders*, towing a single otter-trawl net. All caught biota were recorded. Following this initial assessment, the survey then continued from 1972-2006 opportunistically, at different times of year or multiple surveys per year (Figure 2), with data contributing to a range of projects over that period (Lenanton 1974, Penn 1977, 1980, Dybdahl 1979). Each survey was completed in a single night, however, which species abundances were record varied, with western king prawn and blue swimmer crab (*Portunus armatus*) being the only two species consistently recorded (Figure 2). In 2002, the RV *Flinders*, was replaced with the RV *Naturaliste* pulling twin otter-trawl nets of the same configuration as the RV *Flinders*, essentially doubling the swept area.

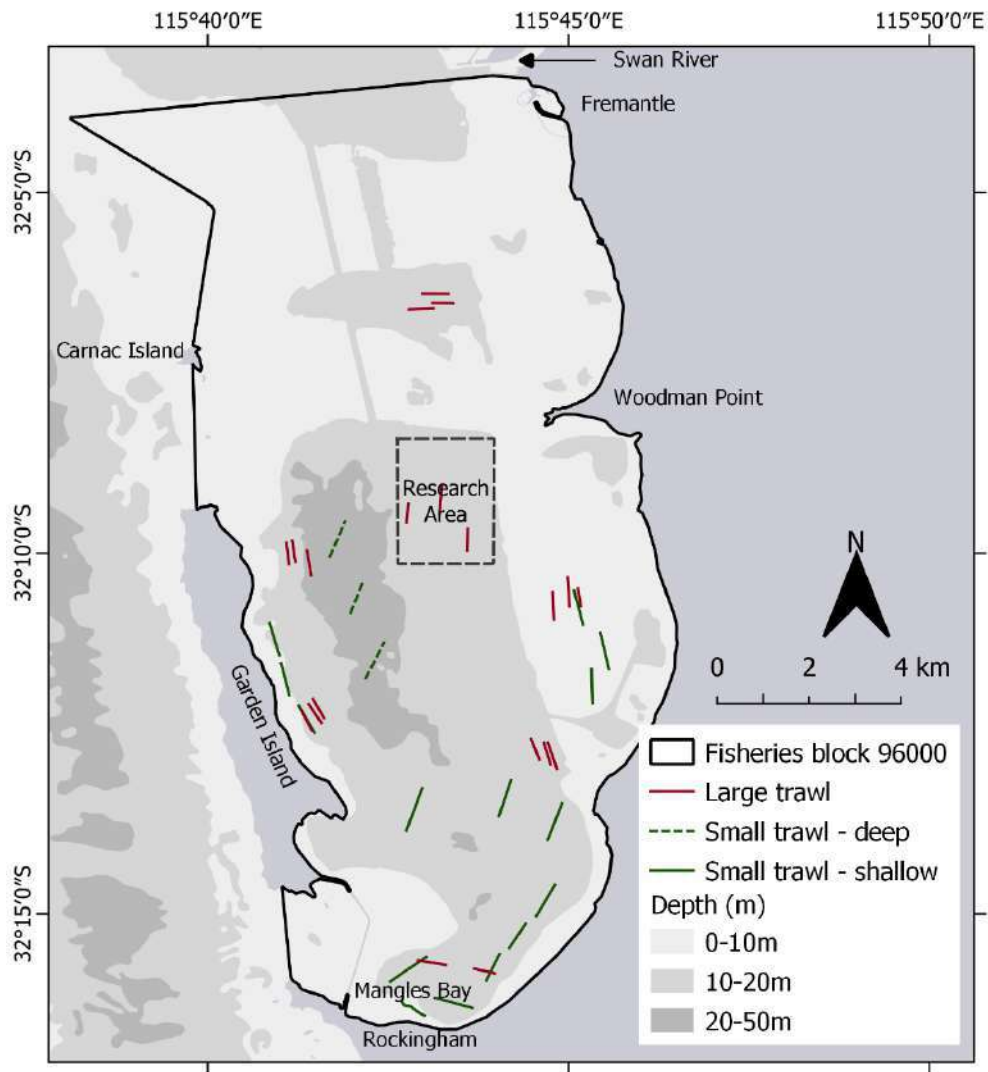


Figure 1. Site map of CS showing the locations of the 'Research Area' and large and small trawl sites. The boundary of the CS commercial fisheries block (96000) is also presented.

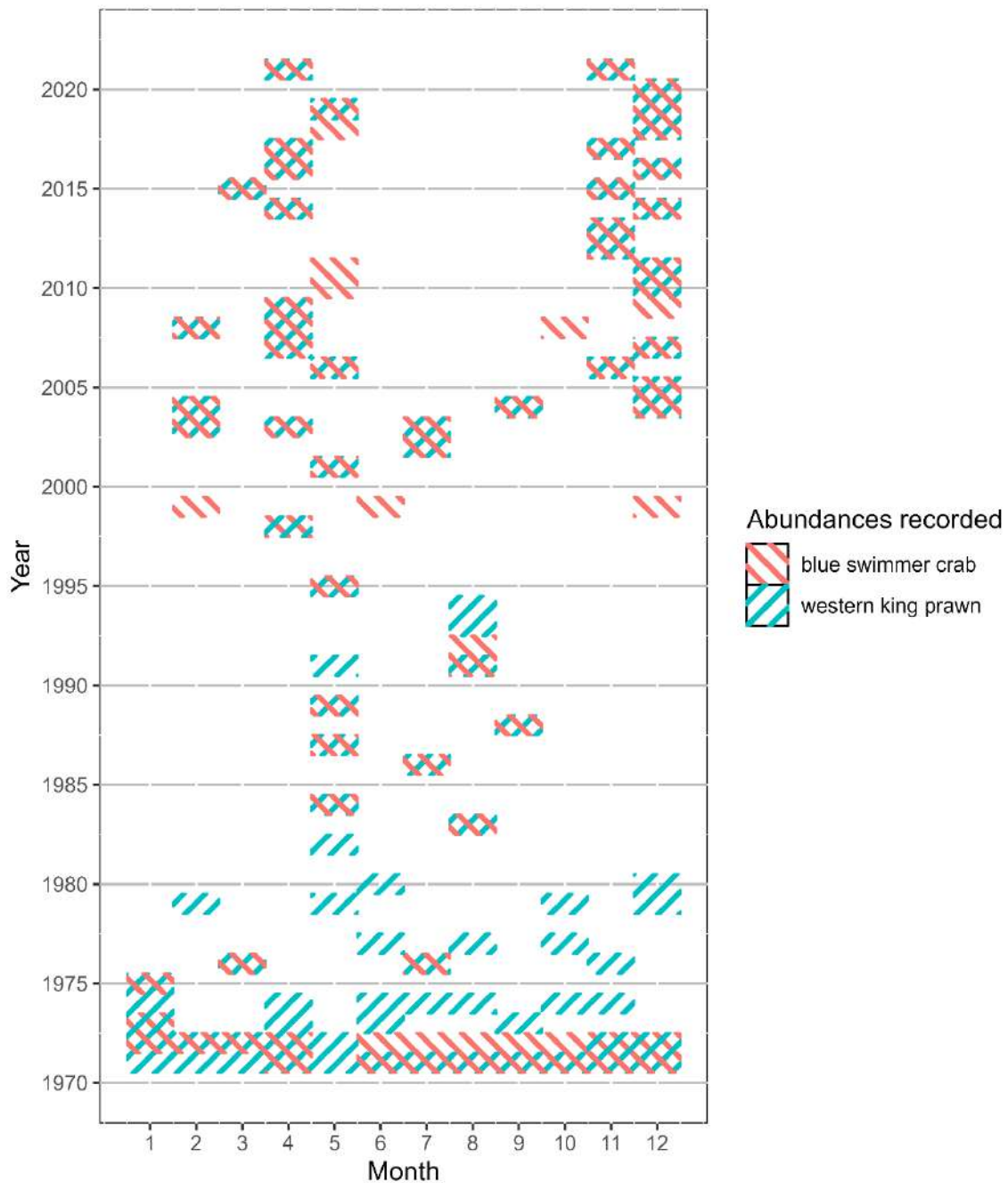


Figure 2. Available abundance records for western king prawn and blue swimmer crab within the 'Research Area' in central CS, based on the large otter-trawl net, deployed from the RV Flinders or RV Naturaliste.

In 2007, following the decline of the Cockburn Sound Crab (CSC) fishery, the annual survey was significantly redesigned to monitor the abundance of blue swimmer crab. As crab commercial fishing effort was concentrated on the shallower banks nearer to seagrass habitats, the deeper (>20 m) and generally muddy 'Research Area' was not considered to be the best indicator of overall crab abundances within the fishery. Therefore, in redesigning the survey, the trawls were no longer limited to deeper muddy habitats in the 'Research Area' but rather to seven sites throughout CS (Figure 1), each with three, five-minute tows (Sampey et al. 2011). To allow comparison with the previous data, one site with three replicates was positioned within the 'Research Area'. A second annual survey was also added with the objective of sampling crab recruits in April-May and crab breeding stock in

November-December (Figure 2). While the primary objective was to sample blue swimmer crab, the abundance of western king prawn continued to be recorded.

All abundance data were converted to densities, based on the swept area of each shot. Using the full CS dataset since 2007, spring 'breeding stock' and autumn 'recruits' indices were calculated for blue swimmer crab using separate linear models. Each model analysed $\log(\text{density})$ with year and site as factors. The estimated annual abundance index values reflect the marginal means for each year.

The 'Research Area' dataset from 1971-2021 was also used to estimate the yearly average density of blue swimmer crab and western king prawn within the deeper parts of CS. For each survey the average density within the 'Research Area' sites was calculated, based on the swept area of the nets and number of shots. For each species a separate linear model was fit to predict the natural log of density. Day of year was included as a cyclical feature by transforming it into two dimensions (sine and cosine) and year was included as a factor. The annual standardized density index was then calculated using the estimated marginal means (Lenth et al. 2023).

Since 2009, the abundance and size of snapper were also recorded and are discussed further in Section 4.3.3.

Juvenile blue swimmer crab survey

To develop a blue swimmer crab juvenile index for the CSC fishery, DPIRD have conducted annual surveys since 2002 during April, May and June, when recruiting blue swimmer crabs become susceptible to sampling gear. These surveys utilized a small otter-trawl, with a 4.5 m headrope (effective opening width of ~3 m) and height of 0.5 m, constructed from 51 mm mesh in the wings and 9 mm mesh in the cod end, and with a 10 mm ground chain attached to the foot rope, towed behind a ~7.5–8.5 m research vessel. Each month, six sites were sampled, each with three replicates, that were distributed around CS (Figure 1). Trawls were conducted at night, at a speed of ~2.7 kts for nine minutes, equating to an approximate distance of 750 m (c. 2,250 m² swept area). For all surveys the number and size (carapace width – CW) of all crabs were recorded, along with size at maturity and ovigerity for females. The weight (g) of each crab was also estimated using the species-specific CW-weight relationship (Johnston & Yeoh 2020).

Data collected from juvenile recruitment trawl surveys were used to calculate an annual juvenile recruitment index. All crabs in each sample were firstly allocated as juveniles (0+) or adult (1+) according to size using a monthly sex-specific CW threshold, obtained from a seasonal von Bertalanffy growth curve (Bellchambers et al. 2006; Johnston et al. 2021; Johnston et al. 2011) that separated the two-year classes. The juvenile (0+) catch rate data (number of 0+ crabs 100 m⁻² trawled) from each replicate trawl in the shallow water sites (Figure 1) were then incorporated into a GLM (log-linear distribution), with site, month and year as explanatory factors, with mean annual juvenile index and 95% CL estimated.

Baited remote underwater video survey

A winter baited remote underwater video (BRUV) survey has been conducted annually in CS since 2008. The survey commenced as part of preliminary investigations into a potential impacts of a proposed 'Kwinana Quay' port development (Wakefield et al. 2009, 2013), and then continued as a means of observing changes in abundance of juvenile snapper within CS. Initially, the survey included 51 sites of three replicates each, south of Woodman Point covering six main habitat types: seagrass, limestone (i.e. reef), silt basin, sand plateau, rock walls and dredged channels. It was subsequently determined that the silt basin samples were overrepresented in the survey and very few fish were observed there, so the survey was reduced to 37 sites in 2010 (Figure 3). Each year the surveys have been completed in June-August to primarily observe juvenile (0+ and 1+) snapper before they begin to leave CS.

BRUV data have been processed by DPIRD and university staff to record the relative abundance of all species present, based on the maximum number of individuals of each species present in a single frame (MaxN). Further details on data processing are provided in (Wakefield et al. 2013, Davoit et al. 2017). While collected, no MaxN data are available for 2018-2020 as the videos have not been processed. In 2021, stereo cameras replaced the mono camera setup, thereby allowing fish to be measured in the software 'Eventmeasure' (<https://www.seagis.com.au/event.html>) using fork length.

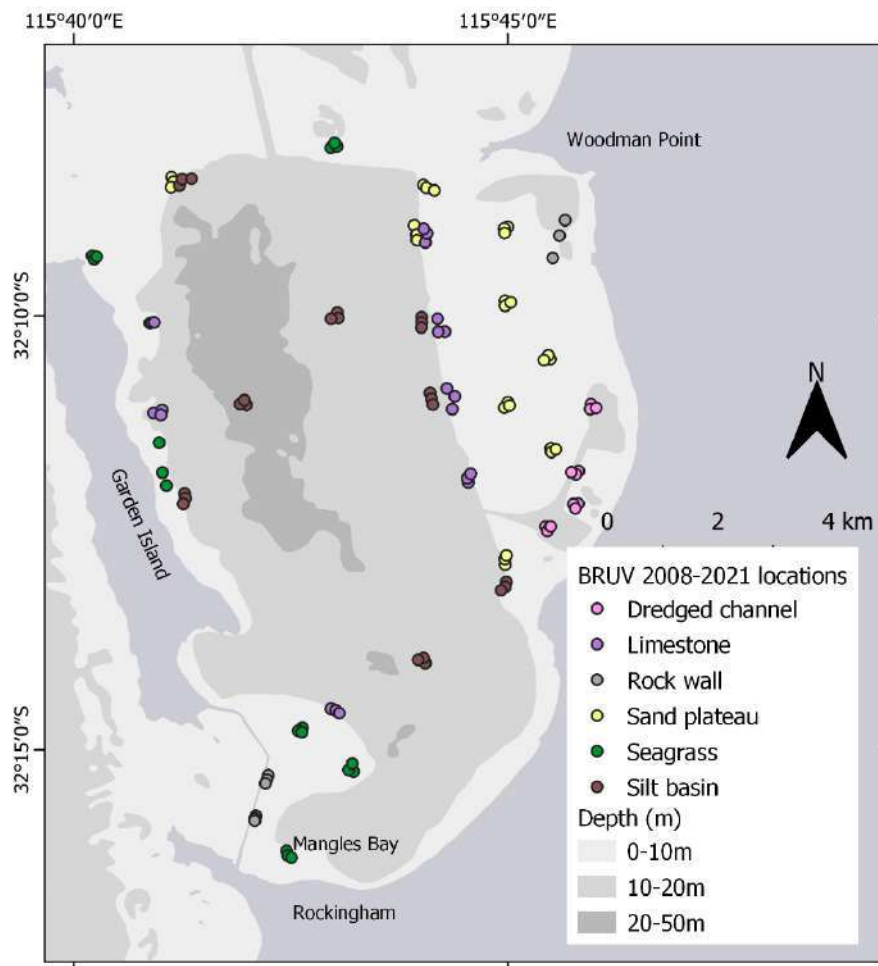


Figure 3. Location of BRUV sites, with associated habitats that were consistently sampled in CS between 2008-2021.

Nearshore recruitment survey

Since 1993, DPIRD have monitored the annual abundance of juvenile fish along the south-western WA coast using beach seine netting (Gaughan et al. 2006, Brown et al. 2013). The time series was formed from data collected under different projects that were primarily designed to first develop, and then maintain, an annual recruitment index of nearshore finfish species for south-western Australia.

These monthly surveys utilized a 61 m net in nearshore nursery sites during daylight hours, from September to January each year. Abundance of each finfish species was recorded, and lengths were measured for up to 50 individuals per species per haul. As part of this monitoring program, Mangles Bay in southern CS was sampled from 1999-2002, 2005-2016 and 2020-current. During the different projects that contributed data to this time series, there were additional samples collected at night, during other months of the year and with increased replication. However, to allow comparability between years, these data were excluded.

During the early phases of the project (1996-2002; FRDC projects 96/105 and 1999/153), the abundance of only 20 commercially and recreationally important finfish species were recorded. No data were available from January 2016 to October 2020.

3.2.2 Commercial catch and effort data

Since 1975, WA commercial fishers have been required to provide monthly information to DPIRD's (or its predecessor the Department of Fisheries) Catch and Effort Statistics (CAES) database. Within CAES fishers report location based on 'fishing blocks' of which CS was introduced as a specific fishing block (96000; Figure 1) in July 1977. Total commercial catch and catch per unit effort (CPUE) were calculated for a number of key species as an approximate measure of relative abundance trends over time within CS. While catch data can be considered a reliable indicator of removals, CPUE as a measure of relative abundance can be problematic with hyperstability (where CPUE remains high despite abundance decreasing) common (Harley et al. 2001, Maunder et al. 2006). So, while commercial CPUE is considered in light of changing methods and management over time, this study places greater emphasis on fisheries-independent survey data.

Since 1977, fishers have recorded 24 different fishing methods in the CAES database within CS. Where these methods are considered comparable (e.g. handline and hand reel) these have been merged, however, gear-specific CPUE have been calculated and only the most common fishing methods have been presented. As data are commercially sensitive, CAES data are anonymized and only reported for species and years where fishers approved the publishing of their data, or more than three licensed fishers were actively fishing.

For fisheries with less than three operators, operators gave permission to publish total catch information of key species, however, only anonymised effort data are presented for squid and octopus.

3.2.3 Recreational fishing data

Cockburn Sound is popular amongst recreational fishers and in 1996/97 was ranked as the second busiest area for boat fishing in WA (Sumner & Lai 2012). However, while recreational fishing surveys have been conducted in the Perth metropolitan area since 1973, there has been a limited focus on CS as a specific area (Tate et al. 2020).

Historically, a variety of different survey designs and spatial scales were used to collect recreational fishing data across the West Coast Bioregion (WCB) and Perth metropolitan area (Lancelin to Mandurah) making direct comparisons of recreational catch and effort in CS challenging. Methods used to collect recreational fishing data in the Perth metropolitan area include creel and access point surveys of boat and shore fishing in 1973 and 1997 (Lenanton & Hall 1976, Ayvazian et al. 1997); a roving creel survey of shore-based fishing conducted annually since 2014, completed between Ocean Reef to Woodman Point included ~11 km of coastline within CS (Tate et al. 2022); and five statewide phone diary surveys of boat-based fishing conducted since 2011, using the recreational boat fishing license (RBFL) that was introduced in 2010 as the sampling frame (Ryan et al. 2013, 2015, 2017, 2019, 2022). The phone diary surveys were designed to provide estimates of boat-based recreational fishing participation, effort and catch at a statewide, bioregion and zone levels.

Comparisons can be made for two on-site surveys conducted in CS in the early 2000s. The studies used a bus route survey method to sample boat ramps likely to access CS including Leeuwin, Woodman Point, Sutton Road, Kwinana Beach, Palm Beach and Point Peron boat ramps. The first conducted in 2001/02 focused on the recreational catch and effort from CS and Geographe Bay, while the second used the same methodology in 2005/06 as part of a larger survey covering the entire WCB. Catch and effort estimates for both surveys were produced for both recreational fishing and crabbing in CS (Sumner & Lai 2012).

3.2.4 Aquaculture monthly production

The only long-term data available from the aquaculture facilities within CS are total output reported to DPIRD through the Aquaculture Production Returns system. This provides a total yearly production per facility and are confidential for CS due to there being less than three license holders.

3.2.5 Statistical analyses

Generalised Linear Model (GLM) analyses have been undertaken to obtain standardized annual estimates of key biota that consider other relevant factors such as month and location which also accounted for missing values. The long-term trends in the key biota were identified. Some biota with good data were identified for further analysis to assess the effects of environment on the variation in biota abundance.

3.3 Assessment of biological and environmental effects on key biota

An assessment of the direct and indirect environmental effects on the key biota was undertaken using the data collated in sections 4.2 and 4.3. Statistical analysis such as GLMs were used to examine the relationships between biological and environmental variables and the annual relative abundance of key biota. The effect of events such as the 2011 extreme marine heatwave (MHW) were also assessed.

Depending on the data availability for the key biota, the assessment examined the environmental effects on different life history stages, such as spawning, larvae and juveniles, to identify what aspect of the life history may be vulnerable to environmental factors. This also provided valuable input into the climate change risk assessment.

Case studies were undertaken on the following biota or summarized from publications: blue swimmer crab, western king prawn, snapper, rabbitfish (*Siganus* sp.), yellowfin whiting (*Sillago schomburgkii*), southern garfish (*Hyporhamphus melanochir*), sandy sprat (*Hyperlophus vittatus*), little penguins (*Eudyptula minor*), Australian sea lions (*Neophoca cinerea*), Indo-Pacific bottlenose dolphins (*Tursiops aduncus*) and invasive marine species.

3.4 Climate change modelling projections downscaled to the coastal environment.

The WWMSP project *Provision of multi-decadal ocean boundary conditions and field measurements* provided open ocean boundary conditions for the period 2000-2020 and future climate scenarios (to 2100) under two Shared Socioeconomic Pathways (SSP) emission scenarios: (i) SSP2 represented a “middle of the road” scenario that assumed historical patterns of development; and (ii) SSP5 assumes an energy-intensive, fossil fuel-based economy (‘high’ emission).

The projections from the hydrodynamic modelling were used to assess the exposure component of the risk assessment of the biota to the climate change projections.

3.5 Risk assessment of the effects of climate change on the key biota

A risk assessment of the effects of climate change on the various biota in CS was undertaken using the biological and ecological risk assessment categories outlined in Fulton et al. (2020). This approach applied a traits-based scoring method to determine a species’ sensitivity to climate change. The sensitivity was based on methods developed by the South-east Australian Climate Change group (Pecl et al. 2011) and has been previously applied to WA commercial and recreational species (Caputi et al. 2015a and b).

The ‘sensitivity’ of the species to climate change was assessed in terms of their productivity and distribution. Pecl et al. (2011) identified that climate change impacts can be expressed by a change in a species’ abundance, distribution and phenology. They considered that higher productivity species and those whose life stages occur over a large spatial distribution would be less sensitive (i.e. more resilient) to climate change stressors. Similarly, species that were sensitive to changes in the timing of their life cycle events (phenological changes such as spawning, moulting and migration) may be less

resilient. Fulton et al. (2020) added a fourth category, 'quality', as climate change may impact the quality of flesh and therefore its desirability by commercial and recreational fishers.

Fulton et al. (2020) assessed the four categories of abundance, distribution, phenology and physiology using 19 attributes (Table 2). Scores of one to three were given to each attribute representing 'low', 'medium' and 'high' sensitivity to climate change. The scores for each of the four categories were averaged to obtain scores for each category. These four scores were then added to get an assessment of the relative sensitivity of species to climate change across all the categories. The uncertainty associated with any of the assessments, such as lack of scientific evidence or data, was acknowledged and a pre-cautionary approach was adopted by selecting a ranking on the higher side of the range (i.e. more sensitive to climate change). These scores were based on the available literature information for the species and the expertise of the relevant scientists and reviewed to ensure that the interpretation of the criteria was consistently applied. The species were then ranked and assigned a score of five to one based on their relative sensitivity to climate change.

Table 2. Biological categories used to assess the risk of climate change on each species. The attributes and risk levels to assess species sensitivity are derived from Fulton et al. (2020).

Description of the change and implications for the species	Species attributes that affect their sensitivity to climate change	Low sensitivity (1)	Medium sensitivity (2)	High sensitivity (3)
Abundance: Changes in the total (or local) population size, which alters the CS specific availability of a particular species.	Fecundity – egg production	> 20,000 eggs per year	100 – 20,000 eggs per year	< 100 eggs per year
	Recruitment period – successful recruitment event that sustains the abundance of the fishery	Consistent recruitment events every 1-2 years	Occasional and variable recruitment period	Highly episodic recruitment event
	Average age at maturity	≤ 2 years	2 – 10 years	> 10 years
	Generalist vs. specialist – food and habitat	Reliance on neither habitat or prey	Reliance on either habitat or prey	Reliance on both habitat and prey
	Sensitivity to ocean acidification	Not shelled and no reliance on shelled species	Not shelled, but reliant on shelled species (as prey or habitat)	Shelled species
Distribution: Changes in the geographic location (range) of where the species mainly reside. This can alter access (especially if it shifts beyond CS) or costs (if further from ports or infrastructure). It can also undermine spatial management (e.g. as the species is no longer covered by a closure meant to protect a spawning aggregation).	Capacity for larval dispersal or duration	> 2 months	2 – 8 weeks	< 2 weeks or no larval stage
	Capacity for adult/juvenile movement	> 1000 km	10 – 1000 km	< 10 km
	Physiological tolerance	> 20° latitude	10 – 20° latitude	< 10° latitude
	Spatial availability of unoccupied	Substantial unoccupied habitat; > 6° latitude or longitude	Limited unoccupied habitat; 2 – 6° latitude and longitude	No unoccupied habitat; 0 – 2° latitude or longitude
Phenology (timing): Changes in the timing of biological events. This can change accessibility (e.g. the fish may no longer be in the system at the same time of the year), abundance (as recruitment may fail if mismatches occur), or it may undermine seasonal management measures (e.g. if spawning or migration is earlier/ later, a seasonal fishery may miss the resource).	Environmental variable as a phenological cue for spawning or breeding	No apparent correlation of spawning to environmental variable	Weak correlation of spawning to environmental variable	Strong correlation of spawning to environmental variable
	Environmental variable as a phenological cue for settlement or metamorphosis	No apparent correlation to environmental variable	Weak correlation to environmental variable	Strong correlation to environmental variable
	Temporal mismatches of lifecycle events	Continuous duration; > 4 months	Wide duration; 2 – 4 months	Brief duration; < 2 months
	Migration (seasonal and spawning)	No migration	Migration is common for some of the population	Migration is common for the whole population
Physiology: Changes in the quality of the species.	Fat and muscle content (capacity for energy storage)	High fat and muscle content (capital breeder)	Intermediate	Low energy storage (income breeder)
	Body size	Large (> 100 cm)	Medium (20 – 100 cm)	Small (< 20 cm)
	Metabolic capacity	High metabolic capacity	Medium metabolic capacity	Low metabolic capacity
	Disease or parasite load	Low disease and parasitic load	Medium disease and parasitic load	High disease and parasitic load
	Physiological tolerance and response curve	High tolerance	Medium tolerance	Low tolerance
	Oxygen sensitivity	Low sensitivity (< 2 ml/l O ₂)	Intermediate (2 – 5 ml/l O ₂)	High sensitivity (> 5 ml/l O ₂)

The ‘exposure’ component of the risk assessment was based on the historical and projected trends of environmental variables that may affect the species (addressed in project aims 1-4). The exposure score, or likelihood of being negatively impacted by climate change, was determined based on the categories in Table 3. Relevant experts for each species of interest were consulted to determine these scores.

The sensitivity and exposure components were then multiplied to obtain a relative risk ranking for each species being considered:

Climate Change Risk = Sensitivity x Exposure.

This risk assessment approach provides a comparative basis for identifying species that may have the highest risk of being affected by climate change and a priority for monitoring and further investigation for climate change adaptation. However, socio-economic factors are also relevant to the priority setting process for assessing climate change effects as undertaken by Caputi et al. (2015a).

Table 3. The exposure (or likelihood) rankings used in the risk assessment of species to climate change in CS.

Exposure rankings
1. Remote or potentially positive effect
2. Negative effects are unlikely
3. Negative effects are possible
4. Demonstrable negative effects are evident

Table 4. The final risk assessment levels for species to climate change within CS. This was obtained by multiplying sensitivity and exposure scores.

Level	Category
1-2	Negligible risk
3-4	Low
5-9	Medium
10-15	High
16-20	Severe

The effect of climate change in CS was assessed within the context of the climate change effect on the lower west coast of WA, which may be affected by southward expansion of the ranges of some tropical species as observed during the 2011 extreme MHW.

The assessment was undertaken for the 14 fisheries species and five species which are iconic to the Perth region. Only species that had sufficient available information were included for the risk assessment.

3.6 Risk assessment of the effects of climate change on invasive marine species

Commercial shipping and naval activities operating within CS and the Port of Fremantle pose a constant risk of invasive marine species (IMS) introductions to the region. As IMS can negatively affect ecosystems and marine industries, infrastructure and resources, biosecurity measures are in place which provide ongoing surveillance and response, where necessary. A baseline marine pest survey for

the Port of Fremantle and CS was conducted during the CSIRO Centre for Research on Introduced Marine Pests (CRIMP) survey in 1999 (Hewitt et al. 2000, Hewitt & Martin 2001). The survey identified two marine pest species, the European fan worm (*Sabella spallanzanii*) and the Asian bag mussel (*Arcuatula senhousia*, formerly *Musculista senhousia*). A further nine species were observed that were introduced or of cryptogenic origin. In 2008, the Western Australian Museum produced a compendium of IMS detailing historic records of non-native marine species identified across WA with 46 species relevant to CS, Swan-Canning Estuary, and the Fremantle region (Huisman et al. 2008).

Ongoing surveillance for the detection of IMS was initiated by DPIRD (then Department of Fisheries) in 2010. A fundamental part of the current surveillance regime is the State-wide Array Surveillance Program (SWASP) conducted in ten major WA ports, including the Port of Fremantle. SWASP principally involves the use of settlement array plates deployed twice per year for two months at a time. The settlement plates provide settlement substrate for marine biota, after which samples are collected and assessed using taxonomic and molecular diagnostics (McDonald et al. 2020). The program has been underway since 2011 with sites at the Kwinana Bulk Jetty and Australian Marine Complex in CS, and within the Port of Fremantle Inner Harbour. In addition, DPIRD has been conducting annual surveillance for the Department of Defence since 2011, with sites at HMAS Stirling, Garden Island, the causeway and the Kwinana Grain Jetty. The surveillance program utilises a suite of methods including benthic sleds, beam trawls, crab traps, crab condos, eDNA sampling through water and plankton, as well as visual transects involving SCUBA, snorkel, and shoreline surveillance for the detection of IMS. Six sites are also monitored using settlement arrays within CS. The array surveillance has been conducted on a constant two-month rotation since 2021.

Port surveys for IMS were conducted on an ad-hoc basis in the Port of Fremantle in 2011, 2013, and 2015 under the National System design (DAFF 2010) and marine biosecurity surveys were conducted in 2014 and 2020. In addition to previously recorded IMS (Hewitt et al. 2000, Huisman et al. 2008), notable marine pest detections by DPIRD from surveillance since 2011 include the cryptogenic white colonial sea squirt (*Didemnum perlucidum*), carpet sea squirt (*Didemnum vexillum*), the invasive strain of dead man's fingers (*Codium fragile* ssp. *Fragile*), Asian paddle crab (*Charybdis japonica*) and the dinoflagellate *Alexandrium catenella*.

In 2014 DPIRD assessed the likelihood of IMS being translocated by commercial vessels into WA, assessing both the bioregional impacts, and port environments risk (Bridgwood & McDonald 2014). The Port of Fremantle assessment identified that 79% of the potential inbound IMS were compatible with the Fremantle Port environment. Cargo vessels, followed by bulk vessels, represented the most common vessel type entering the port, with the number of vessels arriving from international ports almost equal to interstate vessel arrivals. The international last ports of call (LPOCs) representing the greatest risk in terms of numbers of vessels and compatibility of marine pests were Singapore and Indonesia. However, Japan was identified as having the greatest number of introduced marine pest species, the majority of which were classed as high-risk species, to WA (Bridgwood & McDonald 2014).

Surveillance data from CRIMP, SWASP and the ad-hoc IMS surveys record presence only information. Therefore, these surveillance methods do not capture how the abundance of any IMS observed within CS or the Port of Fremantle is changing in response to environmental conditions or other factors. An assessment of how climate change may alter the suitability of CS to specific IMS is therefore based on the biological traits of these species and information published elsewhere.

The IMS were assessed using the same biological and ecological traits-based risk assessment criteria described in Section 3.5 and Fulton et al. (2020). However, in Section 3.5 the risk of climate change to key species native to CS was that the climate and conditions in the future might become less suitable for the species. For IMS the interpretation of risk of climate change is inverted, i.e. that conditions within CS in the future may become more suitable for IMS introductions and for species persisting as a result of climate change. Therefore, species with low sensitivity to negative climate change effects

and low exposure scores are considered to indicate those IMS which would find conditions within CS suitable in the future.

The species selected to be included in the climate change risk assessment process were identified from current state and national IMS lists which are considered 'pest' species. DPIRD conduct surveillance for IMS aligning with the Western Australian Prevention list for Invasive Marine Pests which includes over 80 species, representative of a broad range of taxa, that may be spread principally via biofouling and ballast water pathways, as well as aquaculture introductions (DPIRD 2016). Many of these species are also listed as Noxious fish under the Fish Resources Management Act (1994). Four species from these lists were selected as case studies that: have environmental tolerances that match CS and its predicted climate change shifts; are well studied and have existing data on their invasive potential; and cover different taxonomic groups.

4 Results and Discussion

4.1 Historical environmental data for Cockburn Sound

The main trends observed in CS specific environmental data are summarised in Table 5, with further detail provided in the subsequent subsections.

Table 5. Summary of key historic environmental trends influencing CS that may be relevant to marine species. This section (4.1) describes the observed trends in greater detail.

Environmental variable	Direction of trend	Link to climate change	Brief description
Leeuwin Current strength	↓	Yes	Weakening current (particularly in winter months) and also influenced by El Niño/Southern Oscillation (ENSO) events
Sea surface temperature	↑	Yes	Warming SST, most prevalent in summer. SST also linked to strength of Leeuwin Current and ENSO events
Nitrogen	→	No	Nitrogen levels stable, but much lower than peak industrial levels
Phosphorus	→	No	Phosphorus levels stable, but much lower than peak industrial levels
Chlorophyll- <i>a</i>	→	No	Chlorophyll- <i>a</i> levels generally stable, but much lower than peak industrial levels
Salinity	→	Possible	Hydrodynamic model indicates no changes expected
Dissolved oxygen	→	Possible	No predominant direction of change although short-term falls in dissolved oxygen can occur with extreme climate events
pH	→	Possible	Only short time series available for CS but globally acidification is widely observed
Rainfall and freshwater inputs	↓	Yes	Decreasing total rainfall and surface water flow from the Swan-Canning Estuary, but also increased frequency of summer rainfall events
Seagrass	↑ & ↓	Possible	Small increase in extent but observed decrease in shoot density which has been linked to SST

4.1.1 Southern Oscillation Index, Leeuwin Current and El Niño/La Niña

The poleward-flowing Leeuwin Current transports warmer water south along the WA coastline and is important to breeding and survival of a multitude of marine species (Caputi et al. 2001, Cannell et al. 2012, Lenanton et al. 2017). The strength of this current can be measured by its influence on the Fremantle mean sea level (MSL) (Feng et al. 2004). Increases in Fremantle MSL indicate a strengthening of the Leeuwin Current and vice versa. The Leeuwin Current also results in higher MSL in winter and lower MSL in summer. When the Southern Oscillation Index (SOI) is positive (indicating La Niña conditions) the Leeuwin Current is stronger and the sea level higher. Negative SOI indicates El Niño conditions, weaker current and lower sea level (Bicknell, 2010).

Since records began, the Fremantle MSL has increased at a rate of 1.76 mm yr^{-1} (Figure 4A) which is greater than the rate calculated by Feng et al. (2004) up to 2004 (1.54 mm yr^{-1}). From the 1960s to early 1990s there was a general weakening trend for current strength. However, with the addition of 20 further years of data during which time there were also two strong La Niña events (2010-11 and 2020-22), there has been an accelerated overall trend in the Fremantle MSL. The MSL anomalies (Figure 4B) are regarded as a better index of the strength of the Leeuwin Current than raw MSL values, as they remove the ocean warming trend. Climate models based on 'business as usual' future changes consistently project a weakening of the Leeuwin Current (Stellema et al. 2019) which is consistent with the projected weakening of the Indonesian Throughflow (Feng et al. 2018). This is consistent with previous downscaled climate models that predicted the Leeuwin Current to weaken by $\sim 15\%$ between 1990 and 2060 (IPCC scenario A1B), with the greatest change observed during the winter months (Sun et al. 2012). However, changes associated with the SOI are more variable. Based on historic trends, the intensity of La Niña and El Niño events has increased, and, since 2000 there have been more frequent La Niña events (Caputi et al. 2015a). The 1998-2001 and 2010-11 La Niña events were regarded as particularly pronounced events, and this is also visible in the MSL anomalies (Figure 4B). Similarly, the weaker Leeuwin Current was thought to be a contributing factor to a marine cold spell which commenced with an El Niño event in 2015-2016 (Feng et al. 2021).

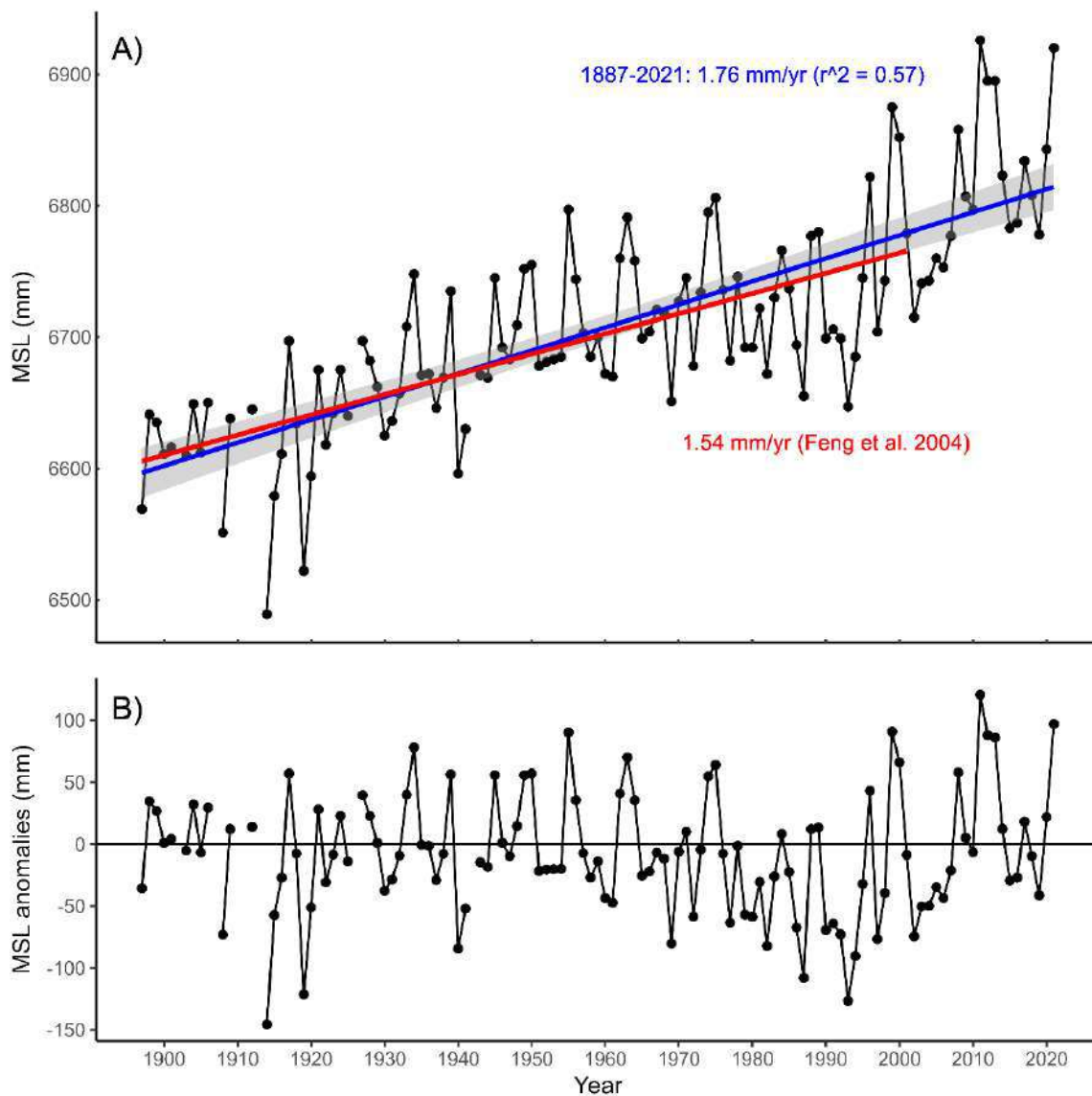


Figure 4. Fremantle annual MSL from 1897-2021 (A). The red trendline indicates the rate of sea level rise as calculated by Feng et al. (2004), and the blue trendline shows the updated trend after incorporating the most recent 20 years of data. The detrended MSL based on the updated trend is depicted in (B).

Sea level rise associated with climate change is also anticipated to increase erosion and inundation of the coast around CS (Gartner et al. 2018). To prepare for these risks, the local government areas of South Fremantle, Cockburn, Kwinana, and Rockingham have all developed coastal adaptation plans which may include substantial modifications to the coastline such as sea walls, groynes, beach nourishment, dune management and revegetation and changes to coastal infrastructure (Cockburn Sound Coastal Alliance 2016a, c b, 2018). These measures all have the potential change the nearshore marine habitats by adding or removing hard substrates and changing patterns of water flow and turbidity levels.

4.1.2 Sea surface temperature

Since records began, the general trend has been a warming of sea surface temperature (SST) within CS (Figure 5). SST in the summer months from the CSMC data shows a small increase in summer temperature of $0.0136^{\circ}\text{C yr}^{-1}$ since the summer of 1985/86 ($F_{1,5887} = 58.75$, $p < 0.001$). However, data within CS are limited to the warmer months, so the most applicable dataset for in situ year-round

measurements are from a nearby site in Warnbro Sound (<10 km south). Marks et al. (2020) determined this site to be a reasonable proxy for temperature fluctuations within CS, while also providing a longer and more complete time series. Based on a GLM fit to year and month the temperature increase was calculated to be $0.023^{\circ}\text{C yr}^{-1}$ (Figure 6). This is consistent with the rate of SST warming for the southwest Australian coast, which has previously been calculated as $0.02^{\circ}\text{C yr}^{-1}$ (Pearce & Feng 2007). The southwest coast has been identified as a hotspot which has been exceeding the global average rate of warming (Hobday & Pecl 2014).

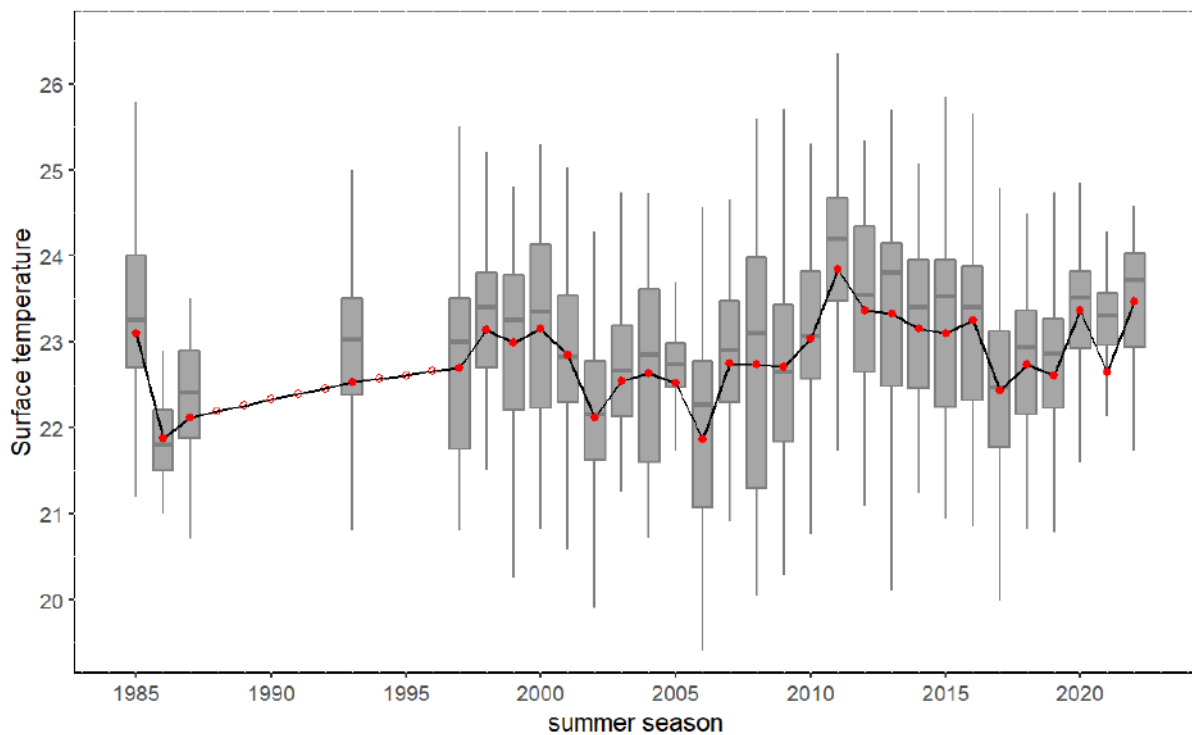


Figure 5. SST during the summer months within CS. Boxplots of the raw measurements collected on behalf of the CSMC. Summer SST index values calculated using a GAM are shown as the red dots and line, with the interpolated index values shown as hollow dots. The model fit is reported in Appendix 1. Summer months based on December to March each year and 'summer season' refers to the year in January.

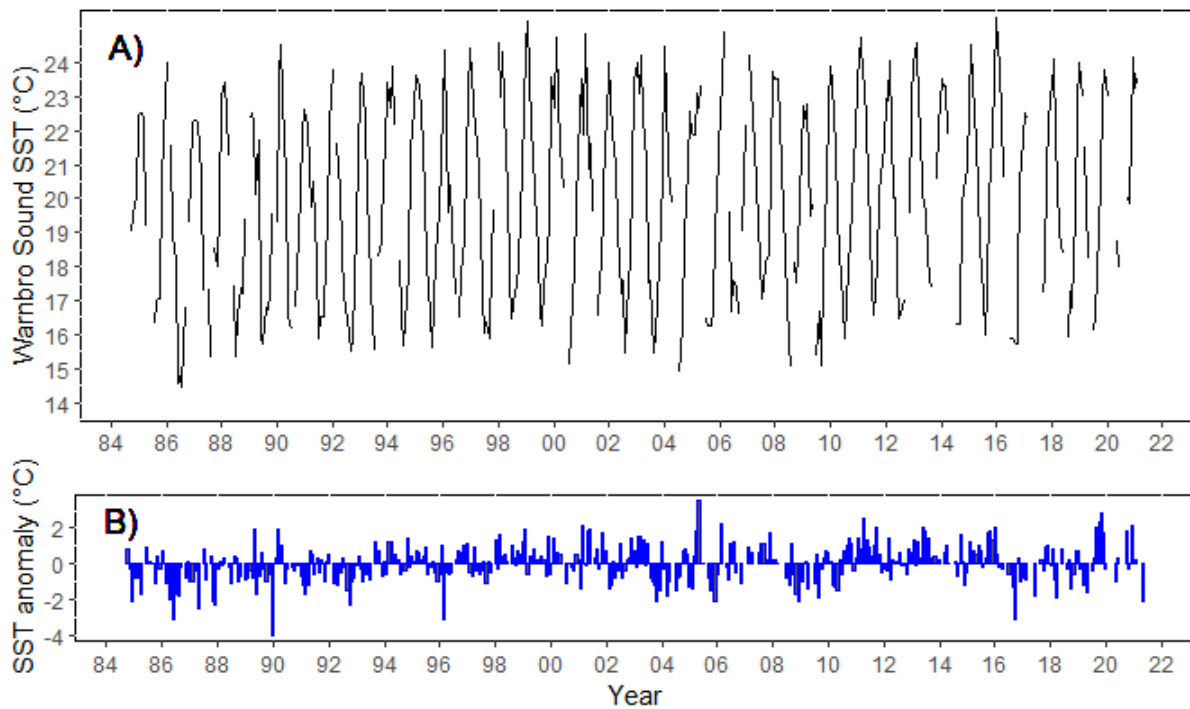


Figure 6. Warnbro Sound monthly SST (A) and deviation from the monthly mean (B) from 1984-2021.

The three most recent La Niña events (1998-2001, 2010-11 and 2020-22) all resulted in elevated summer SST within CS (Figure 5), and a large number of MHW days (Figure 7). The link between La Niña, intensification of the Leeuwin Current and MHWs is well documented in southern WA waters (Feng et al. 2013), and the data suggests the relatively sheltered waters of CS are also affected. The extreme 2011 MHW produced summer SST between 2-4°C above means for that time of year (Pearce & Feng 2013). Within CS a warming anomaly of 2-4°C was observed which persisted for ~12 weeks (Rose et al. 2012). During this time dissolved oxygen was notably lower, however, no fish kills or bleaching events were detected that were directly attributable to the heatwave. Higher temperatures were correlated with decrease in seagrass density but no reports of animal fatalities (Caputi et al. 2014).

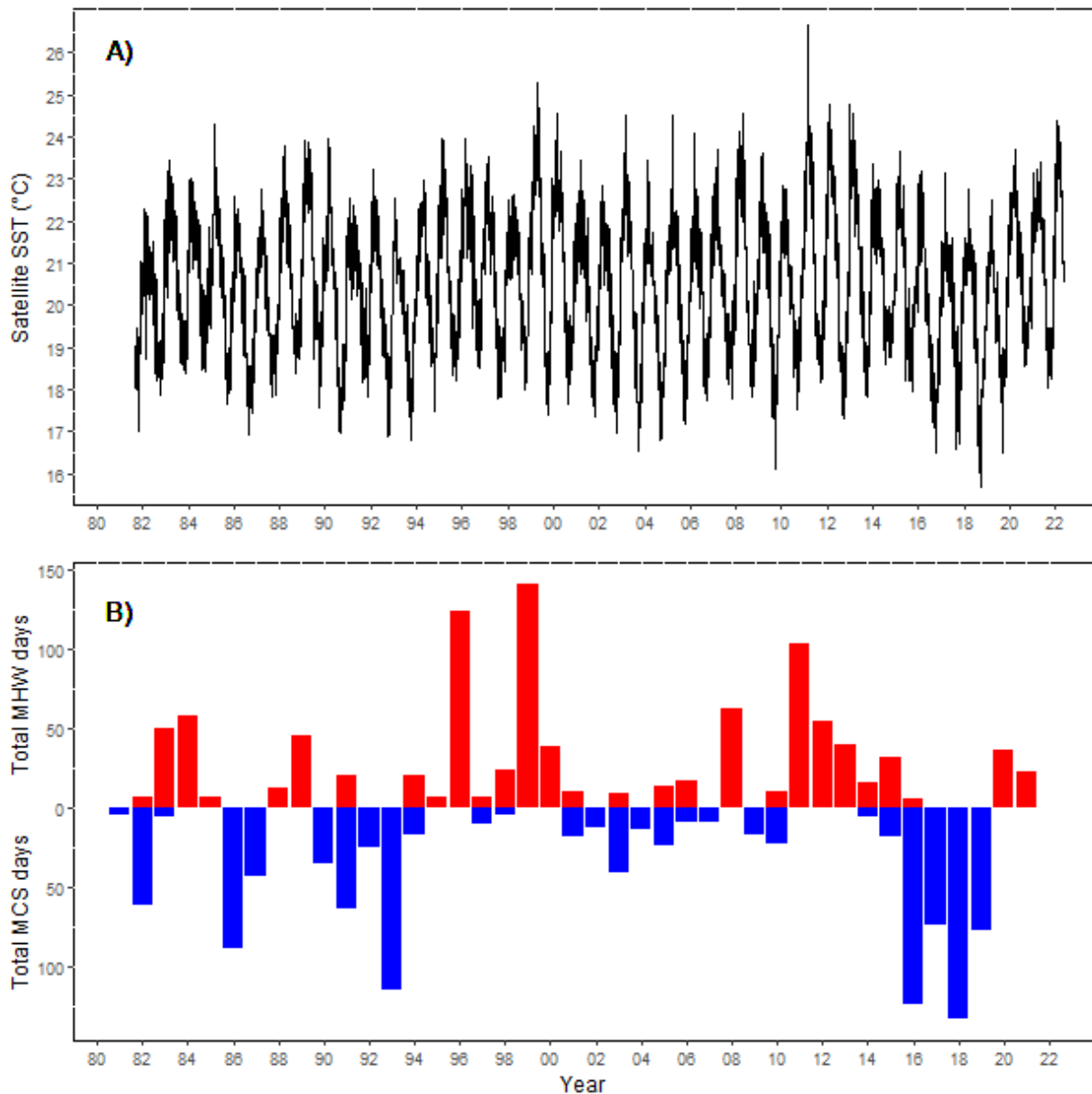


Figure 7. NOAA OI SST V2 satellite measured daily SST (A) and total number of MHW and marine cold spell (MCS) days each year (B) from 1981-2022. The high-resolution dataset was downloaded from <https://psl.noaa.gov/> (accessed 29/05/2022) (Huang et al. 2021a) and the mean from the two datapoints nearest to CS were used (i.e. 32.125°S, 115.625°E, and 32.375°S 115.625°E). These datapoints are approximately 3 km west of Carnac Island and 8 km west of Becher Point. MHW and MCS days defined as per Hobday et al. (2016).

Increasing SST does not appear to be consistent across the year, but rather more prevalent during the summer months (Figure 8). By grouping the monthly means into seasons, the largest change in temperature was observed in the summer months within Warnbro Sound. The average rate of increase was 0.027°C yr⁻¹ and this was the only season where the increase in temperature between 1984/85 and 2021 was significant. This observation within Warnbro Sound contradicts evidence from Caputi et al. (2009) in southwest WA before the extreme 2011 MHW, where little or no increase in temperature was observed in spring-summer, while autumn-winter were the seasons heating most rapidly. Within the satellite data (Huang et al. 2021a), no seasons had significant linear trends in SST over the 41 years of data.

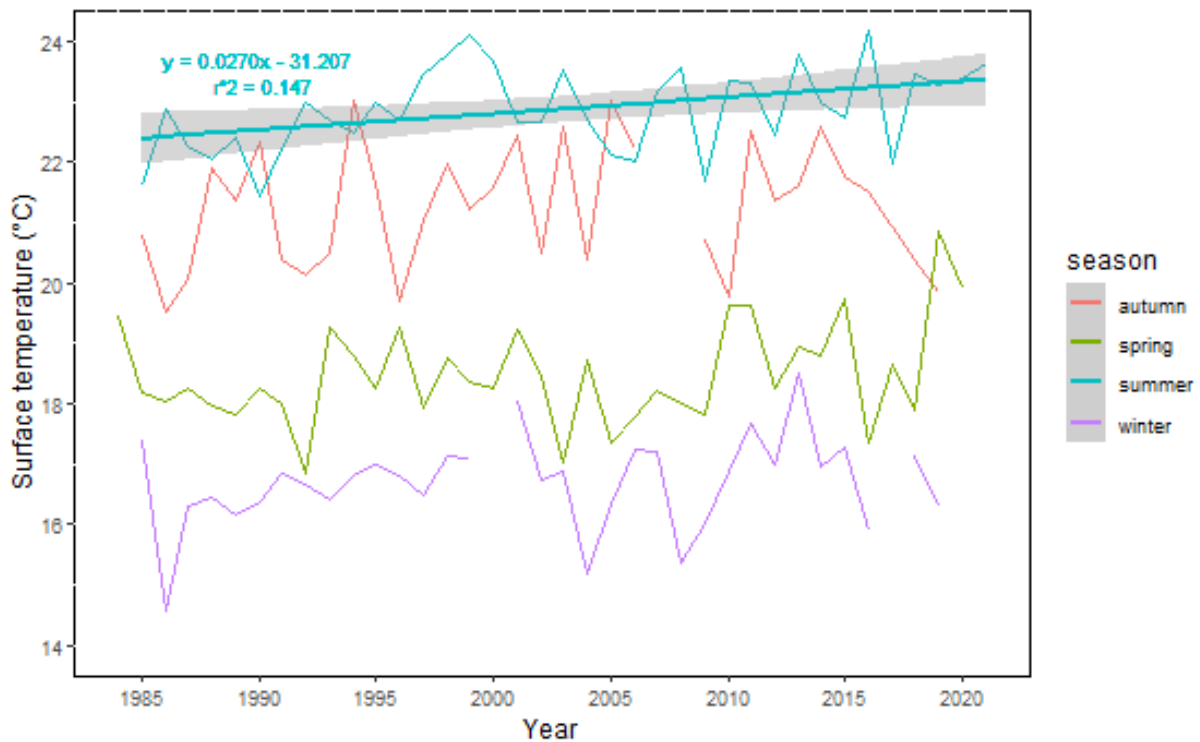


Figure 8. Warnbro Sound SST logger data since 1985 split by season. The linear trend is only displayed for summer as this was the only season with a significant ($p < 0.05$) trend.

In addition to SST, CSMC monitoring sites also record bottom temperature for each sample. These data are not presented within this report as the temperature at the bottom was generally very similar to SST within CS, following similar seasonal and interannual changes. However, the recorded bottom temperature within the CSMC data at sites >10 m deep were generally between 0.2 - 0.5°C cooler than SST.

4.1.3 Cockburn Sound Management Council environmental data

Nitrogen

South-western Australia's coastal waters are low in nutrients and primary production is generally considered to be nitrogen limited (Lourey et al. 2006). However, the development of heavy industry and rapid urbanisation around the coast of CS between 1950-1980, resulted in large amounts of discharge into CS, elevating the levels of nutrients and primary production (Keesing et al. 2016). The discharge sources were primarily from the CSBP fertilizer plant, Woodman Point Wastewater Treatment Plant and Kwinana Nitrogen Company (Keesing et al. 2016). In the late 1970s the annual load of nitrogen directly discharged in CS was 1820 t and this was reduced to 57 t by 2000 and zero in 2015 (Gartner et al. 2018). From the early 1980s a number of steps have been taken to clean up CS. In 1984 the Woodman Point Wastewater Treatment Plant discharge was rerouted outside CS through the Sepia Depression Ocean Outlet Line, which was later modified in 2004 to accept additional industrial water thereby further reducing inputs to CS. Water quality sampling in CS began in 1982/83 on behalf of the CSMC. The peak total nitrogen concentrations measured in CS were in the summer of 1984/85 with an index of $455 \mu\text{g L}^{-1}$ and individual samples measuring over $700 \mu\text{g L}^{-1}$ (Figure 9). This has decreased over time and has remained relatively stable at 115 - $145 \mu\text{g L}^{-1}$ since 2005. Groundwater sources are now thought to be the main sources of nitrogen input, and these have remained steady over recent decades (Gartner et al. 2018). The removal of nitrogen inputs to CS is believed to have changed the system from one of excess nitrogen to a system in deficit (Greenwood et al. 2016). While the rerouting of industrial discharge began prior to the 1982/83 when the CSMC data collection began,

total nitrogen concentrations from this first year are consistent with that from a more limited dataset collected between 1977-81 (Cary et al. 1995) which reported total nitrogen as $352 \pm 30 \mu\text{g L}^{-1}$ (S.E).

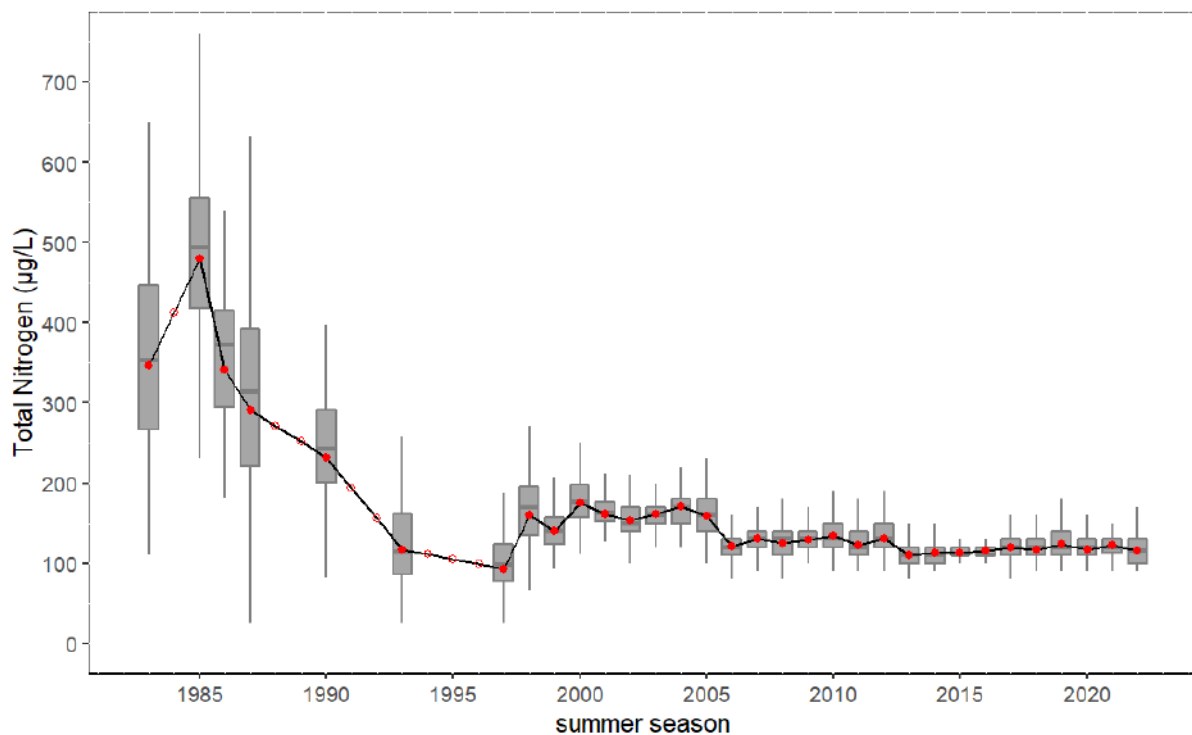


Figure 9. Total nitrogen concentration during the summer months within CS. Boxplots of the raw measurements collected on behalf of the CSMC. Summer total nitrogen index values calculated using a GAM are shown as the red dots and black line, with the interpolated index values shown as hollow dots. The model fit is reported in Appendix 1. Summer months based on December to March each year and 'summer season' label refers to the year in January.

Phosphorus

The only other nutrient for which comparable time series data exists is total phosphorus which shows a similar trend of decreasing in the 1980s and 1990s (from approximately $74 \mu\text{g L}^{-1}$ in 1982/83) before stabilizing in the 2000s ($\sim 12-15 \mu\text{g L}^{-1}$) (Figure 9). Total phosphorus in CS between 1977-1981 was $78 \mu\text{g L}^{-1}$ (standard error 7) (Chiffings 1979, Cary et al. 1995) indicating the high nutrient load had been sustained over a prolonged period. The sources of phosphate are thought to have been from the adjacent urban and agricultural land, the fertilizer plant which began discharging water into CS in 1969, the wastewater treatment facility and Garden Island current and historic uses (Gartner et al. 2018).

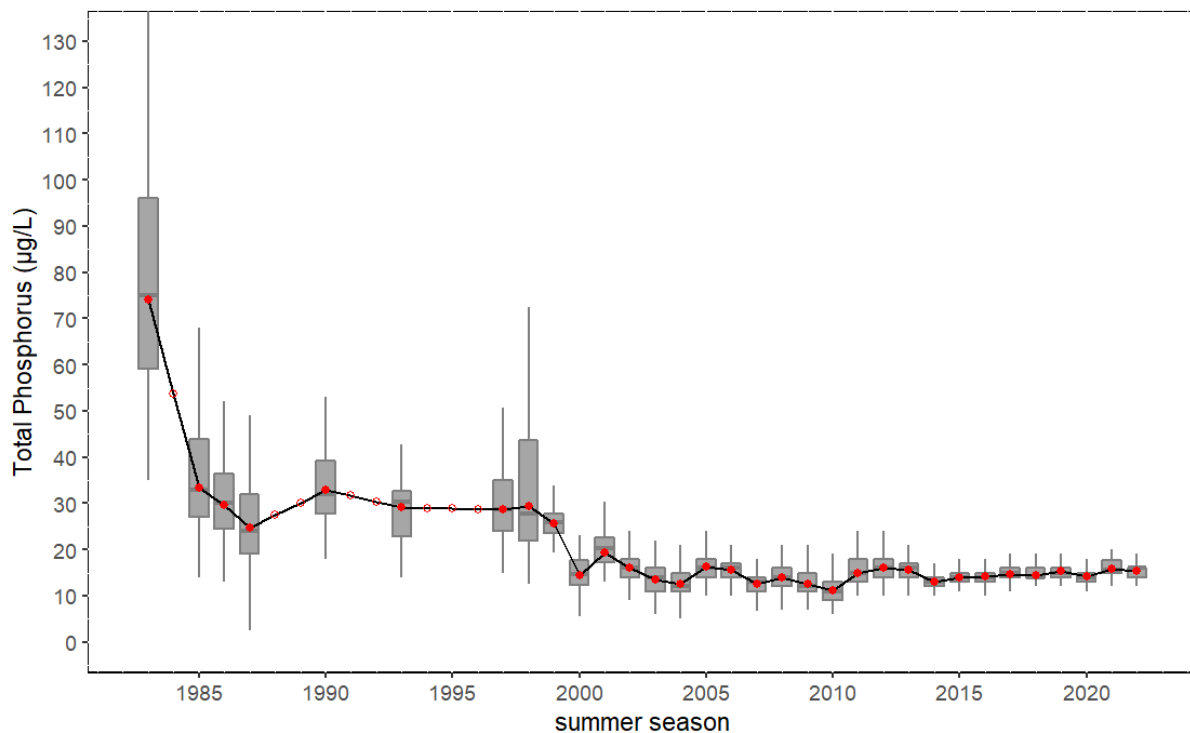


Figure 10. Total phosphorus concentration during the summer months within CS. Boxplots of the raw measurements collected on behalf of the CSMC. Summer total phosphorus index values calculated using a GAM are shown as the red dots and black line, with the interpolated index values shown as hollow dots. The model fit is reported in Appendix 1. Summer months based on December to March each year and 'summer season' refers to the year in January.

Chlorophyll-*a*

Primary production in CS, using chlorophyll-*a* as a proxy, shows an increase occurring in the early 1980s and peaking during the late 1980s to early 2000s before declining. Summer chlorophyll-*a* index values peaked in 1990-1993 ($1.38\text{-}1.58\ \mu\text{g L}^{-1}$) and then remained high until 2004 when the summer chlorophyll-*a* index dropped below $1.00\ \mu\text{g L}^{-1}$ (Figure 11). A second peak occurred between 2011-2013 ($1.04\text{-}1.27\ \mu\text{g L}^{-1}$). Although not presented in Figure 11, chlorophyll-*a* had been measured as part of other studies prior to the establishment of the CSMC monitoring program. Chiffings (1979) reported that chlorophyll-*a* levels were generally between $5\text{-}10\ \mu\text{g L}^{-1}$ from November 1974-April 1975. From August 1977-November 1978 chlorophyll-*a* levels within CS ranged between $1\text{-}5\ \mu\text{g L}^{-1}$ (Chiffings 1979), with mean chlorophyll-*a* concentrations between 1977 and 1981 of $2.8\ \mu\text{g L}^{-1}$ (standard error of 0.3) (Cary et al. 1995). These levels suggest primary production had already decreased in CS as nutrient levels reduced prior to the establishment of the CSMC water quality monitoring program. The decline in primary production is consistent with reductions in nutrient load to CS from several anthropogenic sources. As a result of the changes in nutrient loads entering CS, it is unlikely that chlorophyll-*a* concentrations will return to those of the 1990s so that the environment has experienced a regime shift in productivity.

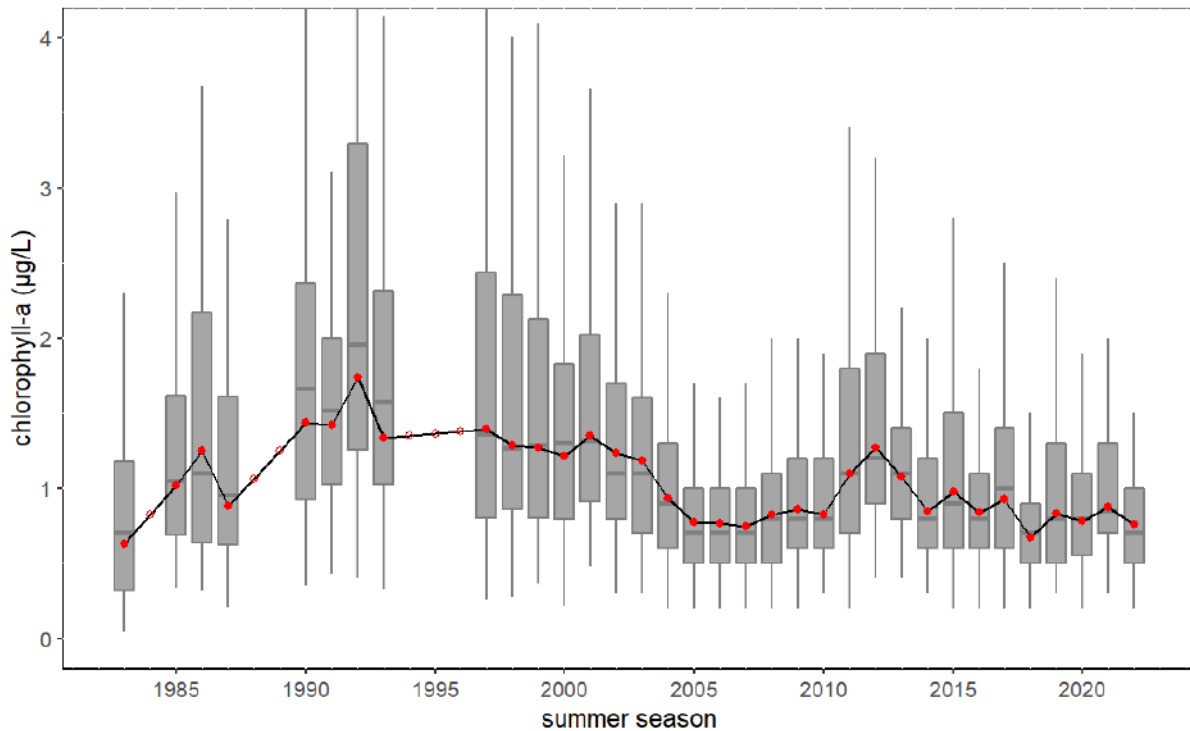


Figure 11. Chlorophyll-*a* concentration during the summer months within CS. Boxplots of the raw measurements collected on behalf of the CSMC. Summer chlorophyll-*a* index values calculated using a GAM are shown as the red dots and black line, with the interpolated index values shown as hollow dots. The model fit is reported in Appendix 1. Summer months based on December to March each year and 'summer season' refers to the year in January.

Estimates based on phytoplankton biomass (chlorophyll-*a* concentrations) indicate that phytoplankton are the dominant contributor (73%) to primary production within the CS; similarly, nitrogen budget calculations attribute 90% of the biological nitrogen demand in CS to phytoplankton (Gartner et al. 2018). Information from a long-term phytoplankton community composition dataset (1999–2012) indicates there was a step-change in phytoplankton cell density in early 2005, which may be associated with shifts in community composition, including a decline in silicoflagellates and increase in diatoms (Helleren 2016, Gartner et al. 2018). There has been no research conducted on the ecological implications of this shift and flow-on effects are therefore unknown.

Salinity

The sea surface salinity of the south-western WA coastline has been increasing at a rate of 0.03 ‰ per decade (Pearce & Feng 2007). However, this was not evident from the CSMC data, which has had significant interannual variation in summer surface salinity (~2 ‰), but no general direction of change (Figure 12). As a semi-enclosed water body, the salinity of CS is influenced by surface and groundwater sources, mixing with ocean water, and weather events, such as heatwaves and heavy rainfall (BMT, 2018; A. J. Smith et al. 2003). The Perth Metropolitan Desalination Plant came into operation in 2006 and releases hypersaline wastewater into CS (180 ML day⁻¹ at a salinity of 65 ‰ (Water Corporation, 2009)). However, subsequent monitoring has shown that the discharged water is rapidly mixed, and the plume is only detectable for up to 1.0-1.5 km from the exit of Stirling Channel, in the dredged basin on Kwinana Shelf (Water Corporation, 2009).

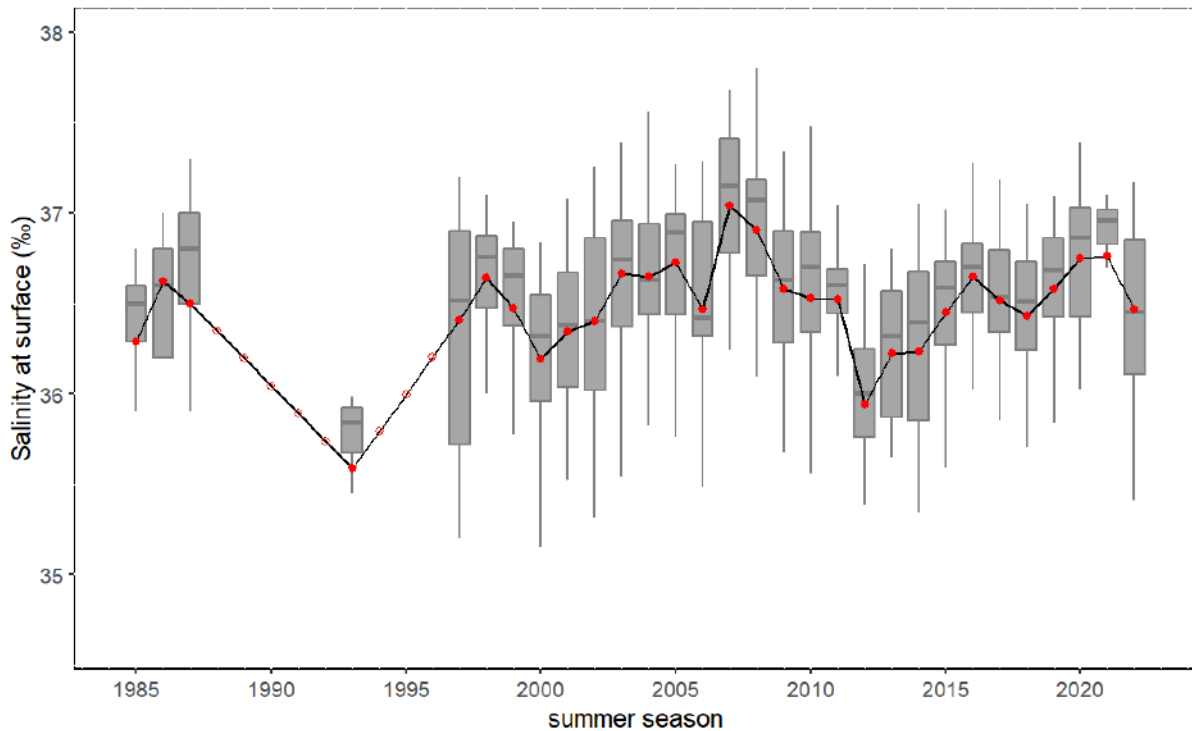


Figure 12. Sea surface salinity during the summer months within CS. Boxplots of the raw measurements collected on behalf of the CSMC. Summer surface salinity index values calculated using a GAM are shown as the red dots and black line, with the interpolated index values shown as hollow dots. The model fit is reported in Appendix 1. Summer months based on December to March each year and 'summer season' refers to the year in January.

Dissolved oxygen

Summer dissolved oxygen (DO) levels have been measured within CS since the summer of 1984/85 (although data gaps exist). These have been recorded at both the surface and bottom at each site, with samples at the bottom averaging $\sim 0.26 \text{ mg L}^{-1}$ less than at the top of the water column. The CSMC data which is collected over a 16-week period in the summer shows that DO levels slowly decrease through December-February, before rising again in late February-March. The interannual variation in DO is much larger than any overall trend (Figure 13). Presented is the seabed DO index which is comparable in shape although lower than the surface values (not presented). Although under specific environmental conditions where thermal stratification occurs, low oxygen conditions at depth can occur. Decreasing DO levels within CS during the 2011 MHW were observed (Rose et al. 2012). During this heatwave the lowest DO concentration observed was 3.12 mg L^{-1} , with concentrations falling as much as 4 mg L^{-1} in a week. However, the decreased levels returned to near-typical levels within two weeks. A decrease in DO was also identified as a contributing factor in the 2015 fish kill within CS (DoF 2016).

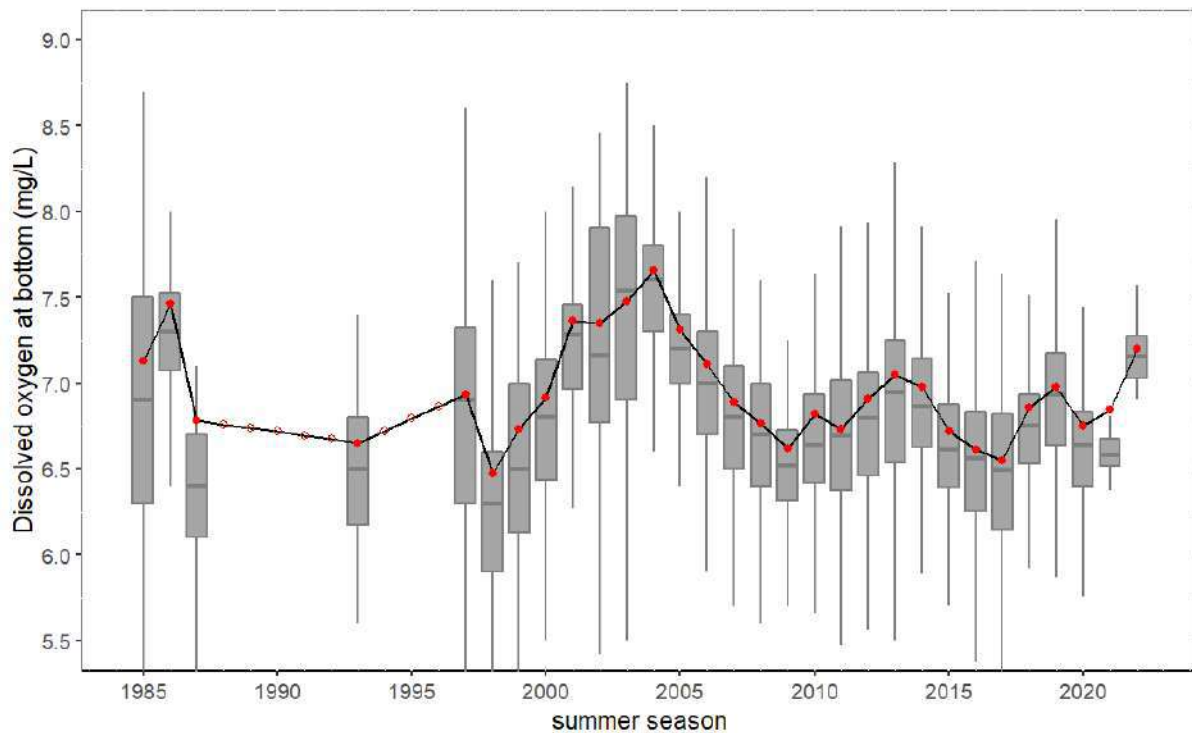


Figure 13. Bottom dissolved oxygen during the summer months within CS. Boxplots of the raw measurements collected on behalf of the CSMC. Summer bottom dissolved oxygen surface salinity index values calculated using a GAM are shown as the red dots and black line, with the interpolated index values shown as hollow dots. The model fit is reported in Appendix 1. Summer months based on December to March each year and 'summer season' refers to the year in January.

pH

No interannual trend in pH was observed within CS from the CSMC data (Figure 14). The first year of pH data collection within CS was in the summer of 2004/05, and prior to 2010 CSMC data only recorded pH to one decimal place. As such, the data are limited to assess any trends in pH within CS. Globally, open ocean water has been acidifying at a rate of 0.02 pH per decade, however, coastal ecosystems are much more variable with trends in pH for different ecosystems ranging from -0.023 to 0.023 yr^{-1} (Carstensen & Duarte 2019). Carstensen and Duarte concluded that the driving forces of pH in coastal ecosystems are dependent on the quantity and source of freshwater inputs, the extent of mixing with oceanic waters and the rate of metabolism within the ecosystem. High rates of photosynthetic activity can remove CO_2 and increase pH (Buapet et al. 2013), whereas heterotrophic systems increase CO_2 thereby lowering pH. The rate of metabolism is in turn influenced by the nutrient load. Since CSMC started measuring pH, CS has generally been in a low nutrient state, potentially limiting the importance of biological metabolism on pH.

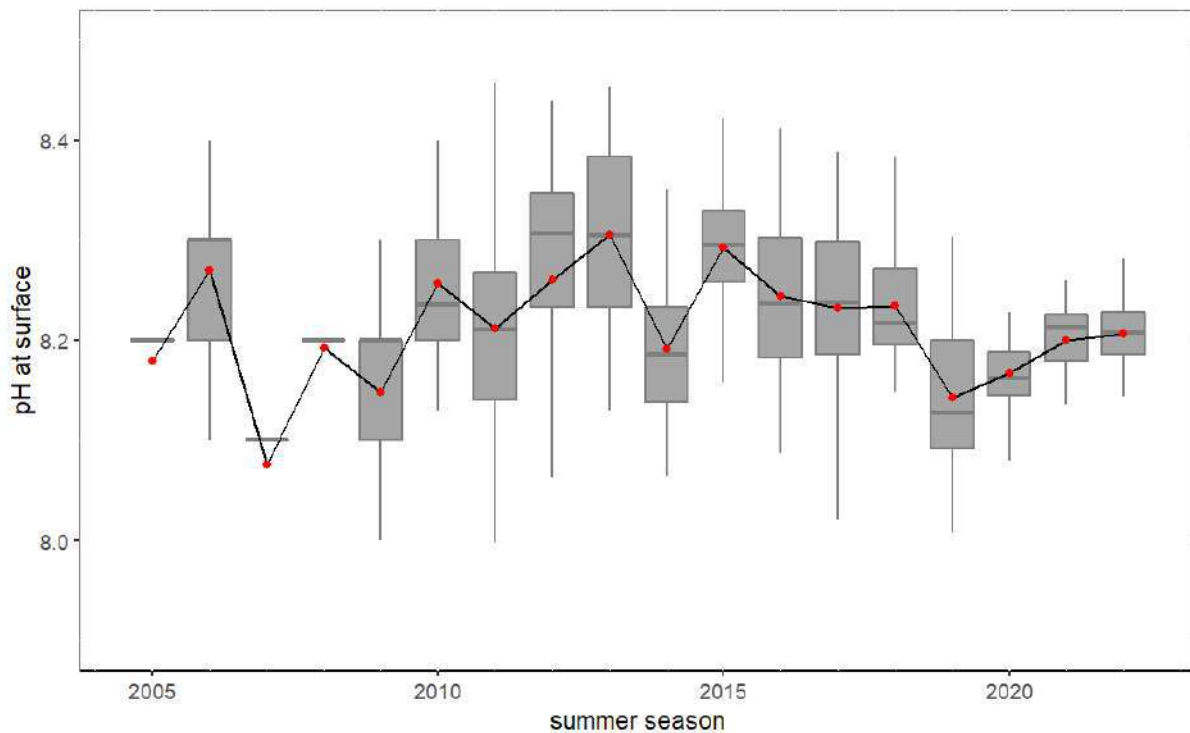


Figure 14. pH at the surface during the summer months within CS. Boxplots of the raw measurements collected on behalf of the CSMC. Summer pH index values calculated using a GAM are shown as the red dots and black line. The model fit is reported in Appendix 1. Summer months based on December to March each year and 'summer season' refers to the year in January.

4.1.4 Rainfall and freshwater inputs

Annual rainfall within the Perth region has been decreasing at a linear rate of ~ 15 mm per decade (Figure 15), which is consistent with broader trends in southern WA (Gartner et al. 2018). Rainfall in Perth typically peaks in June and July and is driest in December-February. The decreasing trend in annual rainfall has primarily occurred through a decrease in rainfall during the wetter months (Figure 16), while there has been an increase in the frequency of summer rainfall events. Since 1970 there have been three main unseasonal heavy summer rainfall events which resulted in flushing of the Swan-Canning Estuary during the summer months, with the most recent event being 2017 (Figure 17). Decreasing winter rainfall has the potential to influence the marine habitats of CS, by reducing outflow from the Swan River and decreasing replenishment of groundwater (Gartner et al. 2018). Historically, winter rainfall has resulted in Swan-Canning Estuary freshwater discharge entering CS. The decreasing winter rainfall in Perth has reduced the amount of surface freshwater and total river discharge, and this has been observed in the Swan River flow (Figure 17). Freshwater flows would have been further reduced by damming the Swan-Canning Estuary tributaries. The Swan-Canning Estuary is also a source of nutrient inputs into CS (Robson et al. 2008), so it's likely that reduced outflows from this river would also reduce the total nutrients discharged into CS.

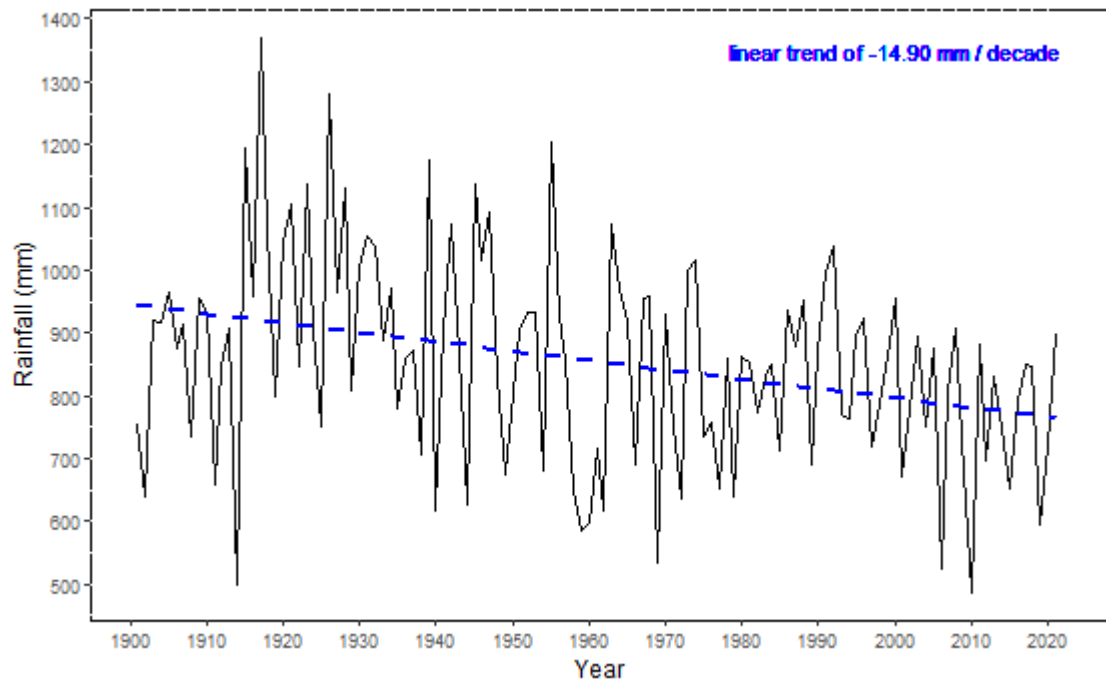


Figure 15. Annual rainfall for Perth from 1901-2020. The black line shows the total annual rainfall for only those years with 12 months of data. The dashed blue line shows the linear trend.

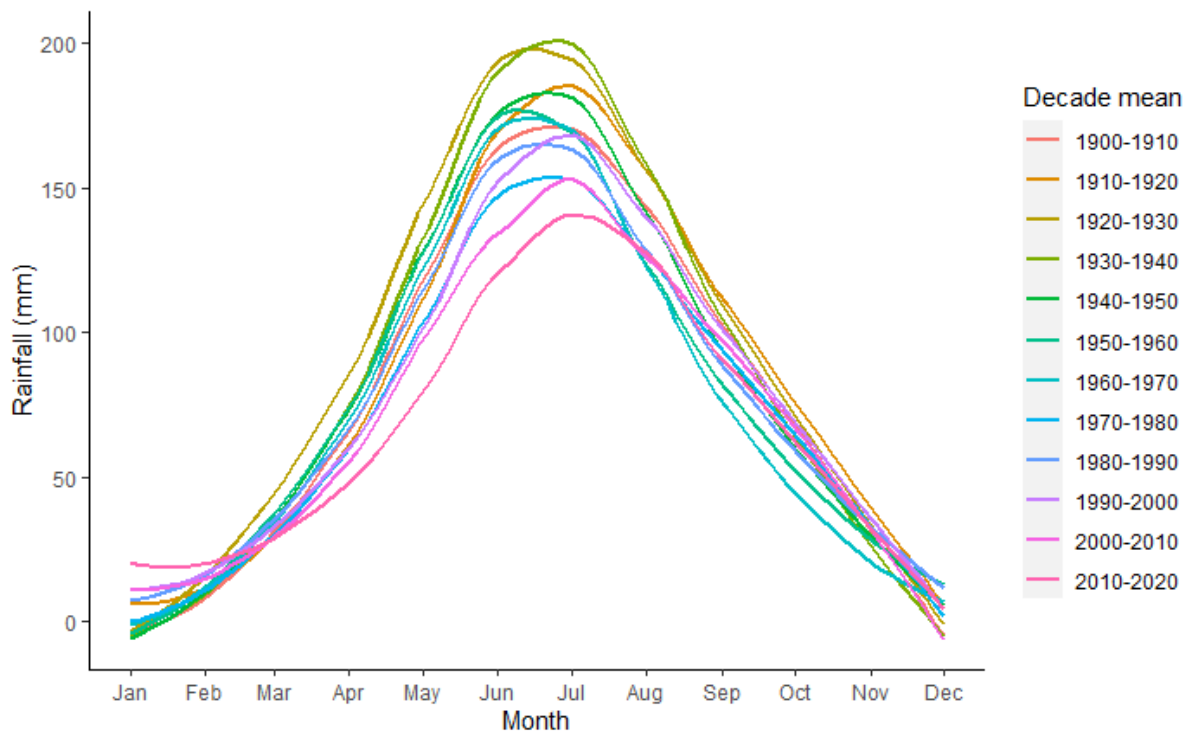


Figure 16. Perth monthly mean rainfall by decade since 1901.

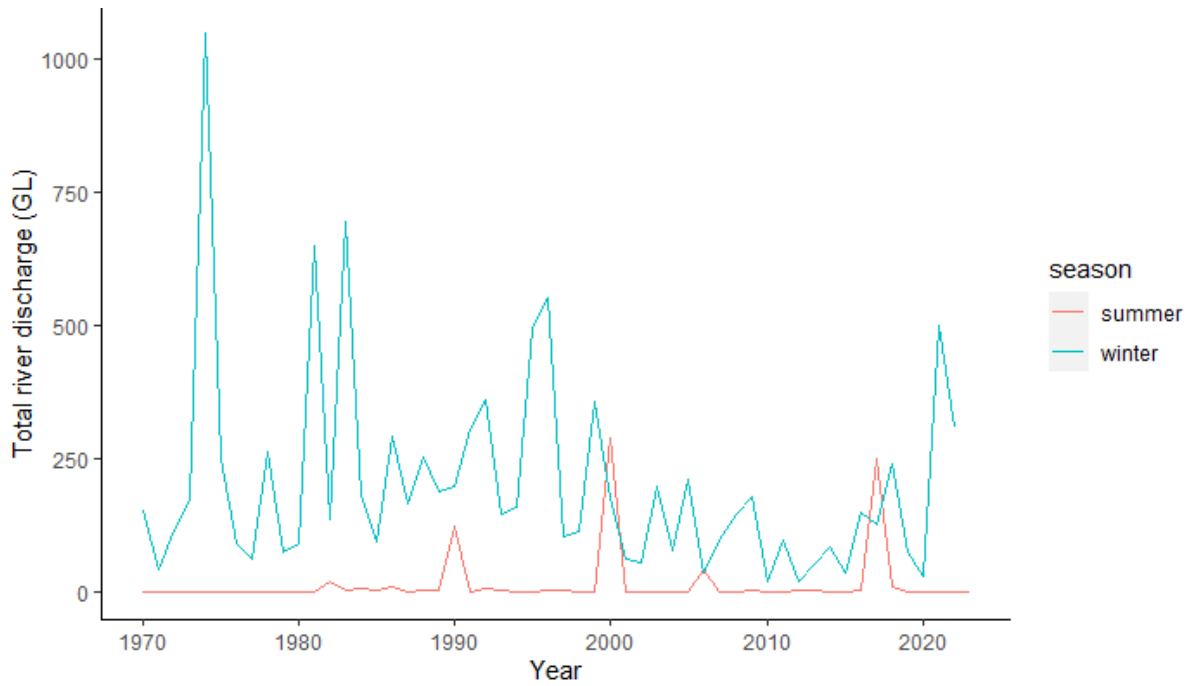


Figure 17. Swan River (Walyunga site) discharge during the summer and winter months.

4.1.5 Seagrass

The long-term decrease in the extent of seagrass meadows within CS has been well-documented (Kendrick et al. 2002). Rapid declines in seagrass extent were first noted in the 1960s and 1970s and attributed to reduced water quality due to the industrial expansion of Perth and municipal sewage outflows being discharged into CS (BMT 2018; Cary et al. 1995). By 1981, it was estimated that only 740 ha of seagrass meadows remained compared to 2929 ha in 1967 (Figure 18) (Kendrick et al. 2002), and an estimated >4000 ha pre-disturbance in 1954 (Cambridge & McComb 1984). The increase in nutrients stimulated the growth of phytoplankton and epiphytes, which in turn reduced the amount of light reaching the seagrass. Following efforts to clean up CS during the 1980s and 1990s the decrease in seagrass extent ceased, however, despite substantial improvements to water quality in the 2000s the seagrass recovery has been slow. Additional studies completed on behalf of the CSMC have updated the seagrass maps periodically over the last 20 years (Hovey et al. 2013; Hovey & Fraser 2018). Updated maps have shown that between 2008 and 2017 seagrass meadows gained 132 ha (Figure 18) and this was most noticeable in the meadows immediately adjacent to Woodman Point (Hovey & Fraser 2018).

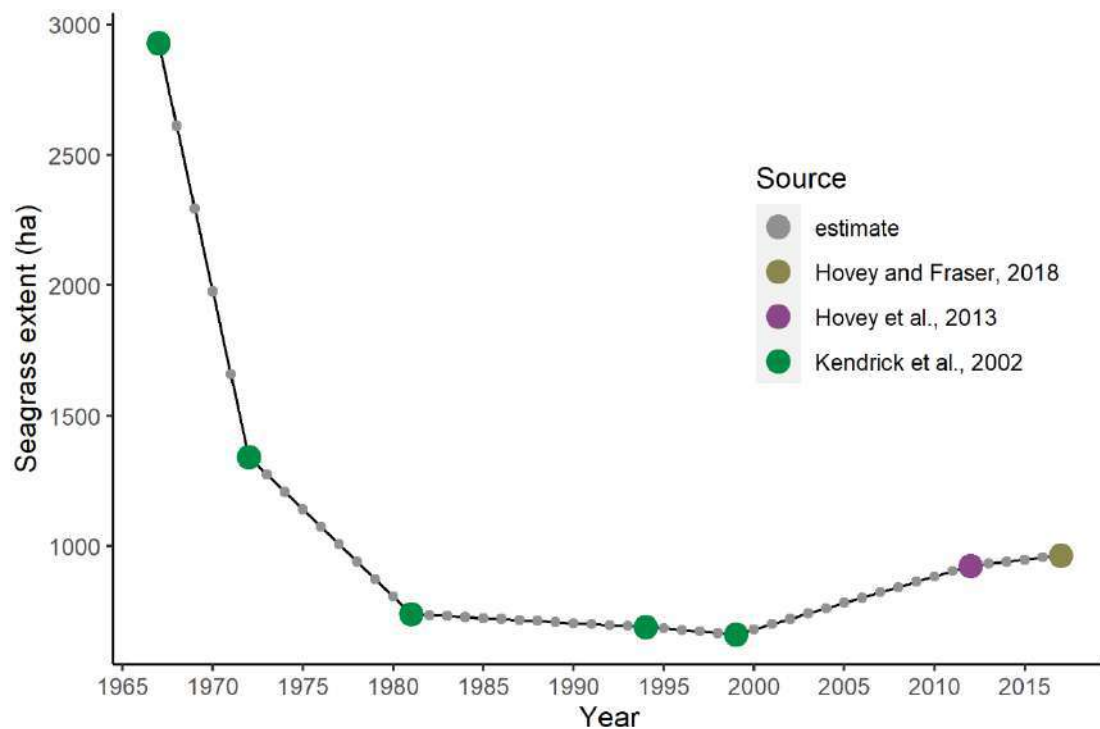


Figure 18. Approximate extent of cover of seagrass within CS, south of Woodman Point, derived from multiple published mapping projects. Between published studies the extent of seagrass has been estimated each year based on an interpolation. It is worth noting that the study area used Kendrick et al. (2002) was ~14% smaller than the subsequent studies, although the more recent data could not be accessed to allow an equivalent comparison.

Despite indications of recovery, there also remains a persistent decline in seagrass health at some sites within CS. Eleven seagrass monitoring sites were established in 2003 around CS at varying depths and environmental conditions and have been surveyed annually. Mean and median shoot density has significantly declined at two monitoring stations with several others observing a potential downward trend, and no sites have had a significant increasing trend in shoot density (CSMC 2020). The net outcome is that while seagrass extent may be increasing the total biomass of seagrass appears to be decreasing (Vidyan 2018). If the thinning of seagrass meadows were to continue, this could potentially reduce resilience and threaten the ecosystem functions of seagrasses in CS. While it is evident that seagrass health can no longer be regarded solely as a nitrogen related water quality issue, the reasons for these declines remain speculative; recent research suggests physical (temperature and sediment quality) and biogeochemical variables in the water column and sediment processes may help explain ongoing stress to some seagrass meadows (Caputi et al. 2014, Fraser & Kendrick 2017, Gartner et al. 2018). For example, seagrass shoot density at several of the monitoring sites decreased following the 2011 MHW (Caputi et al. 2014).

The health and extent of seagrass is important for a wide range of fish and aquatic organisms, while also contributing to nutrient recycling, sediment retention and providing an important source of organic matter. Seagrasses respond rapidly to changes in environmental conditions, such as light and nutrient availability, making them good indicators of the state of the marine environment (CSMC 2018).

The extent of seagrass loss north of Woodman Point is also undocumented, as previous studies (discussed above) only produced maps for the embayment south of Woodman Point. There are extensive seagrass beds through this area, particularly on Parmelia and Success Banks, which may have also experienced die-off of seagrass. Furthermore, physical removal of sediments to create the shipping channels and extract lime sands have contributed to seagrass loss (Oceanica Consulting 2011).

However, it is unclear whether seagrass coverage north of Woodman Point decreased due to poor water quality between 1960 and 1990s, to the extent of that observed in the more enclosed area to the south.

4.2 Time series of data on the abundance of the key biota

4.2.1 Fisheries-independent data

Large otter-trawl

Catch rate data from the large otter-trawl in CS were used to create a seasonal index of adult blue swimmer crab since 2007/08 (Figure 19). The survey, in its current design, began following the collapse of the stock within CS that led to the closure during 2005/06-2008/09. As such, the seasonal index does not provide a snapshot of healthy, pre-collapse stocks. Crab densities from the large trawl show the partial recovery and then subsequent collapse that resulted in the second closure in 2013/14 that is still ongoing. Despite the ongoing fishery closure, crab densities have not recovered in the same way they did following the first closure.

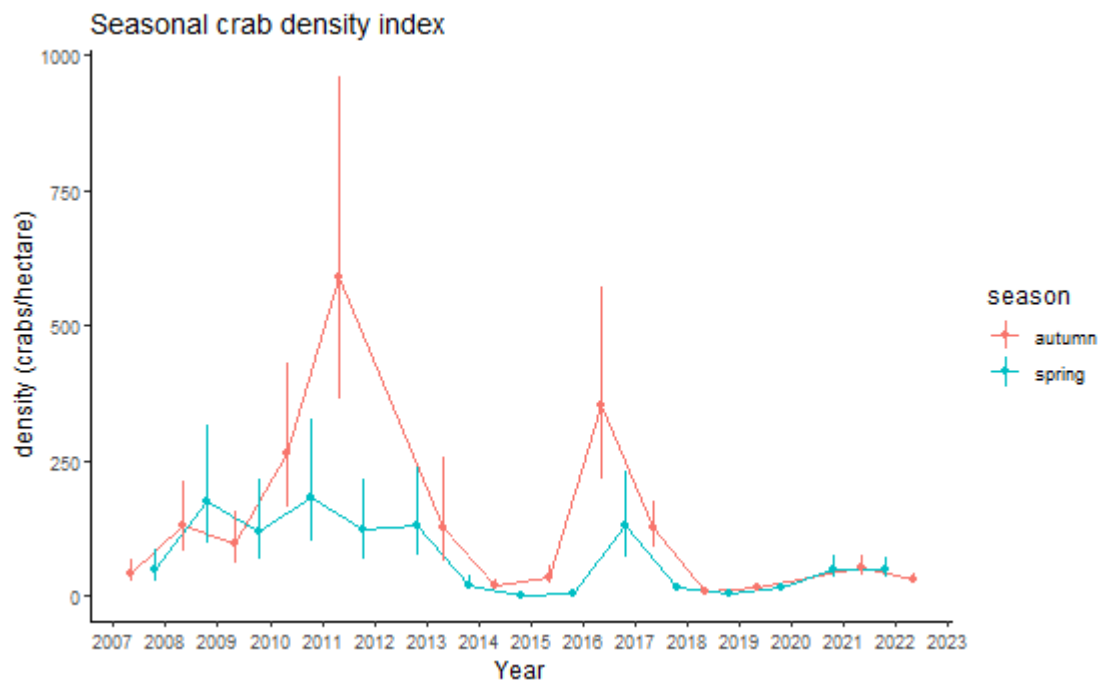


Figure 19. Seasonal blue swimmer crab density index, along with associated 95% confidence intervals, based on large otter-trawl data from seven sites within CS. Autumn samples were from April-May and spring samples were October-December.

The annual indices of blue swimmer crab and western king prawn densities, calculated for the central CS 'Research Area' provides a longer time series (Figure 20), for this specific habitat. In general, densities showed an increase from 1970 to 2000 for both species then declined from the late 1990s and early 2000s to the current levels. These figures, and the factors that potentially contributed to the changes in abundance for these two species are discussed in Section 4.3.1 and 4.3.2.

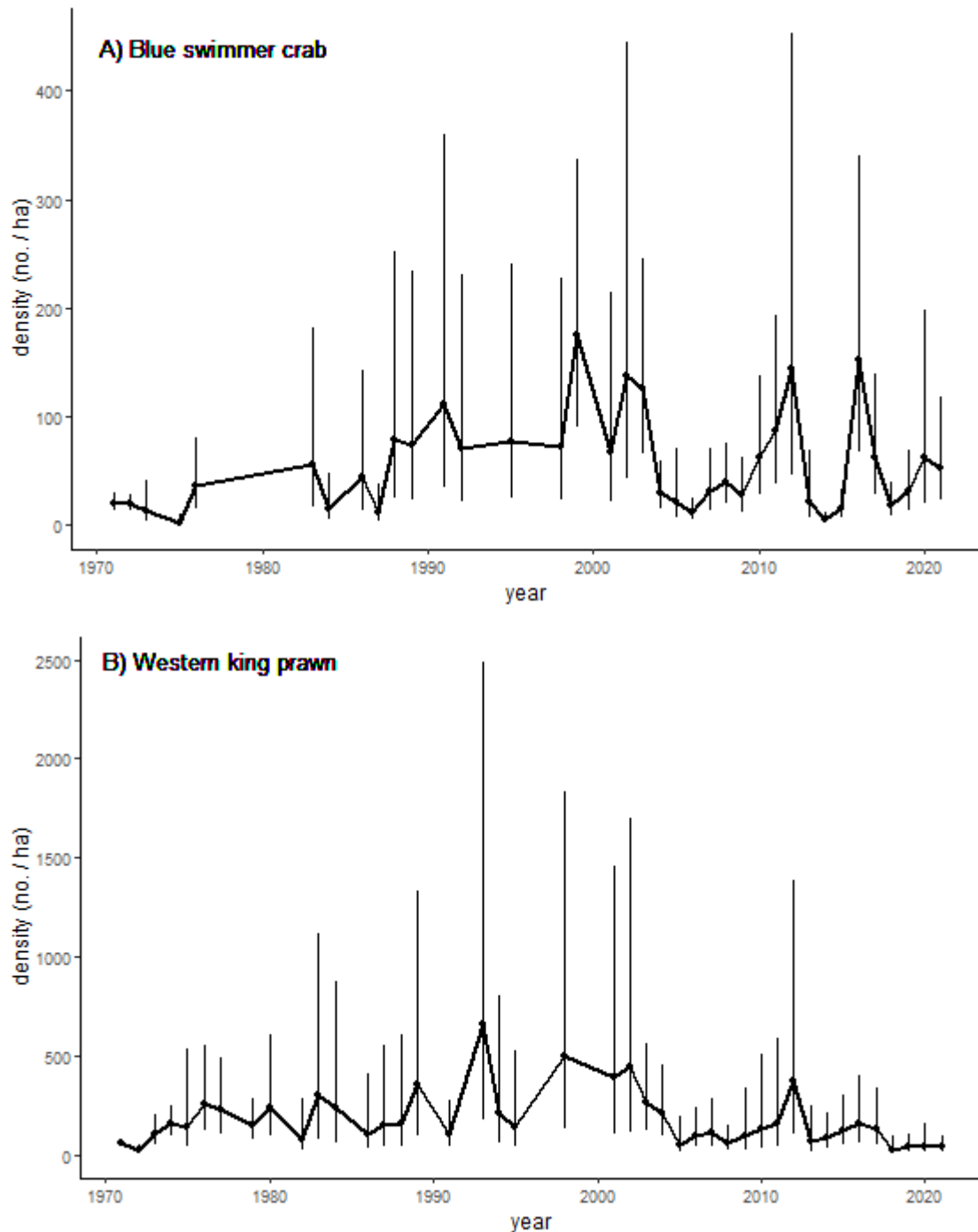


Figure 20. Least square mean densities of blue swimmer crab (A) and western king prawn (B) from the 'Research Area' within CS, along with associated 95% confidence intervals.

Juvenile blue swimmer crab survey

The juvenile blue swimmer crab index shows poor recruitment of crabs between 2004-09 and 2013-current which led to the two periods of closure previously mentioned (Figure 21). This recruitment index for the CSC fishery contributed part of the evidence base to manage the stocks until 2023 when it was discontinued (Johnston et al. 2011a b, 2020, Caputi et al. 2021). Possible contributing factors for this trend are discussed further in Section 4.3.1.

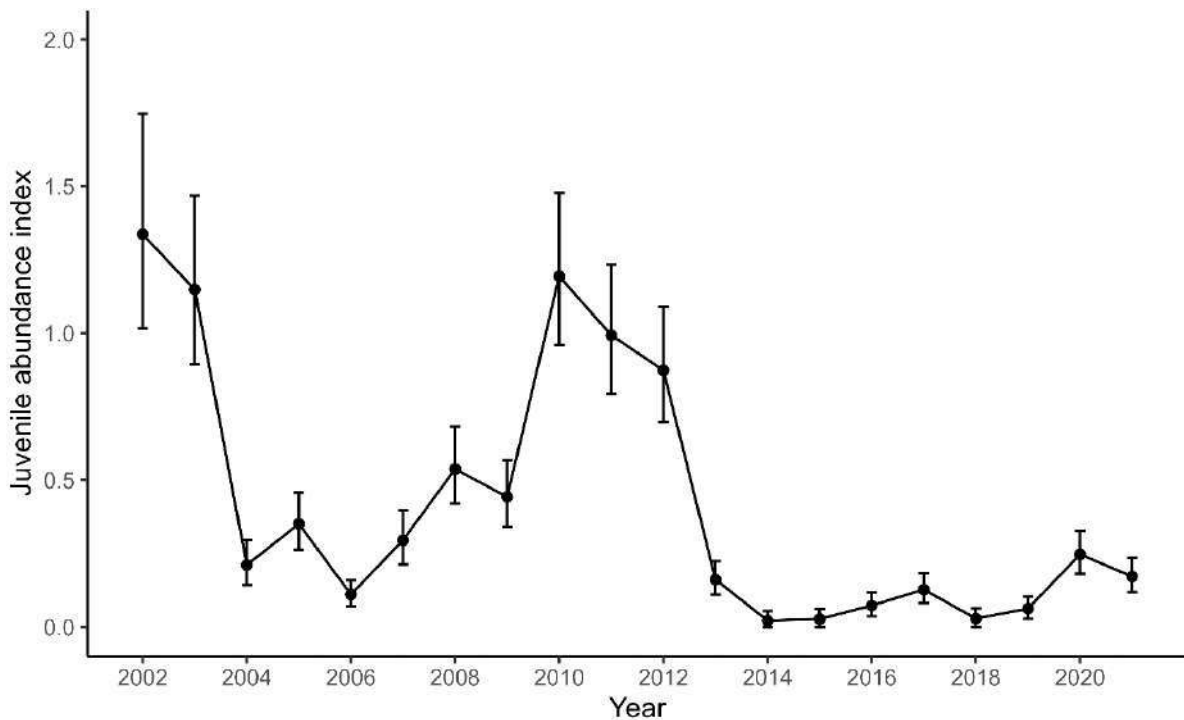


Figure 21. Standardised recruitment index (number of juvenile 0+ crabs) for blue swimmer crab in CS as reported in Johnston et al. (2022) during the recruitment period (April-June) from 2002-2021. Error bars display 95% confidence limits.

Baited remote underwater video

From 11 years of analysed BRUV data collected in CS between 2008 and 2021, there have been 108 fish species identified to species level (plus 40 fish taxa identified to genus or family level). The ten most prolific taxa from CS were: trevallies (*Pseudocaranx* spp.), weeping toadfish (*Torquigener pleurogramma*), western butterfish (*Pentapodus vitta*), yellowtail scad (*Trachurus novaezelandiae*), western striped grunter (*Pelates octolineatus*), tarwhine (*Rhabdosargus sarba*), snapper, silverbelly (*Parequula melbournensis*), obtuse barracuda (*Sphyræna obtusata*) and rabbitfish (Figure 22). Previous analysis of these data observed interannual differences in fish communities that may have been driven by the 2011 MHW (Davoit et al. 2017). Their research found a decrease in the number of taxa and total MaxN during the heatwave, however, both rapidly rebounded in the following years. These trends can be seen in some of the most prolific taxa observed on the BRUVs (Figure 22). For instance, trevallies, western striped grunter, tarwhine and the weeping toadfish all had relatively low abundances in 2011 and 2012 before increasing in abundance in the following years. Other species, such as western butterfish, yellowtail scad and rabbitfish had only brief peaks in abundance following the MHW. Six of the 10 species showed marked increases in 2021.

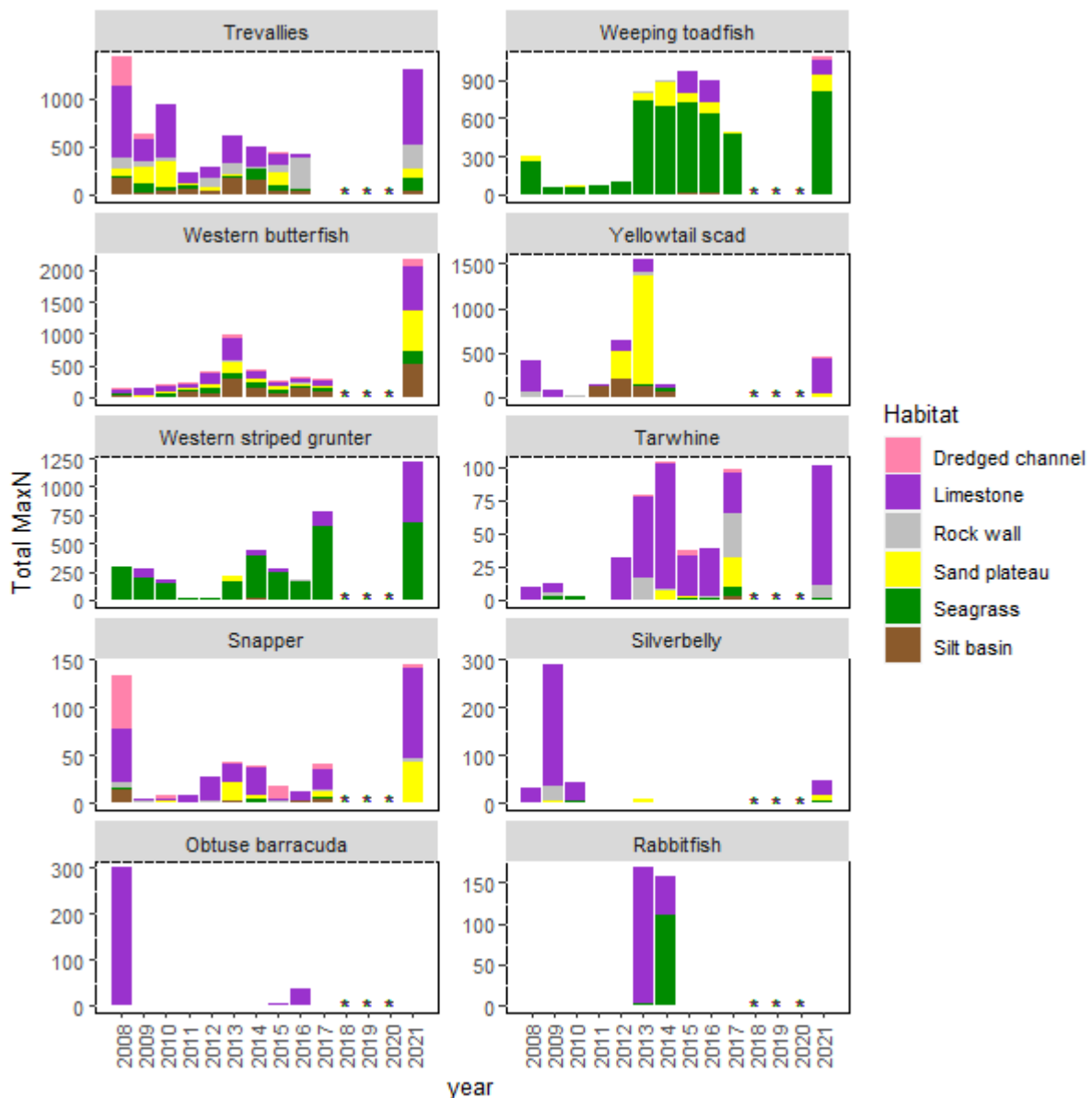


Figure 22. Total MaxN by year of the 10 most prolific species in CS, based on the 37 BRUV stations consistently sampled between 2008 and 2021. Although the survey was carried out from 2018-2020 the videos have not been processed to determine MaxN values (*). Clupeid and sillaginid species are not displayed despite these taxonomic groups being in the most prolific taxa observed.

Community level analysis of change over time in fish observed on BRUVs in relation to climate and other environmental factors is beyond the scope of this current project. However, work is ongoing by DPIRD and Murdoch University to examine the tropicalisation of demersal fish communities in CS in relation to MHWs. Species specific patterns are discussed in further detail for snapper (Section 4.3.3) and rabbitfish (Section 4.3.4).

Nearshore fish recruitment index project

The nearshore fish recruitment index project surveyed the Mangles Bay site in 16 different years between 1999-2022. Prior to 2005 the abundance of only 20 recreationally or commercially important species were recorded (Figure 23), with six regularly observed (>2 individuals per shot on average): western trumpeter whiting (*Sillago berrus*), sea mullet (*Mugil cephalus*), King George whiting (*Sillaginodes punctatus*), tarwhine, yellowfin whiting and yelloweye mullet (*Aldrichetta forsteri*). Since 2005 the abundance of all species (except for sandy sprat and hardyhead (Atherinidae) species) were

recorded, with a total of 63 different fish taxa observed from 13 years of data. The most prolific non-target species were the southern longfin goby (*Favonigobius lateralis*), weeping toadfish, western striped grunter, western gobbieguts (*Ostorhinchus rueppellii*) and common silverbiddy (*Gerres subfasciatus*) (Figure 24). Annual variation in abundances of these frequently observed 11 species were apparent (Figure 23 & Figure 24) although there is no direction of long-term change. These data are currently being reviewed.

The diversity of species and total abundance of fish have fluctuated at the Mangles Bay site over the 16 years (Figure 25), however, there has not been a predominant direction of change. There was a small decrease in the total abundance of fish observed at the Mangles Bay site in 2011 and 2012, which may be associated with the 2011 MHW. It would be more appropriate to explore the relationship between temperature, and other environmental factors, on total and individual species abundances, using the full Pinnaroo Point to Cape Arid National Park (east of Esperance) nearshore fish recruitment index dataset, rather than on the single site within CS. However, that is beyond the scope of this report.

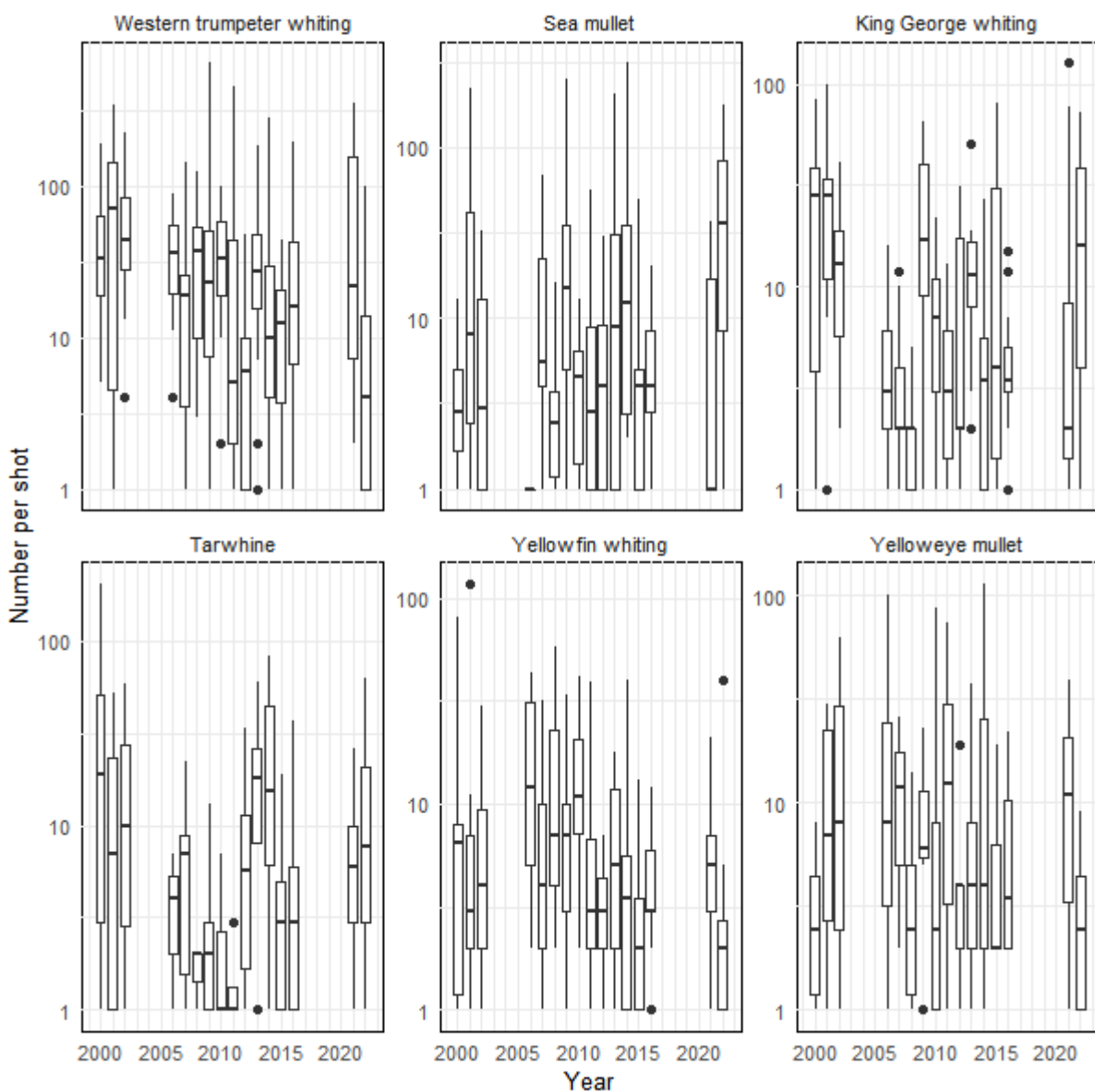


Figure 23. Abundance of the six most prolific commercially or recreationally targeted species observed in Mangles Bay from the annual September-January recruitment beach seine surveys between 1999-2022 in descending order. Outliers are displayed as black dots. While recorded in high abundance within the dataset, sandy sprat is not presented as these were not consistently counted in all years.

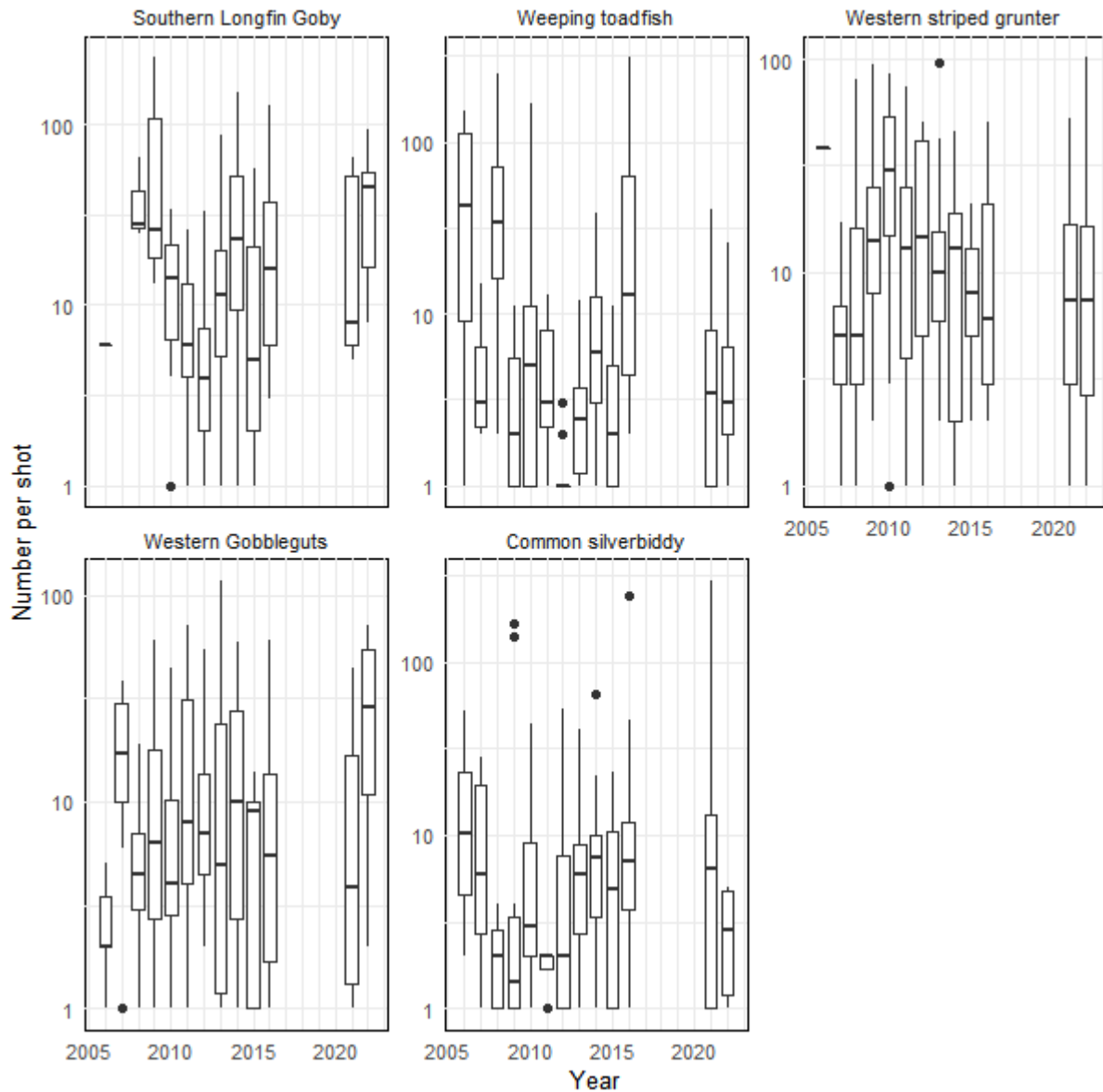


Figure 24. Abundance of the five most prolific species observed in Mangles Bay (excluding those shown in Figure 23) from the annual September-January recruitment beach seine surveys between 2005-2022 in descending order. Outliers are displayed as black dots. Note atherinid species are not presented as these were not counted in all years, with the four species observed grouped as a single record in other years.

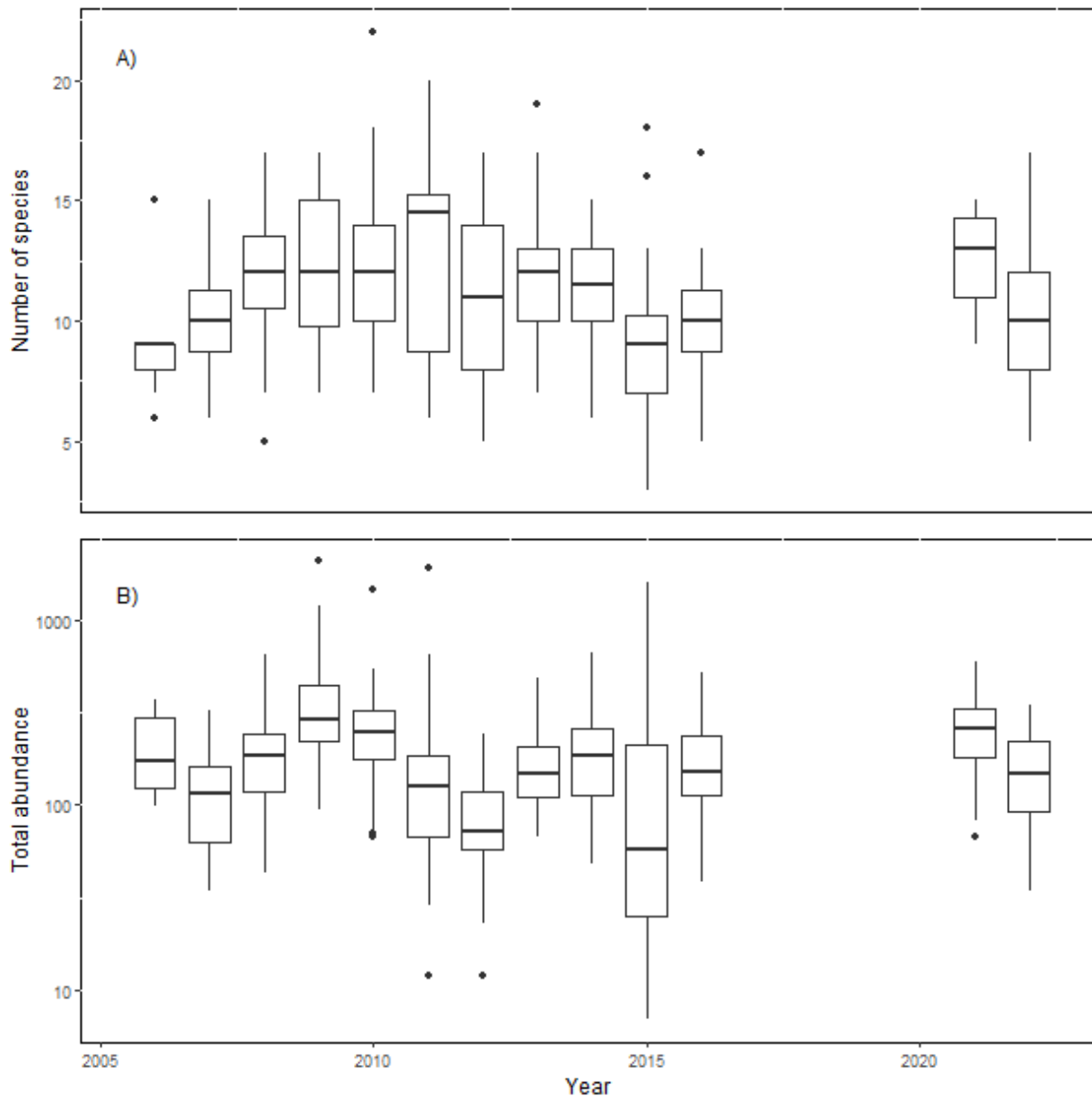


Figure 25. Boxplots of the (A) total number of species per shot and (B) total number of fish across all taxa per shot. Outliers are displayed as black dots. Data are only presented for those years when all taxa were recorded (i.e. the summer of 2005/06 to 2021/22).

4.2.2 Commercial monthly catch and effort statistics (CAES)

Since mandatory CAES reporting was introduced for commercial fishers, ~90 species, or species groups, have been landed within CS, either targeted or as bycatch. The vast majority of these species were not landed consistently each year, and only 20 species have averaged >1 tonne landed per year (Figure 26). CS became a limited entry fishery in 1985 and in the following decade commercial landings peaked for most of the main species, with catches steadily declining since then. This was the case for Australian sardines (*Sardinops sagax*), scaly mackerel (*Sardinella lemuru*), mussels, blue swimmer crab, Australian herring (*Arripis georgianus*), Australian anchovy (*Engraulis australis*), yellowtail scad, sandy sprat, squid, blue sprat (*Spratelloides robustus*), yelloweye mullet, sea mullet, skates and maray (*Etrumeus teres*). Over the same period Perth herring (*Nematalosa vlaminghi*) also decreased, however, the peak catches for this species were several years earlier, during 1977-1980 at >40 t per year. Australian sardines, the most landed species caught in CS, had three year's catches exceeding >1000 t from 1991-1993, however, since 2000 there have been multiple years when no Australian sardines were caught

within CS. Another baitfish species, scaly mackerel, followed a similar trend with catches peaking in 1984-1986 at ~600 t per year, before decreasing to less than a tenth of that by the mid-1990s. It is likely the steady decline is partially attributable to decreasing productivity in CS as the environment became less nutrient rich (Figure 9-11; Marks et al. 2021). However, changes to fisheries management and market demand will also have changed the commercial catches, while not reflecting changes in a species' abundance.

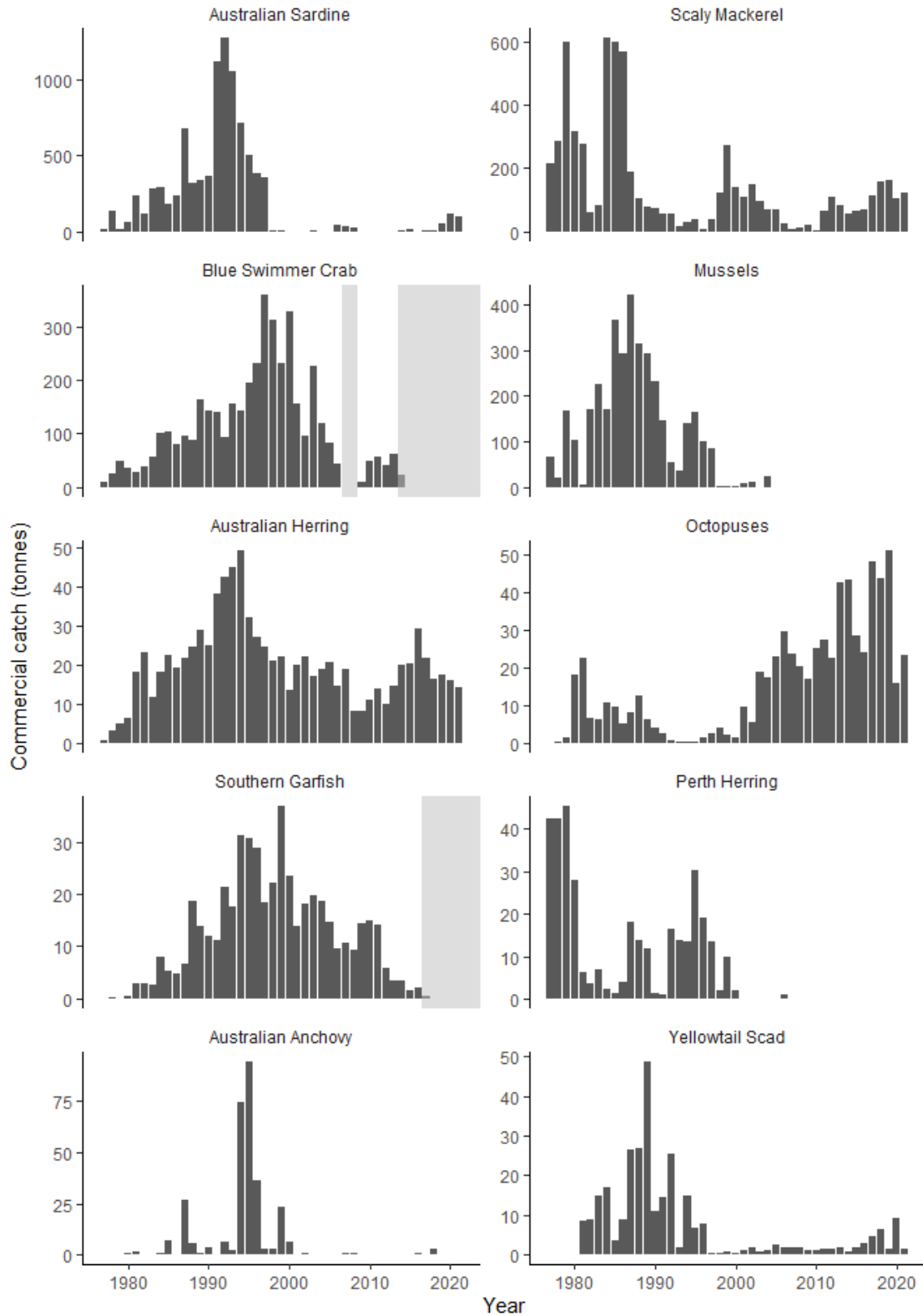


Figure 26. Annual total catch between July 1977-2021 for the 20 most landed species, or species groups (by total weight), reported in the DPIRD CAES system as landed within fisheries block 96000. Total annual catch has been aggregated across all fisheries operating within CS irrespective of gear type. Grey shaded areas indicate years where a fishery was closed preventing the landing of that species. Species are ordered based on total catch (descending order). Note: the category 'General fish' was in use at various times to report catch in CS by multiple fishers.

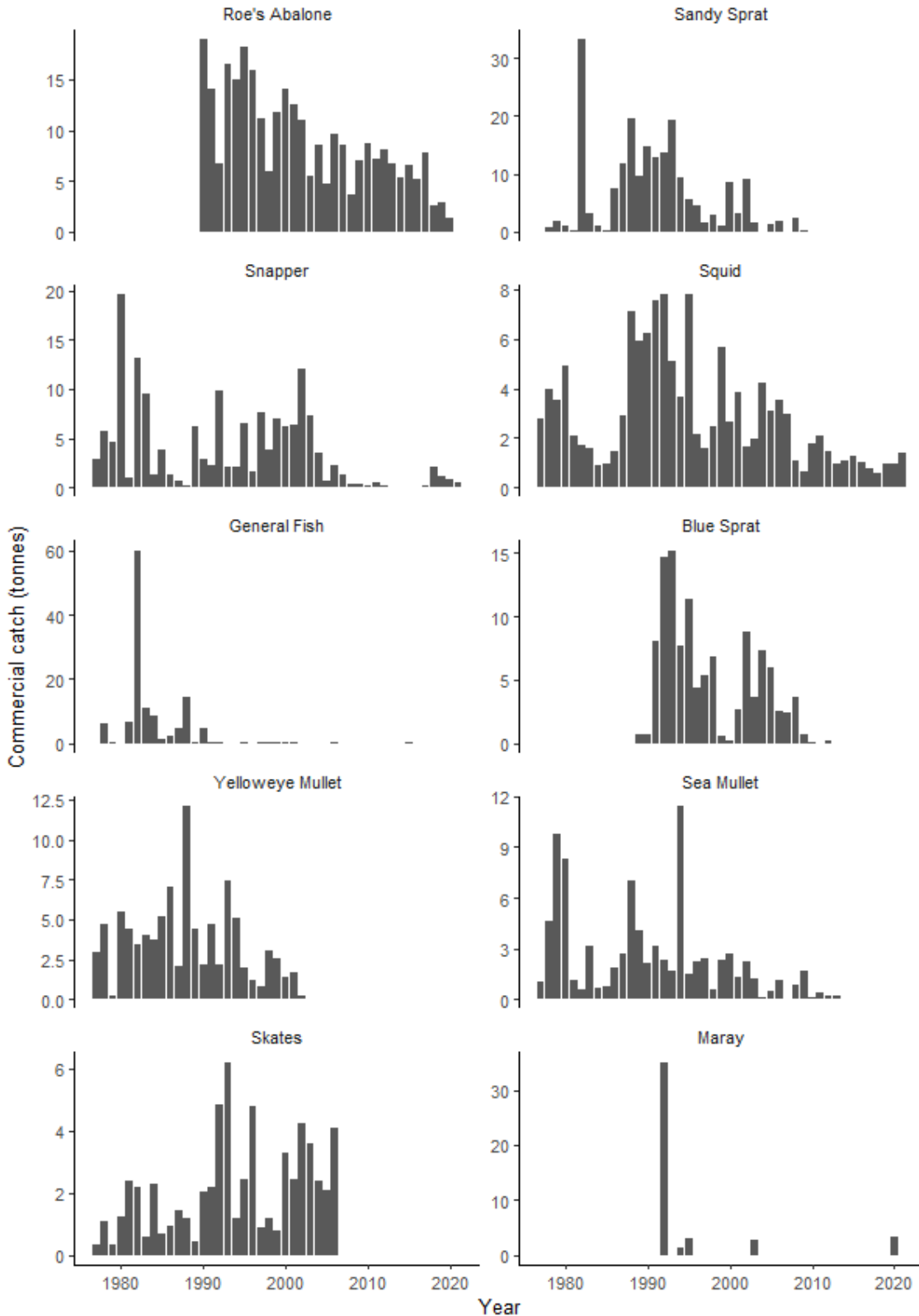


Figure 26 cont. Annual total catch between July 1977-2021 for the 20 most landed species, or species groups (by total weight), reported in the DPIRD CAES system as landed within fisheries block 96000. Total annual catch has been aggregated across all fisheries operating within CS irrespective of gear type. Species are ordered based on total catch (descending order). Note: the category 'General fish' was in use at various times to report catch in CS by multiple fishers.

In 1995, commercial fishing in CS was split into five limited entry fisheries. Revised arrangements for each fishery included, restrictions on the gear that could be used and species that could be retained, and a reduction in the number of licenced fishers in CS through attrition (Millington 1990, Millington et al. 1992). This saw the planned phasing out of mussel fishing within CS in favour of aquaculture production. Fishing for blue swimmer crab, southern garfish and snapper have all experienced periods of seasonal or complete fishing closures within CS (see Section 4.3) which would be reflected in the total landings. By 2021, commercial fishers operated within CS under four different fisheries: Cockburn Sound Line and Pot (CSLP), Cockburn Sound Fish Net (CSFN), West Coast Purse Seine Fishery and the Abalone Managed Fishery. In addition, the CSC fishery, which has been closed since 2014, also has a long time series which has been the focus of multiple studies (Johnston et al. 2021, Marks et al. 2021), and is briefly summarized below and in Section 4.3.1

Of the 20 most landed fish species in CS (Figure 26), only Roe's abalone (*Haliotis roei*) and maray were caught using a single gear type. Catches of Roe's abalone would predominantly have been taken in block 96000 but west of the Garden Island causeway. All other species have been caught at different times using various types of nets, lines and traps, some of which became prohibited as management practices changed.

The major exception to this trend of decreasing catch has been octopus, which has rapidly increased from <500 kg per year in the mid-1990s to >50 t per year 2019 (decreased catches in 2020/21 have been attributed to COVID-19 issues (Newman et al. 2021)). Targeted octopus fishing was established in 2001 and has been in an expansion phase across the entire fishery (Hart et al. 2016).

Squid fishery

The commercial squid fishery within CS was recently described in detail by Yeoh et al. (2021). The predominant squid caught within CS is southern calamari (*Sepioteuthis australis*) which is entirely caught using squid jigging, although in previous decades some squid were retained as bycatch from netting methods. Commercial jigging in CS is limited to CSLP license holders, with only a subset of the fishers allowed to jig being active each year. Squid fishing makes up a small subset of the total days fishing within CS each year. Total catches within CS peaked in the early 1990s at around 7.5 t annually, before slowly decreasing to 0.5-1.5 t per year over the last decade (Figure 27). Catches have generally been aligned with effort (nominal CPUE of 0.5–0.9 kg hook hr⁻¹).

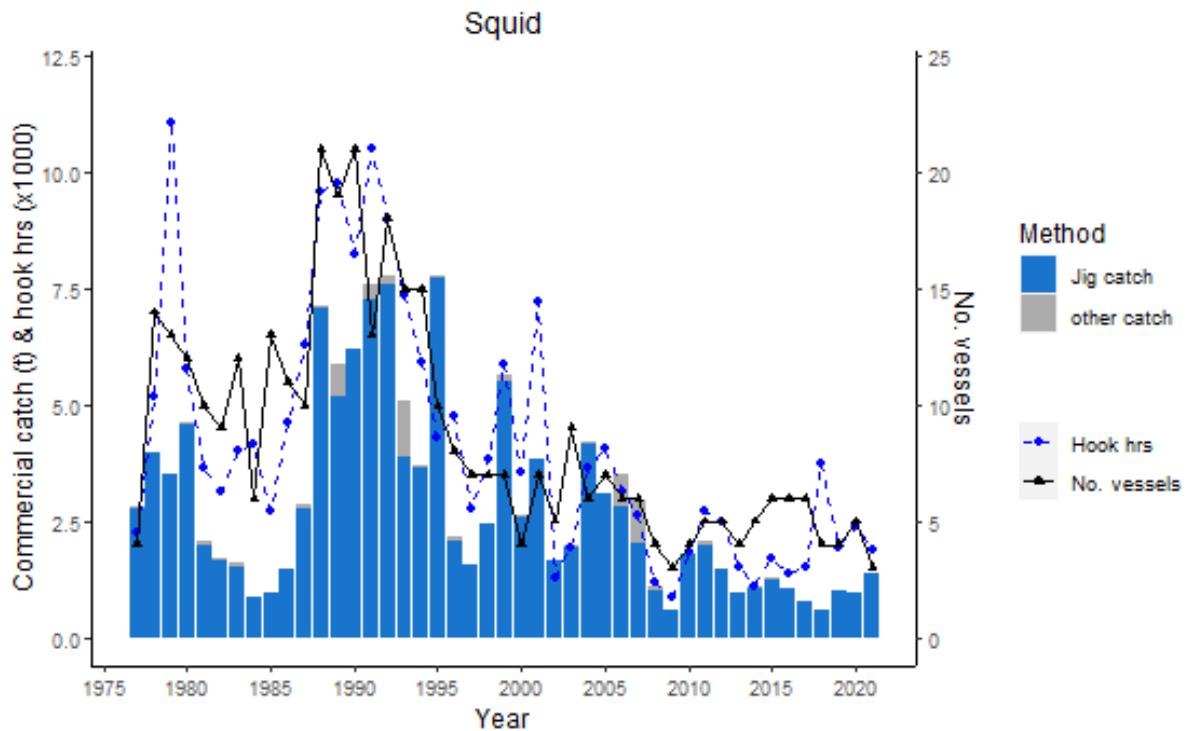


Figure 27. Total annual commercial squid catch and effort in CS (block 96000) from 1977-2021. Hook hours is the total hook hours used by squid jigging vessels.

As per Yeoh et al. (2021), annual standardized squid jigging CPUE values were calculated, accounting for effects of month and fisher (Figure 28). Standardised CPUE, calculated as kg day^{-1} (Figure 28a), shows that catch rates were slowly decreasing during 1977-1996, from $>10 \text{ kg day}^{-1}$ to $\sim 6.0 \text{ kg day}^{-1}$. Catch rates then increased over the next 8 years to a peak of $\sim 17.5 \text{ kg day}^{-1}$ in 2004, before decreasing again to 1996 levels. Over the last five years standardized CPUE have been between $4.1\text{-}8.1 \text{ kg day}^{-1}$. Standardised CPUE calculated as kg hook hr^{-1} remained relatively consistent (Figure 28b), with the peak in 2004 being present but less pronounced, and a second peak occurring in 2014. Also of note from this measure of CPUE, is that the years since 2017 have been the lowest catch rates on record within CS ($0.23\text{-}0.72 \text{ kg hook hr}^{-1}$).

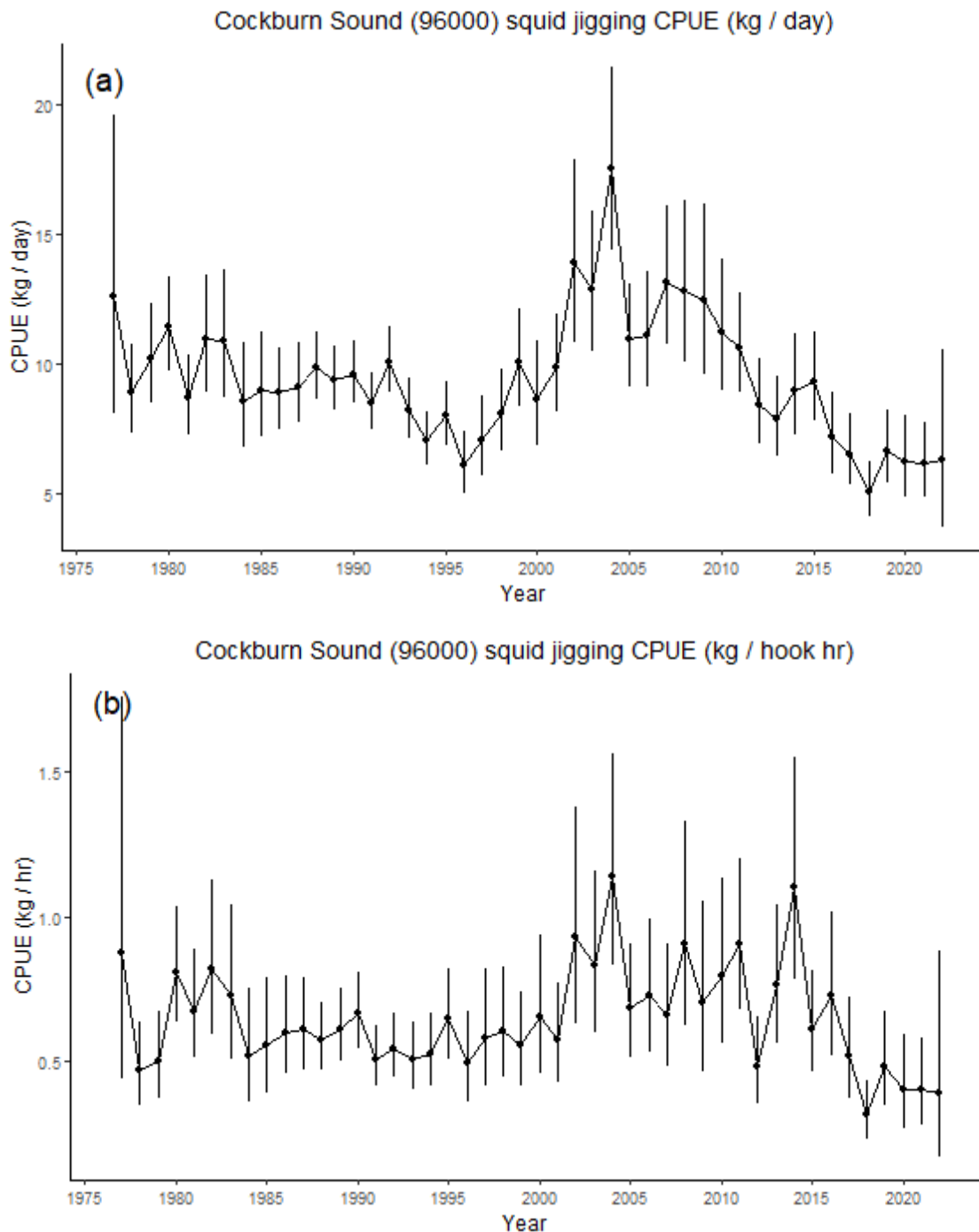


Figure 28. Standardised squid jigging CPUE in terms of kg per day (a) and kg per hook hour (b) in CS (block 96000) from 1977-2021. Values were standardized for month and vessel ID using a generalised linear model. Only data from fishers active in ≥ 5 years were used to calculate annual standardized CPUE.

Octopus fishery

Western rock octopus (*Octopus djinda*) are commercially harvested as part of the CSLP fishery. The fishery was established in 1995, with entry limited to 34 license holders. While previously considered a bycatch species used for bait and of limited value, in the early 2000s the market for octopus for human consumption grew rapidly (Hart et al. 2018). In May 2015, to more effectively manage fishing effort within CS, the octopus component of the CSLP was transitioned to a pot entitlement scheme with a total of 13,005 units (i.e. pots) permitted. While trigger traps are the predominant trap type

used to target octopus within the WCB, within CS the fishery has historically used longline-set unbaited shelter pots. Fishers operating in the CSLP are required to fill out a daily catch and effort logbook, with details including the total weight for the day and number of pots hauled.

Prior to 2002, most octopus caught within CS were caught using the method 'Potting'. Potting consisted of various trap designs, such as tyres, clay pots and PVC pipes (DoF 2005), but may have also included crab traps catching octopus as bycatch. In 2002, a method code specific for octopus pots (OP) was introduced allowing the fishing effort to be more accurately monitored. Total catch within CS rapidly rose from <2 t in 2000 to ~20 t in 2003 (Figure 29A) and then ranged 20-50 t per year over the last 20 years. Catches fell dramatically in 2020-2021 due to a range of factors associated with COVID-19 (in particular reduced market demand).

Nine license holders currently have pot entitlements within the CSLP fishery, however, in all years since the pot entitlement scheme was introduced, some license holders have been inactive in each year (Figure 29C). Over the last 20 years the total effort has increased, however, at the same time CPUE has increased. The Octopus Interim Managed Fishery, which covers the WCB and South Bioregion, has been in a controlled expansion phase since 2016 (Hart et al. 2018). However, controlled expansion has not been planned for the CSLP fishery, with the total pot allocation being unchanged since 2015. The steady increase in total catches over the last 20 years are generally attributed to increased market demand, and not changes to the environment. The limited number of CSLP fishers, who have different fishing strategies, and the limited number of years under the current set of control measures, mean there are insufficient data to examine the more subtle impacts of climate on octopus relative abundances based on CPUE. However, individual fishers have reported observing variability in catches which may in part be attributed to changes in water quality (e.g. turbidity), noise disturbance (e.g., pile driving), and food availability.

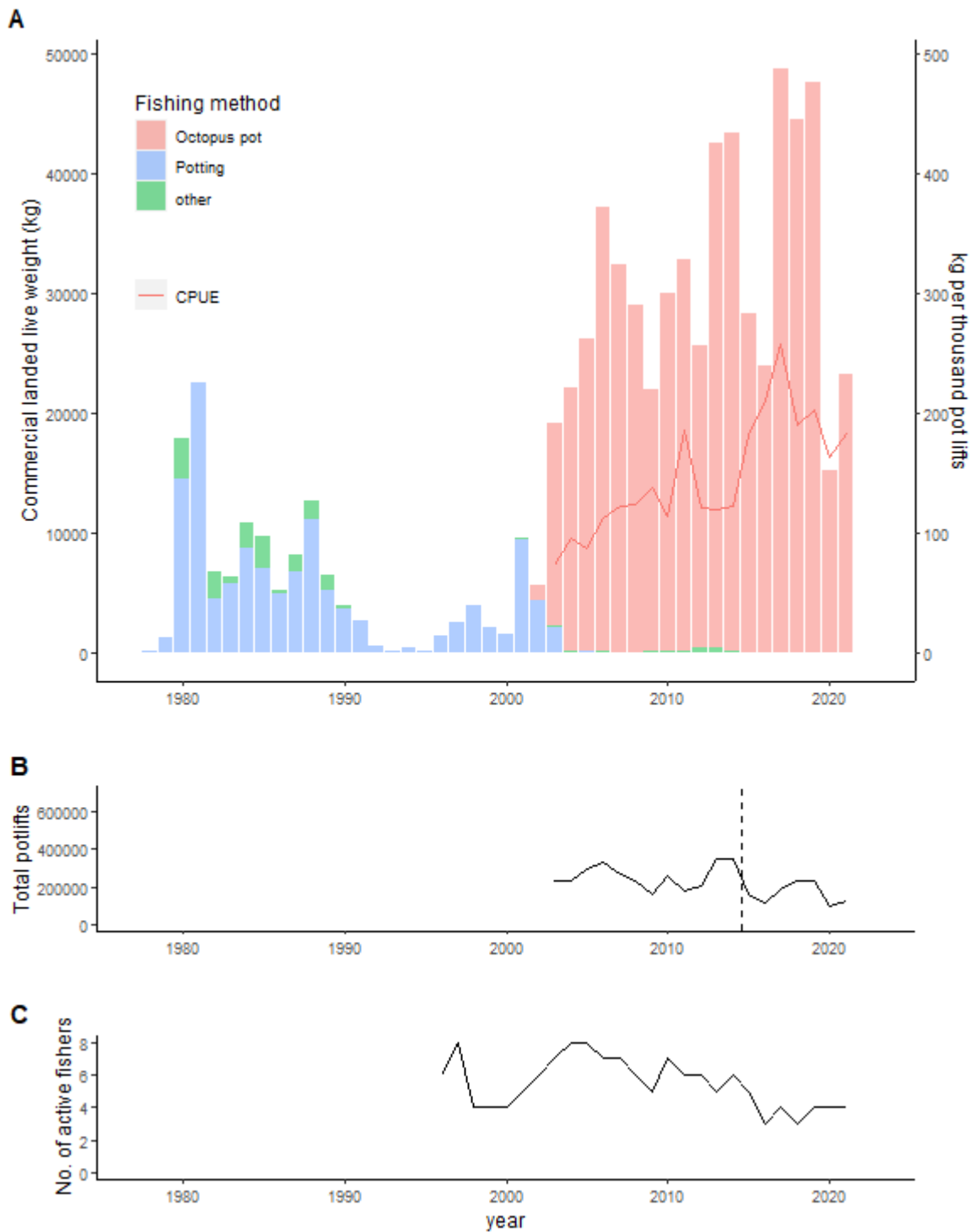


Figure 29. (A) Total annual landed live weight of octopus commercially harvested within CS and CPUE (kg live weight per 1000 pot lifts). (B) Total effort (as pot lifts) since 2003. The pot entitlement scheme was introduced in 2015 thereby limiting fishing effort within CS (dashed line). Total effort and CPUE cannot be reliably calculated prior to 2003 as fishers were not consistently recording the use of octopus specific pots. (C) The total number of active CSLP license holders since the fisheries establishment in 1995.

Cockburn Sound Crab Fishery

Commercial crab fishing in CS started in the 1970s using gill nets, with catches increasing from ~50 t in the late 1970s to ~150 t in the early 1990s (Figure 30). This was associated with a large increase in

effort to over 3,000 km of gill nets set within CS in 1991. Up to 1995 there were few restrictions on fishers other than a prohibition on taking berried females and a minimum size (130 mm CW). In 1995 the *CSC Fishery Management Plan* was introduced, converting the fishery from gill nets to purpose-designed hourglass traps to reduce the impact on non-target species. The management plan consolidated controls on gear specifications, season and daily time restrictions, size limits, retainable species and the number of license holders. Catches increased following the introduction of traps, as these proved to be more efficient than gill nets and were effective all year round (Johnston et al. 2011a, 2020). Although the total number of traps was reduced from 1600 in 1998 to 800 by 2003/04, catches continued to decline leading to a closure in December 2006. Informed by fisheries-independent monitoring, the CSC fishery was reopened in December 2009 with further restrictions on season length, number of traps and legal crab size limits. However, commercial catch rates remained comparable to those immediately before the closure suggesting the legal biomass was low. Based on further evidence from the fisheries-independent monitoring of egg production index and the juvenile recruitment index, the commercial (whole fishery) and recreational (south of a line between Woodman Point and Carnac Island) fisheries were closed in 2014 and have not been reopened. A more detailed history of the CSC is provided in Johnston et al. (2020).

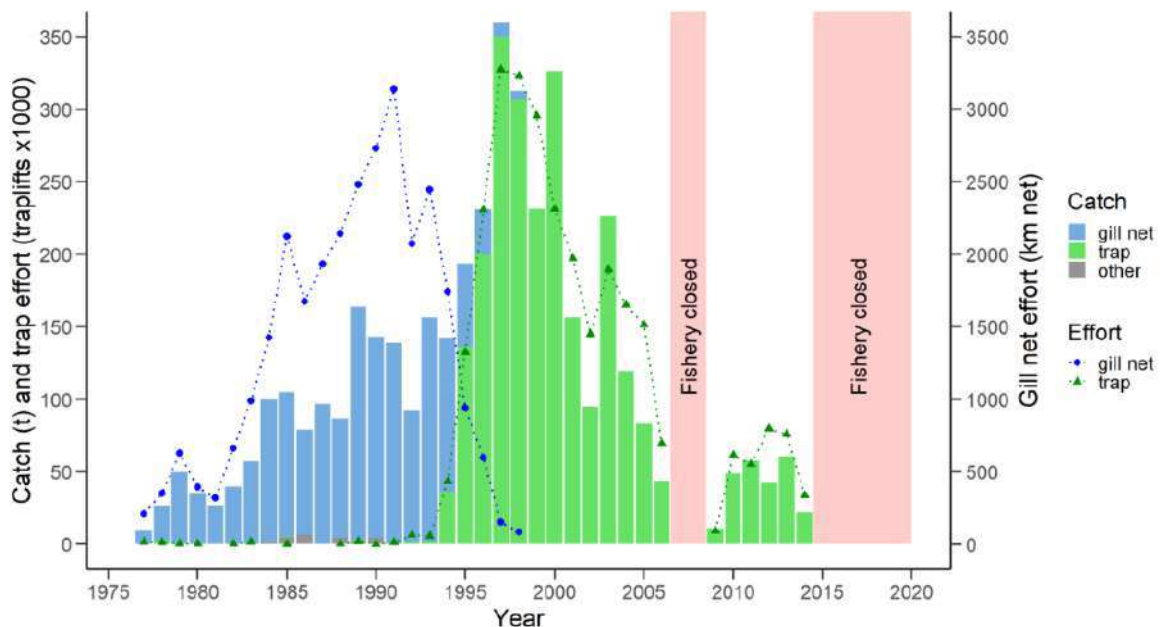


Figure 30. Total annual commercial catch (t) and effort of blue swimmer crab within CS. Effort is method dependent based on km of gill nets set, or total number of trap lifts. Total catch from other fishing methods was negligible so effort is not displayed. The fishery was first closed to fishing between 2006 and 2009 reopening under modified management before a second closure since April 2014 (showed as pink). Figure from Johnston et al. (2020).

4.2.3 Recreational catch and effort

Amongst boat-based recreational fishers in the Perth metropolitan region, the most-commonly caught finfish species in 2021 were school whiting (*Sillago sp.*), Australian herring, and snapper (Tate et al. 2022). Western rock lobster (*Panulirus cygnus*), blue swimmer crab and squid were the most commonly caught invertebrates (Ryan et al., 2022). Australian herring and school whiting were the main species retained by shore fishers in the Perth metropolitan area between 2010 and 2022. In 2010 17% of the retained shore-based catch was southern garfish however this declined to <2% in following years as the stock declined and subsequent closure put in place in 2017.

Creel surveys conducted in 2001/02 and 2005/06 found blue swimmer crab, Australian herring, King George whiting and school whiting to be the main recreational species caught in CS. The total recreational line fishing effort decreased from 135,000 ($\pm 23,000$ 95% CI) hours in 2001/02 to 128,000 ($\pm 8,000$) hours during 2005/06. Recreational crabbing effort also declined over this period, from 32,000 ($\pm 10,000$) hours in 2001/02 to 14,000 ($\pm 3,000$) hours during 2005/06. This decline in recreational crabbing effort was mirrored in the harvest which also declined from 25 t in 2001/02 to 4 t in 2005/06 (Sumner and Lai, 2012).

4.2.4 Aquaculture production return

Black mussels (*Mytilus* spp.) were the primary aquaculture species produced in CS, with farms positioned on the Southern Flats and adjacent to the Kwinana Grain Terminal. Aquaculture production returns recorded the quantity and value of produced mussels within CS since 1996/97, although data are confidential since 2012/13 due to <3 license holders operating within CS. Annual mussel farm production within CS was >500 t per annum between 1997/98 and 2006/07, with a peak of 736 t in 2000/01. Production decreased substantially over a 15-year period to <100 t per annum between 2019-2021. In the most recent year, all mussel aquaculture in CS had ceased, with the majority of gear removed from the licence areas. The decrease in production has been attributed to decreased primary production (Figure 11), along with increased predation of mussels by fish and crabs (CSMC 2018). However, as commercial operators are not required to publish these data, it is not possible to draw any further insights into the role climate change or environmental change had on productivity.

4.3 Assessing biological and environmental effects on key biota

Case studies undertaken:

4.3.1 Blue swimmer crab

Cockburn Sound once supported a productive blue swimmer crab (*Portunus armatus*) fishery, with catches peaking at 360 t during the 1990s (Figure 26). However, declines in recruitment (Figure 21) and catches (<50 t) during the mid-2000s resulted in prolonged fishery closures (Figure 30). Recreational blue swimmer crab catches followed a similar decline in the early 2000's to just 4 t in 2005/06 (Section 4.2.3; Sumner & Lai 2012). Excessive fishing pressure, low egg production, low recruitment and unfavourable environmental conditions have all been implicated as potential factors in stock decline (de Lestang et al., 2010; Johnston et al., 2011). However, despite closure to all crab fishing since 2014, neither recruitment nor breeding stock have returned to levels of the mid-2000s (Johnston et al. 2020, 2021). More recently, it has been proposed that blue swimmer crab biomass in CS (biomass dynamics model based on commercial catch data) reflects changes in primary productivity (based on chlorophyll-*a* as a proxy) (Marks et al. 2021). Annual biomass production and maximum sustainable yield were positively correlated with chlorophyll-*a* concentration, implying that the stock is less productive/resilient to fishing pressure when chlorophyll-*a* is below long-term average levels (Marks et al. 2021).

Stock-recruitment-environment relationships

Understanding the fine-scale mechanisms behind recruitment dynamics in this fishery is an important progression, building on the biomass dynamics model applied by Marks et al. (2021). A stock-recruitment environment relationship (SRER) model was initially developed for the CSC fishery in the late 2000s, using commercial catch as a proxy for egg production and recruitment due to the lack of a direct fishery-independent recruitment index at that time (de Lestang et al., 2010). There is evidence that major environmental changes have since occurred in CS, which would be expected to affect the recruitment dynamics of crab populations and therefore warrant re-evaluation of the SRER. This SRER could also be improved through the development of fishery-independent surveys since the early-2000s (Figure 19 & 21; Johnston et al. 2020), which now provide direct estimates of recruitment and egg production without the biases associated with commercial catch data. Moreover, productivity and

other potential environmental variables, such as salinity and dissolved oxygen, were not examined in the previous de Lestang et al. (2010) SRER.

Using more recent fishery-independent trawl data DPIRD developed spawning stock and recruitment indices with a strong stock-recruitment relationship, and an updated SRER based on some key environmental variables (Caputi et al. 2021). The best-fit SRER contained water temperature (SST) and chlorophyll-*a*, as explanatory variables ($R^2 = 0.44$; $p < 0.04$). This relationship suggests that recruitment is best in warmer years and those with higher primary productivity (chlorophyll-*a*), such as 2002, 2003 and 2010 (Figure 31). Further, in years with relatively large spawning stocks (e.g. 2004 and 2013) if conditions are unsuitable because of lower than normal water temperatures and chlorophyll-*a*, recruitment can be negatively impacted.

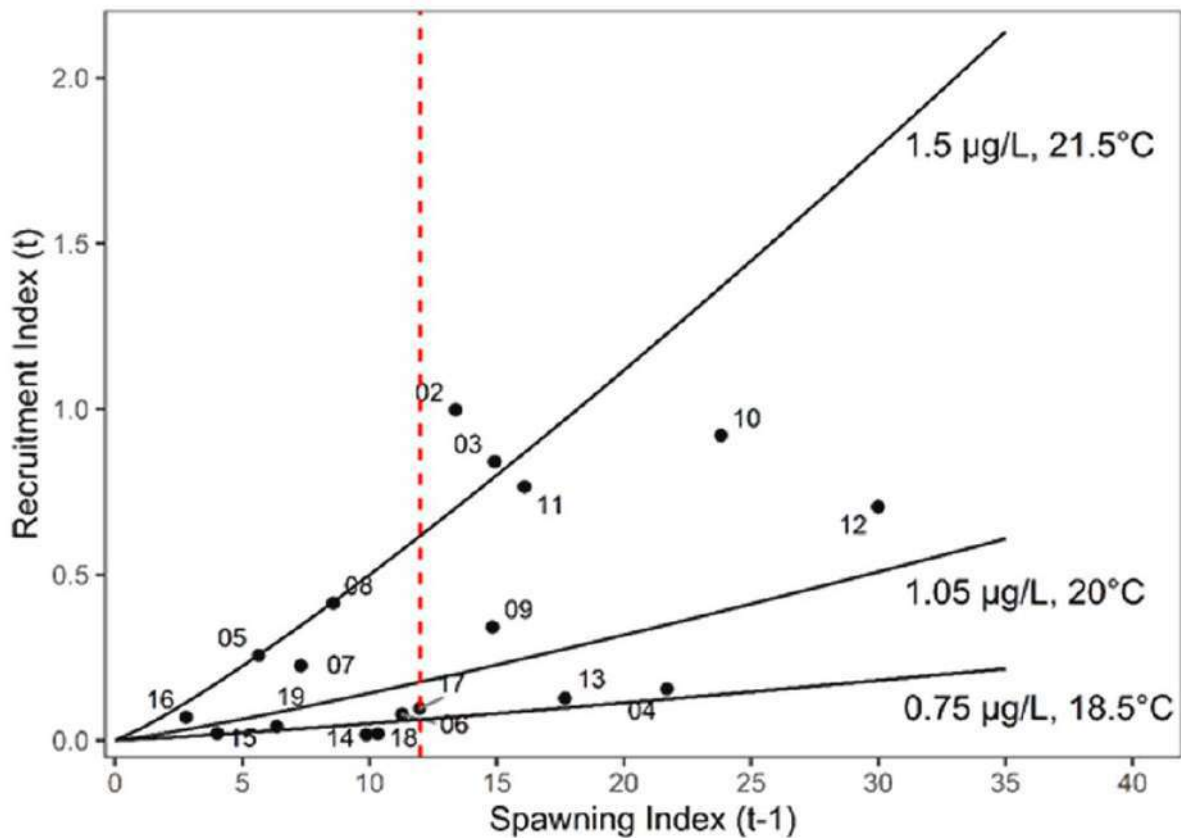


Figure 31. The stock-recruitment-environment relationship of the blue swimmer crab stock in Cockburn Sound between the spawning index (year *t-1*) and recruitment index (year *t*) with the three lines ranging from poor (coolest water temperature and lowest chlorophyll-*a*) to good environmental conditions (warmest water temperature and highest chlorophyll-*a*). The Limit Reference Point (dashed red), the point at which management action is undertaken to recover a stock), and the recruitment years are shown. Figure from Caputi et al. (2021).

DPIRD is developing an improved SRER which uses refined spawning and recruitment indices and considers a greater number of environmental variables. Preliminary results indicate an improved model fit, and suggest that in addition to chlorophyll-*a* and water temperature, salinity will also be a retained variable in the final model (D. Yeoh, DPIRD *unpublished*). Caputi et al. (2021) and unpublished data from Yeoh (DPIRD) shows the important role environment is having on blue swimmer crab abundances in Cockburn Sound. Long-term trends in these variables suggest that while temperature has slowly increased, primary productivity has markedly declined. Due to a tightening of industry regulations, anthropogenic nutrient inputs (e.g., nitrogen; discussed in Section 4.1.3) into CS have

reduced by more than 95% in recent decades (BMT Oceanica Pty Ltd 2017), resulting in a significant decline in primary productivity. With changing environmental management and improved waste management practices, nutrient levels are unlikely to return to those of earlier decades. Therefore, these studies suggest that the warming associated climate change may positively impact blue swimmer crabs in Cockburn Sound. However, as primary productivity also appears to be important and may be limiting recruitment, it is unlikely that stocks will return to historic levels due to the impact of tighter industrial regulations.

In addition to the relationships described above, data from the fisheries-independent large otter-trawls also indicate that chlorophyll-*a* concentrations are important for the abundance of blue swimmer crab within CS. Within the 'Research Area' (Figure 1), which provides the longest time series of crab densities available, there was a positive relationship between the annual crab density index and the chlorophyll-*a* index of the preceding summer ($F_{1,30} = 12.25$, $p < 0.01$, Figure 32). The preceding summer SST (Figure 5) was also initially included in the model but not found to be significant ($p > 0.05$) and therefore not included in the final model.

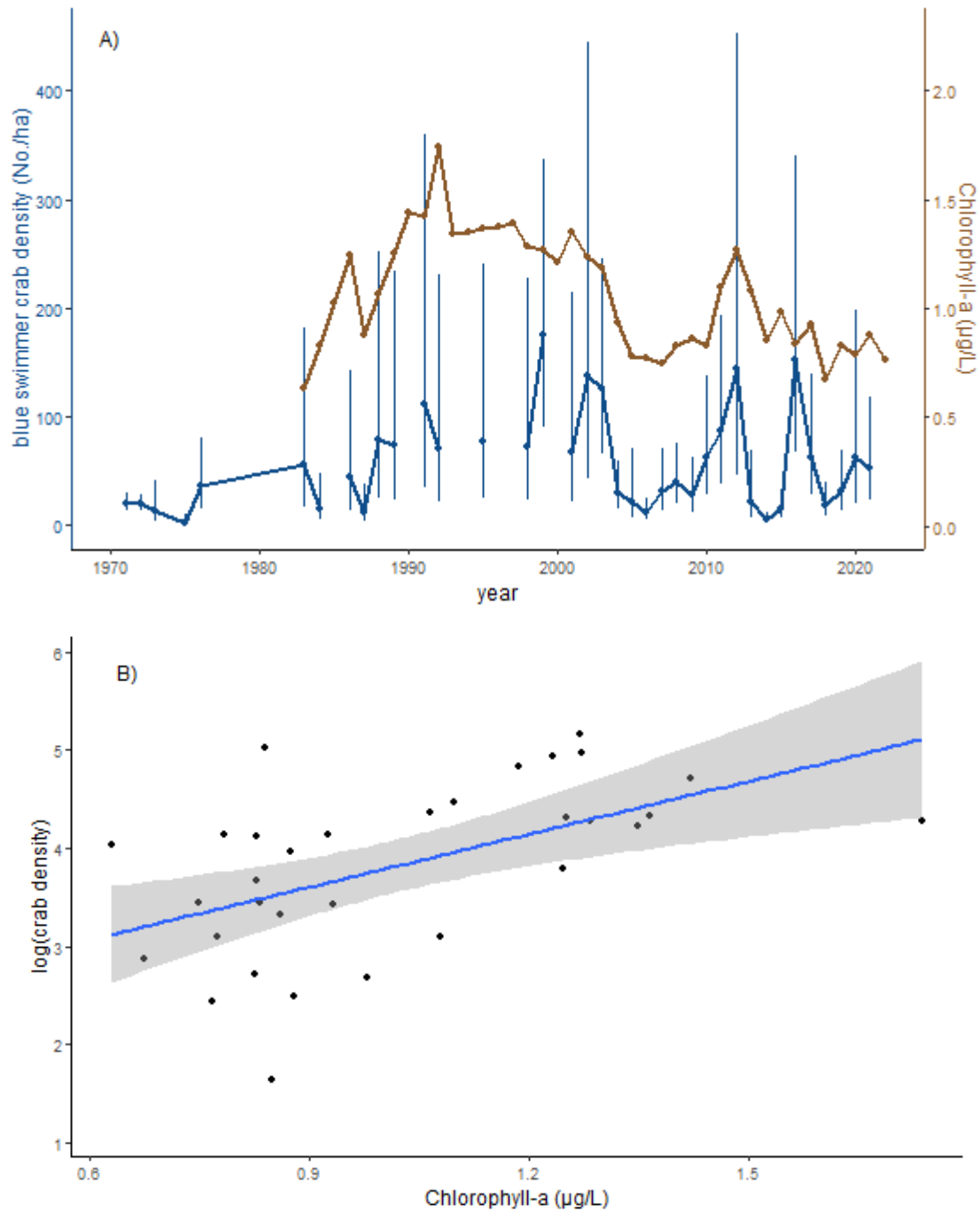


Figure 32. Annual trawl density index of blue swimmer crab in the central CS 'Research Area' and the summer chlorophyll-a concentration index (A). Error bars represent the 95% confidence intervals of the log-transformed crab density index. The natural log of the annual crab density index in relation to the chlorophyll-a summer index (B), is presented with the regression line and 95% confidence intervals.

4.3.2 Western king prawn

As trawlers began operating in CS in the 1950-60s, western king prawn (*Penaeus latisulcatus*) were briefly of commercial interest, before concerns were raised over the impact this fishing method was having over the environment and the commercial and recreational fishing sectors (Penn 1977). First the shallow weed beds were closed to trawling in 1962 and then all of CS was closed to trawling in 1970 (Penn 1977). The fisheries-independent survey, which commenced in 1971, therefore includes ~50 years of western king prawn abundances, despite this species not being exposed to commercial fishing (and negligible recreational fishing).

The 'Research Area' trawls (Figure 1) indicate that western king prawn densities have fallen since the late-1990s and early-2000s, however, unlike blue swimmer crab (discussed in the previous section) there was no fishing pressure for western king prawns. Initially data from the 'Research Area' survey provided valuable insights about the species biology and recruitment (Penn 1975, 1976, 1977, 1980), however, since these early studies no further analysis has used the CS western king prawn data. It is possible that the species in CS is limited by primary productivity given western king prawn's low trophic level and short life cycle. Western king prawn in CS also have a shorter spawning period than populations further north, with spawning activity increasing once the temperature exceeds 17°C (Penn 1980). For CS this generally means spawning October to May. Using a linear model of primary productivity (summer chlorophyll-*a* index; Figure 11) and summer water temperature of the proceeding season (Figure 5) against the annual prawn density index, there was a positive relationship with chlorophyll-*a* ($F_{1,30} = 15.54$, $p < 0.001$) (Figure 33) but temperature was not significant ($p > 0.05$). The importance of primary productivity (chlorophyll-*a*) on western king prawn is interesting given this has also been observed as important in CS for blue swimmer crab (Section 4.3.1).

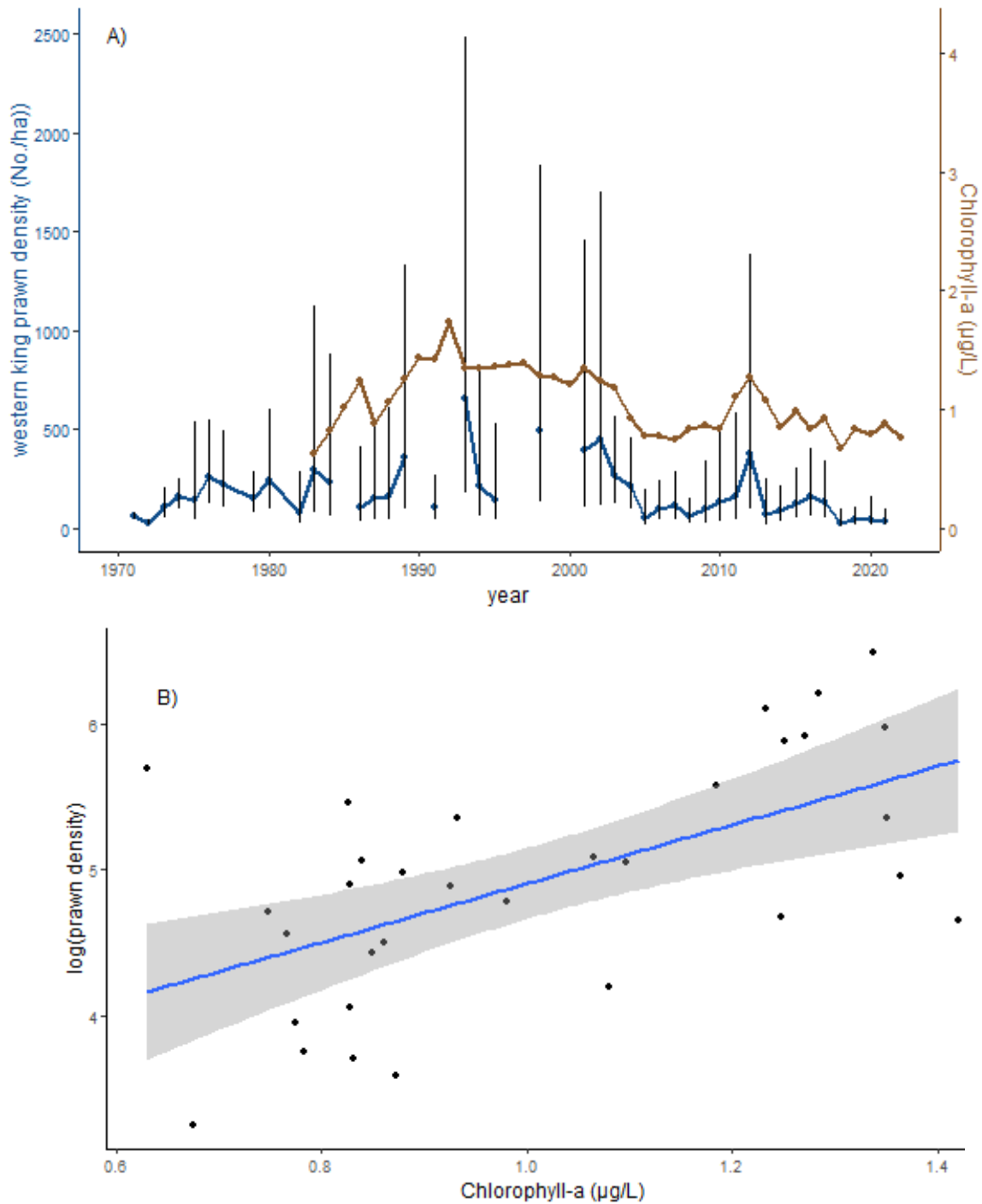


Figure 33. Annual density index of western king prawn in the central CS ‘Research Area’ and the summer chlorophyll-a concentration index (A). Error bars represent the 95% confidence intervals of the log-transformed prawn density index. The natural log of the annual prawn density index in relation to the chlorophyll-a summer index (B), is presented with the regression line and 95% confidence intervals.

4.3.3 Snapper

Owen Anchorage and CS are important spawning and nursery areas for snapper (*Chrysophrys auratus*) in the WCB (Wakefield et al. 2011). Each year between September and January, snapper aggregate in CS to spawn, with some individuals having migrated up to 700 km to spawn (Crisafulli et al. 2019). It is thought that the counterclockwise gyres within CS facilitate egg and larval retention (Wakefield 2010), with some juveniles remaining within the embayment until around 2-years of age (Wakefield et al. 2011). A snapper spawning closure was first introduced in 2000 to protect these aggregations which

are considered an important source of recruitment for the whole stock. The closed area and season have subsequently been expanded multiple times, with the current closure extending from 1st August to 31st January since 2023.

Fisheries-independent surveys of snapper juveniles in CS then began in 2008, and research is ongoing to establish suitable methods to quantify the relative abundance of adult snapper aggregating within CS to spawn (i.e. Aim 4 of WWMSP project *Spatial distribution and temporal variability in life stages of key fish species in Cockburn Sound*).

Within the Perth region, successful recruitment of snapper appears to be highly episodic, with landings over consecutive years dominated by certain year classes. Wakefield (2006) identified strong year classes spawned in 1991, 1992, 1996 and 2000. More recently, age data from recreational and commercial catches indicate strong year classes spawned in 2007 and to a lesser extent 2010 and 2015 (DPIRD, *unpublished data*). However, as cohorts take approximately 4-5 years to reach minimum landing size, it is unclear how successful more recent year's recruitments have been.

Fisheries-independent trawl and BRUV data from CS also show how variable snapper recruitment is between different years (Figure 34 & Figure 35). Large numbers of juvenile snapper were observed using BRUVs in 2008 and 2021, and to a lesser extent 2012-2014 and 2017. While the large trawl data started after the strong 2008 year, the large spike in juvenile snapper in 2021 was also visible. Length frequency data from the large trawls (Figure 36) and the 2021 BRUVs (Figure 37; the first year of stereo video data collection and length measurements), confirm that both methods primarily sample the first (0+) and second (1+) year old juveniles. From 14 years of data the largest snapper caught in the large otter-trawl was 167 mm which would most likely be a member of the 1+ cohort. The 2021 BRUV data suggests older juvenile snapper are also present in CS (Figure 37) despite no juveniles older than ~18 months being detected in the trawls (i.e. 1+ juveniles in April; Figure 36), either due to gear selectivity or sample locations.

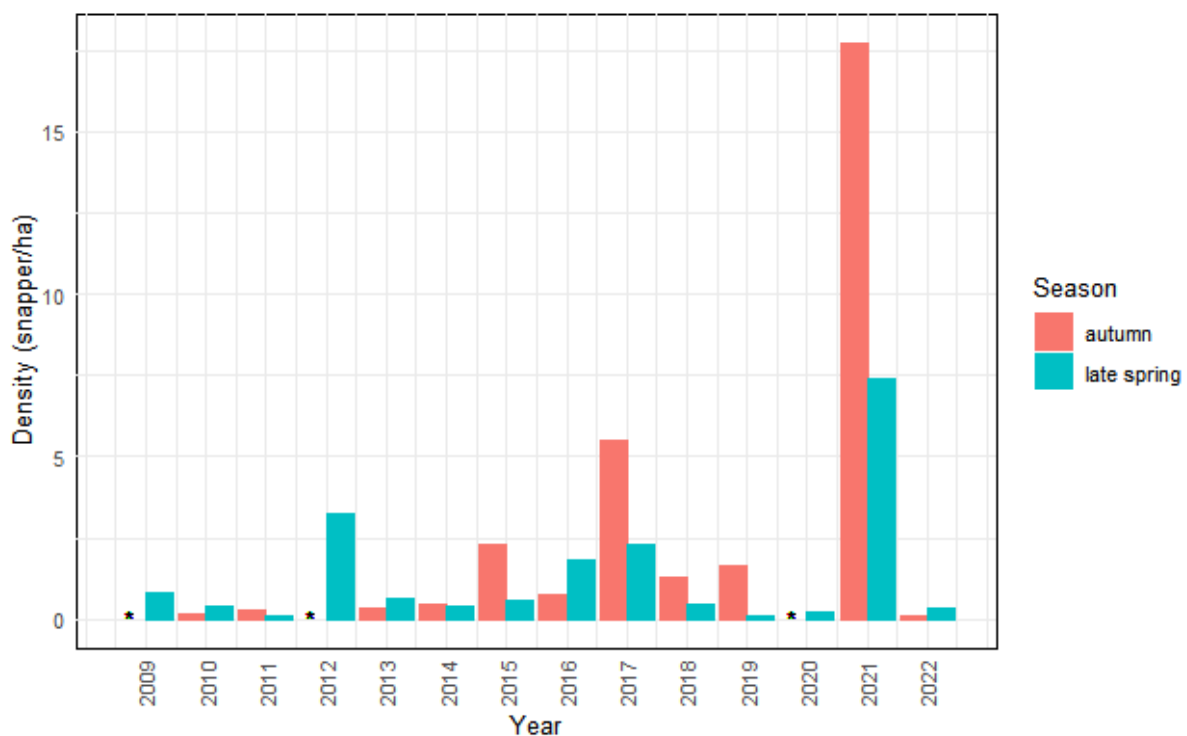


Figure 34. Mean density of snapper caught in the large otter-trawl between 2009 and 2022 grouped by season. Density was calculated having accounted for the swept area of each trawl. Autumn samples were from March-May and late-spring samples were from November-December each year. No survey was completed in autumn of 2009, 2012 and 2020 (*). The large otter-trawl survey was also completed in February in 2022 and 2023 but has not been included in this figure.

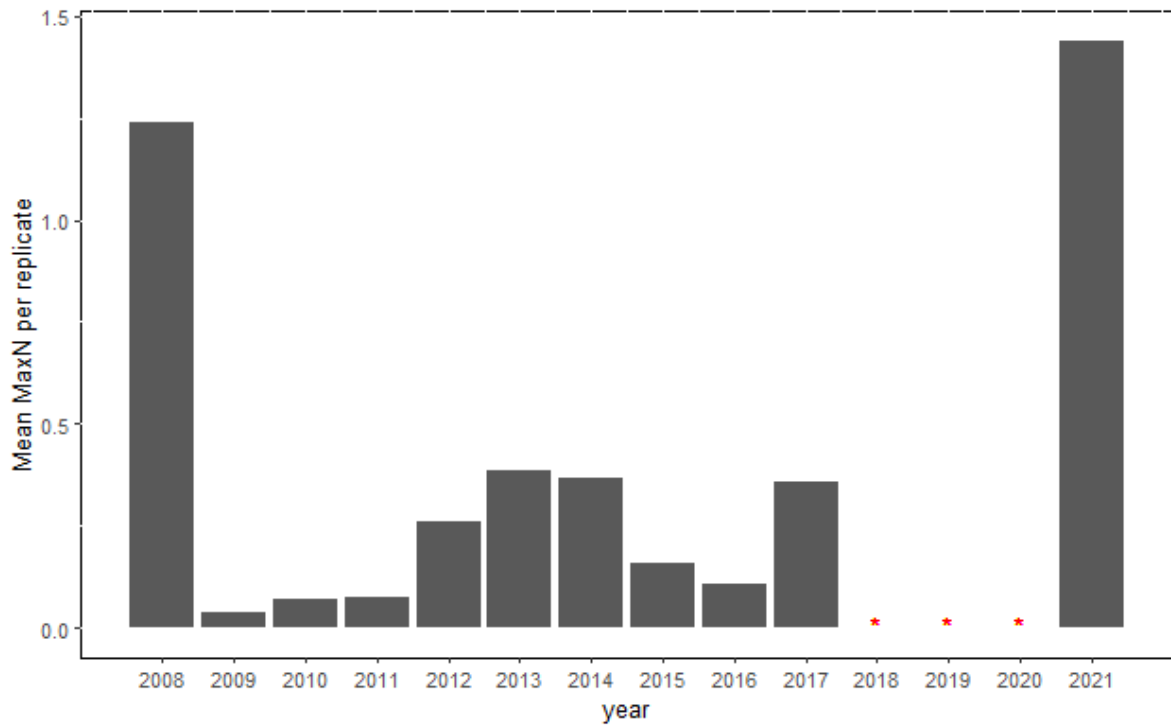


Figure 35. Mean MaxN of snapper per replicate from the annual winter BRUV survey within CS. Data are only presented for the 37 sites that were completed in most years of the survey (Figure 3). Although the survey was carried out from 2018-2020 the videos have not been processed to determine MaxN values (*).

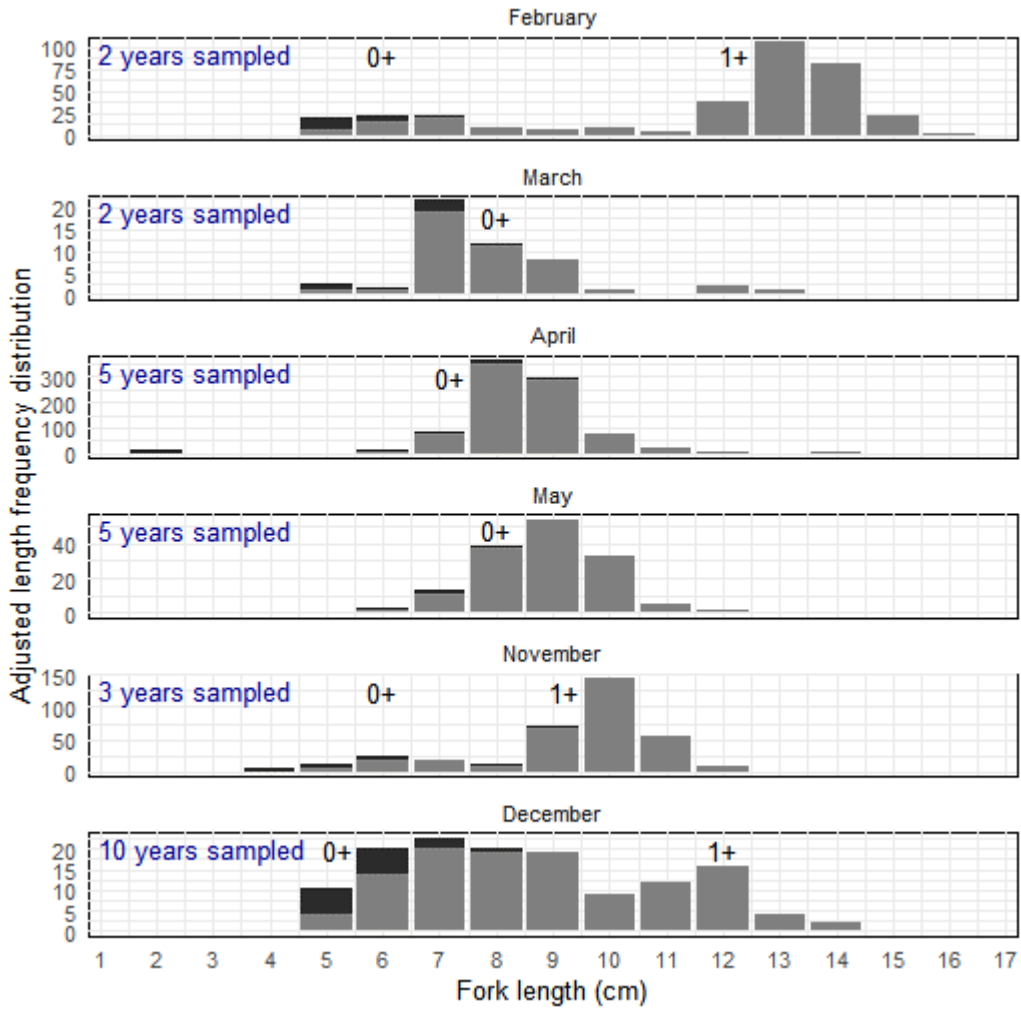


Figure 36. Length frequency distribution of snapper per month, from large otter-trawls in CS pooled across all years. Adjusted length frequency distributions are shown in black accounting for selectivity of the as per Johnston et al. (2008). Separation of the first year (0+) and second year (1+) juveniles are displayed.

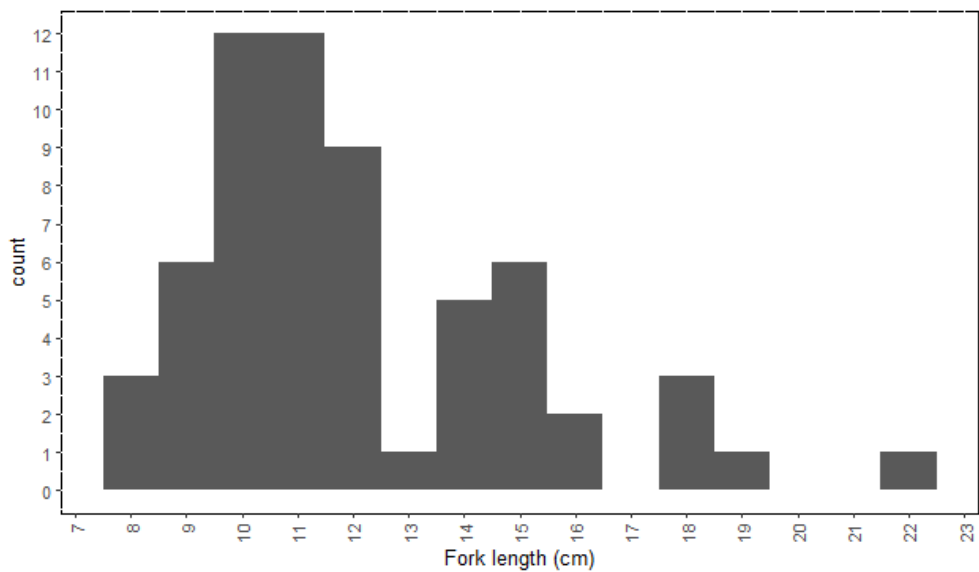


Figure 37. Length frequency distribution of snapper from August 2021 CS BRUVs.

Having split the 0+ and 1+ cohorts from the large trawl data, data were pooled by season (autumn and late spring) and the mean density of snapper, having accounted for swept area, was calculated for each season. An examination of the relationships between the mean snapper density of each cohort and a range of environmental variables during the approximate dates that cohort was spawned was tested using GLMs. However, no significant relationship ($p < 0.05$) was found. The environmental variables tested included the: mean December-January SST, surface salinity, surface chlorophyll-*a*, and DO at the seabed of CS and the total number of days from September-January that were within the optimal spawning temperature (19-21°C; Wakefield 2006). What causes the periodic strong recruitment years for WCB snapper stocks currently remains unknown, as is whether there are links to climate and other environmental conditions. As snapper spend the majority of their lives outside CS, it is possible that successful recruitment years are not dependent on conditions within CS in the first two years of their existence. The links between snapper recruitment and climate or other environmental conditions remains an active area of research within DPIRD.

4.3.4 Rabbitfish

There are two described species of rabbitfish within WA, *Siganus canaliculatus* and *S. fuscescens*, although these may be colour morphs of the same species (Hsu et al. 2011). These species have typically occurred north of the Gascoyne Region, however, during the 2011 MHW juvenile rabbitfish were observed to be recruiting within nearshore waters $\geq 32^{\circ}\text{S}$ (Lenanton et al. 2017). The heatwave produced nearly two years of above average SST within the Perth metropolitan region, including CS (Figure 5, Figure 6 & Figure 7). During this period rabbitfish were observed surviving consecutive winters and establishing a self-recruiting breeding population within CS. Rabbitfish were observed in CS in September-December 2011, as part of the DoF nearshore recruitment survey using beach seines at the Mangles Bay site. Rabbitfish were observed in CS at the Mangles Bay site in subsequent years of the nearshore recruitment surveys until January 2014, and on the BRUV surveys in CS between 2013-2015 (Figure 22).

The first report of rabbitfish in the Perth metropolitan region was from a commercial fisher in the CSFN fishery in the summer of 2011/12. Rabbitfish were then recorded within CAES records in CS for the first time in 2013 (Figure 38). Rabbitfish are predominantly landed in the summer and have continued to be landed each year since 2013, although catches within CS have fallen since the MHW. Recreational fishers also reported catching rabbitfish from January 2012 (Lenanton et al. 2017, Redmap Australia 2023).

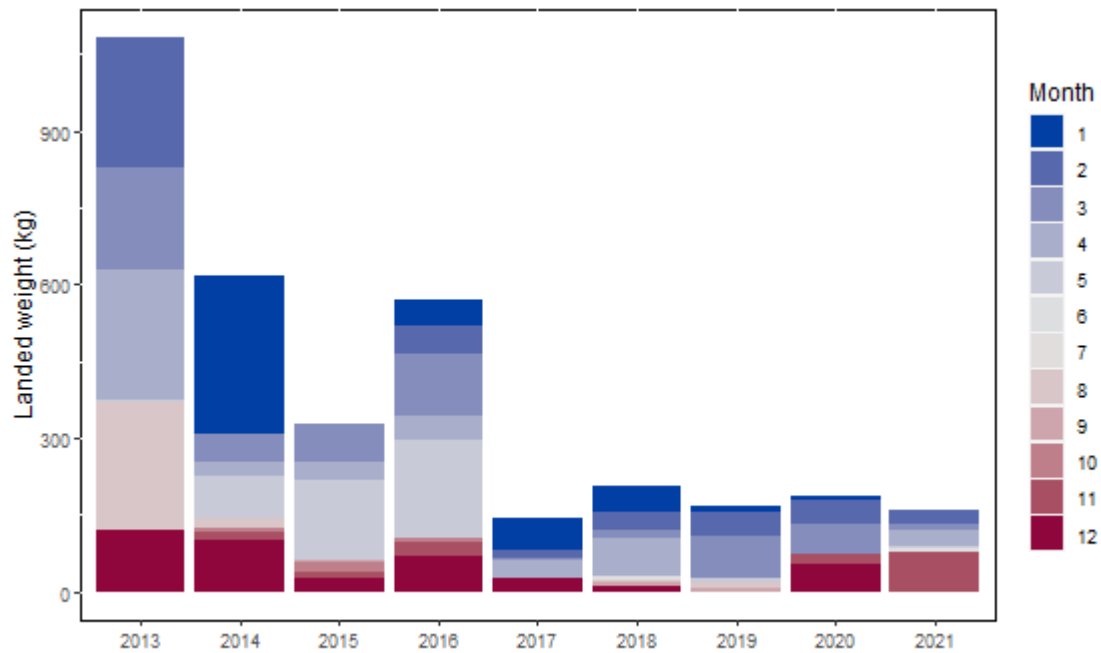


Figure 38. Commercial catches of rabbitfish from CSFN fishery from 2013 to 2021. Data were obtained from CAES data. Prior to 2013 rabbitfish had not been reported in CAES data within CS.

There are a number of other tropical species that have been observed in CS through commercial landings and fisheries-independent data. Sand bass (*Psammoperca* sp.) were regularly reported by a haul net fisher in CS since the 2011 MHW, however, it did not appear in commercial landings due to not being commercially marketed under its common name until 2015 (Lenanton et al. 2017). Sand bass has subsequently been reported in CS CAES data in the summer of 2017/18 and again in 2022/23. This species has also been observed further south in Geographe Bay by DPIRD using BRUVs (Lenanton et al. 2017).

4.3.5 Yellowfin whiting

Yellowfin whiting (*Sillago schomburgkii*) is a temperate marine fish, endemic to south-western Australia. It is a popularly targeted recreational and commercial species for shore-based fishers, occurring in both sheltered sand flats and saline estuaries. Its range extends from Albany to Exmouth, however, within that range a gradual poleward shift in the centre of abundance has been observed since the 1950s which coincides with gradual ocean warming (Smith et al. 2019). Smith et al. (2019) identified the mechanism of this poleward shift to relate to stronger recruitment during extended spawning periods at the southern extent of the range and weaker recruitment at the northern edge due to warming oceans. The species is known to spawn when water temperature is 20-26°C. In the north of the species range that means the yellowfin whiting spawn almost year-round, whereas in the southern extent of the range the spawning period is much shorter. During the 2011 MHW the recruitment was particularly strong in the Perth metropolitan region (especially in the Peel-Harvey Estuary), which resulted in increased catches and catch rates in subsequent years as recruits grew to catchable size (Smith et al. 2019). However, there was only a small increase in total catch of yellowfin whiting (and ‘whittings’) in CS following the MHW (Figure 39).

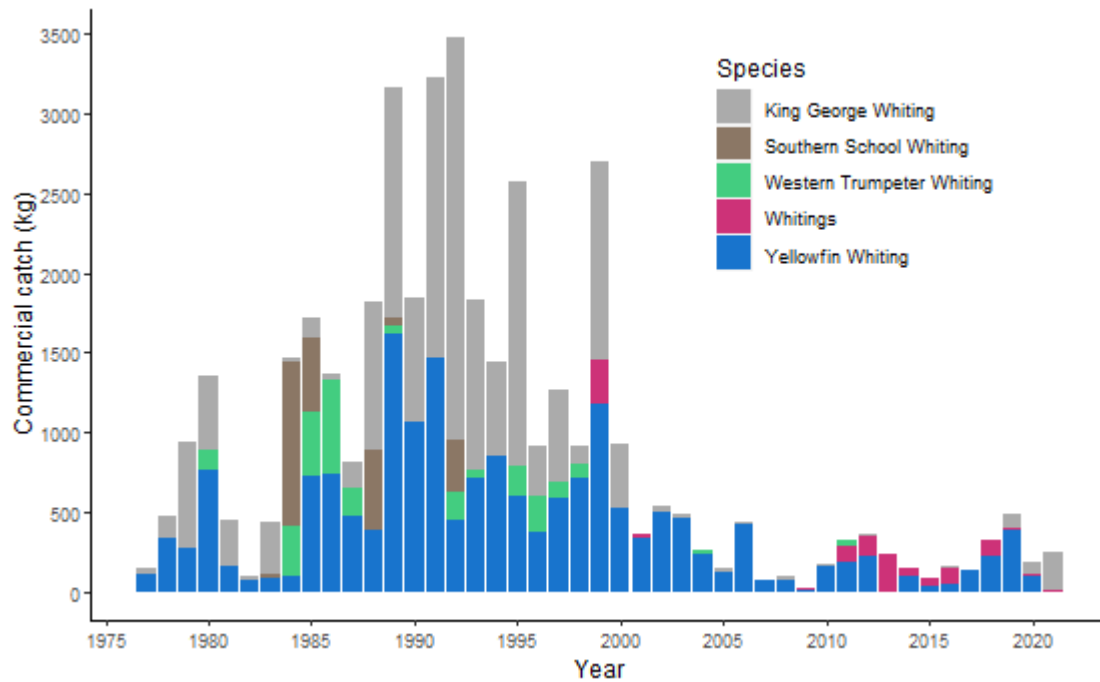


Figure 39. CAES records of annual commercial landings of whiting species caught within CS. The ‘whittings’ class most likely refers to any or a mix of yellowfin whiting, southern school whiting and western trumpeter whiting, which are similar in appearance, particularly when small. Note, in 1987-1988 a single fisher caught an additional ~12 t of yellowfin whiting over six months using a purse seine. Landings from purse seining has not been included in the figure as this method has not been used since 1988.

While yellowfin whiting are present in CS, the evidence indicating whether this species became more abundant following the 2011 MHW is inconclusive. Data from the only nearshore fish recruitment beach seine survey site within CS showed no increased recruitment of yellowfin whiting following the 2011 MHW (Figure 23), although a single site with four replicates provides insufficient data to extrapolate to the entire sound. The recreational monitoring survey data are not available as yellowfin whiting are recorded as a group including multiple whiting species that are similar in appearance. Yellowfin whiting are landed in small numbers by commercial fishers using gill nets, handheld reels and beach seines, although the species is not typically targeted within CS. Over the last 20 years, the total catch of yellowfin whiting within CS has generally been much lower than previous decades (<0.5 t) (Figure 39). As yellowfin whiting, western trumpeter whiting and southern school whiting (*Sillago bassensis*) are all similar in appearance, some fishers listed catch as the non-specific taxon ‘whittings’ rather than specify the species. As commercial fishers do not target this species and the lack of specificity in the CAES data limit the ability to draw meaningful insights from these data.

It is currently too soon to assess whether the recent moderate MHW, which began in 2020, will result in another strong whiting recruitment in southern WA waters.

4.3.6 Southern garfish

Until 2017, CS supported the largest commercial and recreational southern garfish (*Hyporhamphus melanochir*) fishery in WA (Smith et al. 2017). However, following approximately two decades of declines in catch and catch rates, and assessing the weight-of-evidence available, the fishery was closed in 2017 to allow stocks to recover. Commercial catches peaked in 1999 at 38 t and then gradually declined to 10-15 t per year between 2006-2011 (Figure 26). A sharp decline then occurred from 15 t in 2011 to 6 t in 2012 and just 3 t in 2013. Commercial catches continued to decline until the fishery was closed in 2017. It is thought that recreational catch probably exceeded commercial fishing within CS, however, the data supporting this are incomplete (Smith et al., 2017).

Southern garfish are a nearshore, schooling species typically found near seagrass beds. Due to having a relatively small breeding stock size, with low/medium fecundity, poor egg and larval dispersal and strong habitat dependency, they are thought to be particularly vulnerable to overfishing (Smith et al. 2017). Smith et al. (2017) outlined a number of possible causes of the decline of southern garfish in CS. Given the most dramatic decline coincided with the 2011 MHW, this has been suggested as a possible cause of the rapid decline during 2011-2013 (Smith et al., 2017). CS is on the northern edge of the southern garfish range, so it is assumed any long-term rise in summer average SST may be unfavourable to the species. Another potential contributing factor is the decline in shoot density of seagrass (*Posidonia* spp.) within shallow (<5 m) areas of CS. The decline in shoot density has been observed as both a long-term trend (CSMC 2020) and was particularly rapid during the MHW (Caputi et al. 2014). As southern garfish use seagrass beds to reproduce, feed and shelter, any loss of seagrass is likely to negatively impact the stock (Smith et al., 2017). Smith et al. (2017) also identified fishing pressure as a potential contributing factor, however, there have been no surveys of the fishery since the closure to determine whether the stock has been recovering since fishing pressure was removed. The long-term fisheries-independent survey methods utilized in CS (Section 4.2.1) have proven unsuitable for monitoring southern garfish populations as samples from Mangles Bay have only caught southern garfish in six shots over 17 years of sampling and BRUV samples only observed southern garfish in four years of a 11 year time series (all prior to 2013). With commercial fishery data providing the most robust length structure data for monitoring the CS population (Smith et al. 2017), no new data are available to assess whether the species is recovering since the closure of the fishery in 2017.

4.3.7 Sandy sprat (*whitebait*)

The first commercial catches of sandy sprat (*Hyperlophus vittatus*) in CS were in 1969, and commercial catches were consistently reported within CAES from 1978-2009 (Figure 26). In the 1970s the metropolitan sandy sprat fishers came to a 'gentleman's agreement' to only use beach seines and not purse seines (Gaughan et al. 1996), and although a small amount was landed during the 1980s and 1990s with purse seines, beach seining remained the primary fishing method. Annual catches of sandy sprat within CS were relatively small compared with the Bunbury and Warnbro Sound areas. The highest annual catch in CS was in 1982 with 33.3 t, but this was unusual as the next time the total catch exceeded 10 t was in 1987 (11.6 t). During 1987-1994 annual catches were 9-19 t followed by a gradual decrease ever since and no commercial fishing for sandy sprat has occurred in CS since 2009. While the species is no longer targeted within CS, sandy sprat are also an important component of local little penguin diets (Murray et al. 2011), so its abundance is relevant for this iconic species.

The total commercial catch of sandy sprat in WA has declined since the 1990s and early 2000s from over 200 t per year to less than 20 t (Figure 40a). The cause of declining catches is unclear, although climate change is a possible contributor. The lifespan of sandy sprat is only 3-4 years, and evidence suggests that the stocks are strongly driven by recruitment variability (Newman et al. 2021). Considering the entire resource, previous studies have observed a positive relationship between the strength of the Leeuwin Current the previous year and the relative catch of sandy sprat (Caputi et al. 1996, Lenanton et al. 2009). However, since 2008 when Lenanton et al. (2009) updated these analyses, there have been several years of strong Leeuwin Currents, although catches have continued to decline (Figure 40). The relationship observed by Lenanton et al. (2009) was updated to include data to 2022. While there is still a positive relationship between catch residuals and the Fremantle MSL during the previous year, the inclusion of a further 15 years of data weakened the relationship ($R^2 = 0.15$, $F_{(1,43)} = 7.68$, $p < 0.01$). The positive relationship is stronger if the long-term trend of sea level rise (Figure 4) is removed from the lagged Fremantle MSL data (Figure 40; $R^2 = 0.28$, $F_{(1,43)} = 16.1$, $p < 0.001$), suggesting the Leeuwin Current remains an important predictor of sandy sprat population size.

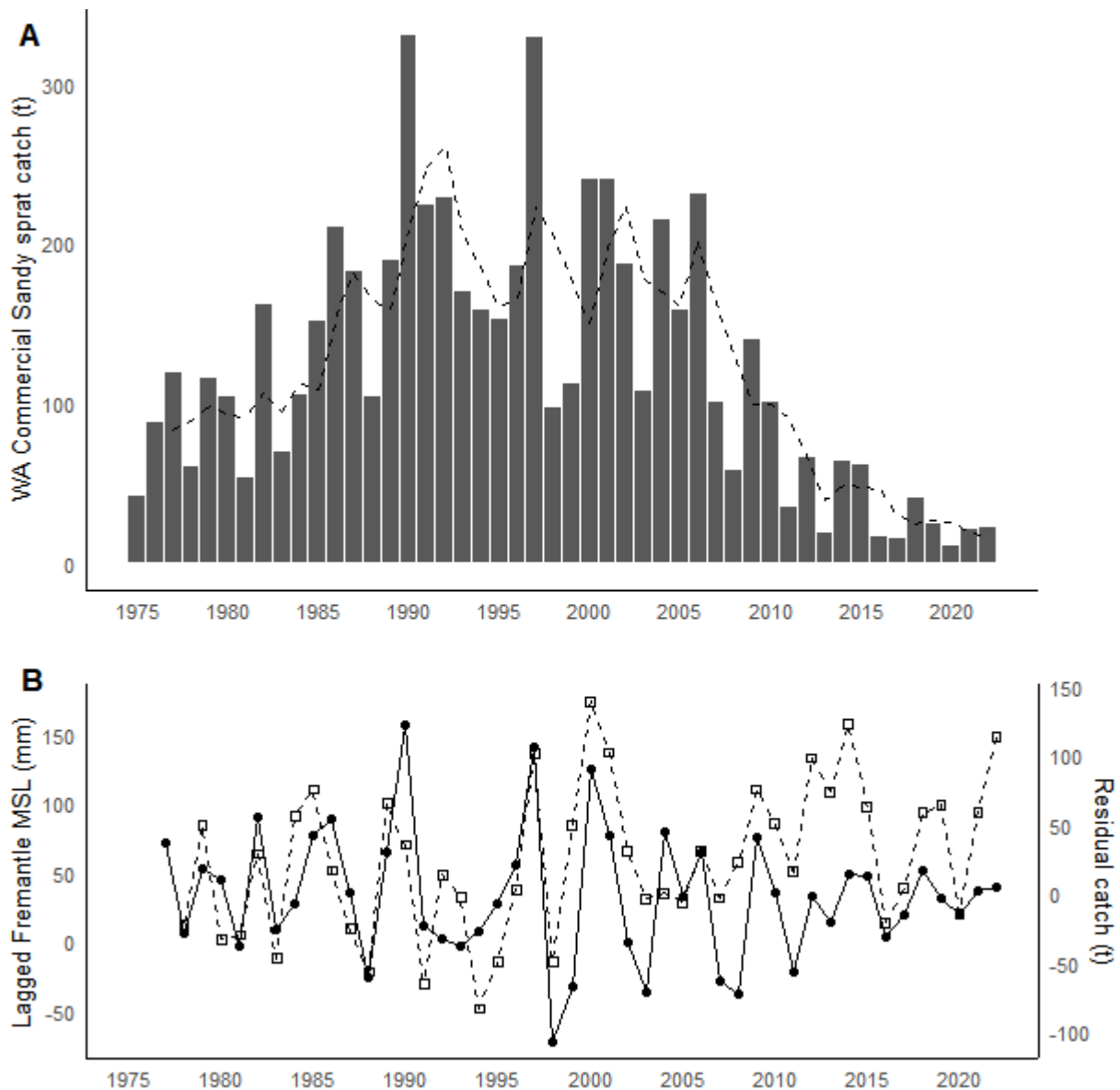


Figure 40. The total annual catch of sandy sprat within WA (Perth to Cape Naturaliste) (A). Dashed line represents the three-year trend. The time series of the residual catch (\bullet), having accounted for the three-year trend plotted against the one-year lagged Leeuwin Current strength (B). Relative current strength based on the Fremantle MSL having removed the long-term sea level rise trend (\square).

The importance of environmental factors on annual sandy sprat catches was also observed by Gaughan et al. (1996) at a finer spatial scale. For the Fremantle region they observed significant correlations between annual catch and rainfall (positive correlation) and lagged Fremantle MSL (positive correlation) during the May-August months in the previous year. The same study also found significant relationships between rainfall and lagged sea level at the other main sandy sprat fishing regions of Warnbro Sound, Mandurah and Bunbury. It was hypothesized that: rainfall would influence the amount of flow through the Swan River, thereby flushing sandy sprat into CS where they can be caught; and Fremantle MSL, as a proxy for Leeuwin Current strength, may be important for spawning and/or retention or survival of larvae and juveniles (Gaughan et al. 1996). However, reanalysis of the annual CS landings data from 1978-2009 (Figure 26) using a linear regression with annual rainfall and one-year lagged Fremantle MSL (from May-August) found no statistically significant correlation ($p > 0.05$). Total annual catch is generally a poor indicator of stock size, especially considering sandy sprat fishers also targeted other species and other areas outside CS at various times of the year. Therefore, it is difficult

to draw conclusions about the importance, or lack thereof, the Leeuwin Current and rainfall on this species specifically within CS without more robust data.

In general, sandy sprat is a poorly understood species within WA. The species range extends to Kalbarri, however Perth represents the most northerly commercial catch region. Although the species stock is classed as ‘unsustainable-inadequate’ the fisheries-independent data being collected are not suitable for assessing this species stock or informing how sandy sprat respond to different environmental conditions.

4.3.8 Redmap species

Redmap (Range Extension Database and Mapping project) compiles and verifies sightings in Australia of out-of-range marine species, observed by members of the public in their local area (Redmap Australia 2023). This project has identified a number of potential range extension species within WA that have had verified sightings within CS (Table 6). This includes two species of finfish which are of commercial and recreational interest in more northerly WA waters: Rankin cod (*Epinephelus multinotatus*) and spangled emperor (*Lethrinus nebulosus*). The 2022 WA Redmap Report Card also identified ten out-of-range species new to the Leeuwin-Naturaliste bioregion (Perth–Point d’Entrecasteaux) (Table 6) (Redmap Australia 2022). Of these ten species, only Rankin cod has been observed within CS. The other nine species have been observed south of CS, which therefore may place CS within the species’ habitable range.

Table 6. List of potential range extension species relevant to CS from Redmap (Redmap Australia 2023). This list of species includes those that were observed within CS, and those which are new to the Leeuwin-Naturaliste bioregion but have been observed south of CS.

Potential range extension species observed within CS	Potential range extension species new to the Leeuwin-Naturaliste bioregion listed in the 2022 WA Report Card (Redmap Australia 2022)
<p>Finfish</p> <p>Common lionfish (<i>Pterois volitans</i>)</p> <p>Greyface moray (<i>Gymnothorax thyrsoideus</i>)</p> <p>Highfin moray (<i>Gymnothorax pseudothyrsoideus</i>)</p> <p>Manyspot blenny (<i>Laiphognathus multimaculatus</i>)</p> <p>Ocellate butterflyfish (<i>Parachaetodon ocellatus</i>)</p> <p>Rankin cod (<i>Epinephelus multinotatus</i>)</p> <p>Schooling bannerfish (<i>Heniochus diphruetes</i>)</p> <p>Spangled emperor (<i>Lethrinus nebulosus</i>)</p> <p>Spotfin porcupinefish (<i>Chilomycterus reticulatus</i>)</p> <p>Spotfin tongue sole (<i>Cynoglossus maculippinis</i>)</p> <p>Stars-and-stripes puffer (<i>Arothron hispidus</i>)</p> <p>Whitebarred goby (<i>Amblygobius phalaena</i>)</p> <p>Invertebrates</p> <p>Ghost crab (<i>Ocypode cordimana</i>)</p> <p><i>Uroteuthis</i> (Photololigo) sp.</p>	<p>Finfish</p> <p>Barred soapfish (<i>Diploprion bifasciatum</i>)</p> <p>Longnose trevally (<i>Platyaranx chrysophrys</i>)</p> <p>Moorish idol (<i>Zanclus cornutus</i>)</p> <p>Ocellate butterflyfish (<i>Parachaetodon ocellatus</i>)</p> <p>Red emperor (<i>Lutjanus sebae</i>)</p> <p>Shark mackerel (<i>Grammatorcynus bicarinatus</i>)</p> <p>Stout moray (<i>Gymnothorax eurostus</i>)</p> <p>Yellowtail angelfish (<i>Chaetodontoplus personifer</i>)</p> <p>Invertebrates</p> <p>Giant mud crab (<i>Scylla serrata</i>)</p>

4.3.9 Little penguin

Cockburn Sound is an important foraging area for little penguin (*Eudyptula minor*) from the Garden Island and Penguin Island colonies (Cannell 2018). However, as little penguin monitoring has been continuously carried out at these two colonies for over 20 years, no time series datasets were available that directly relate to CS. The Garden and Penguin Island colonies are the most northerly little penguin colony and are towards the limit of the species' environmental tolerance (Murray et al. 2011). Analysis of the relationship between SST and breeding success found that higher SST pre-breeding, in April and May, correlate with lower breeding success (Cannell et al. 2012). In fact, the 2011 season, which was during a prolonged MHW, was the lowest breeding success on record for Penguin Island. Both the number of eggs laid and percentage of eggs that made it to fledglings dropped substantially in 2011 (Caputi et al. 2014). The heatwave also resulted in four times the normal number of dead penguins found from August-December 2011, with necropsies identifying starvation as a common cause of death. Cannell et al. (2023) showed that the 1999 and 2011 MHWs both negatively impacted the little penguin colony on Penguin Island. Following these MHWs the breeding participation rate, breeding success, and population size all decreased while the mortality due to starvation increased. The effects of a poor breeding season on the colonies' population continue to be observed over the subsequent three years, as that impacted cohort would have reached maturity and returned to the colony (Cannell et al. 2023). During the MHW, the diet composition also changed with scaly mackerel replacing sandy sprat as the main prey component, and Cannell et al. (2023) hypothesized that this change in diet may have contributed to mortalities caused by novel protozoal parasitic infections which were observed in 2011-2012. The penguins' body condition and breeding success are highly sensitive to fish availability, with breeding pairs extending foraging ranges when prey is limited in supply (Cannell et al. 2012, Cannell 2018). Therefore, climate change associated impacts on prey species (e.g. sandy sprat and southern garfish discussed in previous case studies) are potentially important for little penguins. The net result of these MHWs, and a range of other pressures impacting the Penguin Island colony (e.g. Cannell et al. 2016), has been a decrease in the austral spring population of 80% on Penguin Island (Cannell et al. 2023).

Little penguins are also susceptible to high summer air temperatures. Ambient air temperatures >30°C can induce heat stress (Horne 2010), particularly in incubating penguins, and temperatures >35°C can lead to hyperthermia (Clitheroe 2021). On hot days penguins pant and will go back and forth from the nests to the shoreline during the day to cool off, and for this reason Penguin Island is closed when the daily maximum temperature is expected to exceed 35°C. Still, summers with prolonged high temperatures have been identified as a cause of increased penguin mortality (Cannell et al. 2023). Higher air temperatures and an increased frequency of extreme events are likely to cause additional periods of heat stress for nesting little penguins. Further, climate change is likely to increase the incidence and severity of fires in Australia (Enright & Fontaine 2014). A fire in the immediate vicinity of a colony would pose an immediate risk, while also the loss of vegetation could result in an area no longer being suitable for nesting (Horne 2010), given the role vegetation plays in thermoregulation for natural burrows and nest boxes (Clitheroe 2021).

4.3.10 Australian sea lions

Within the Perth metropolitan region there are six regularly occupied haulout sites for Australian sea lions (*Neophoca cinerea*), of which Carnac Island constitutes 30% of the total metropolitan population (Salgado Kent & D'Cruz 2021). Prior to the 1900s when commercial harvesting and culling of sea lions began, the Perth region was thought to have breeding colonies whereas today only haulout sites remain (Campbell 2005). Monthly monitoring of the Perth metropolitan population by the WA Department of Biodiversity, Conservation and Attractions has found no trend in overall populations between January 2015 and March 2021 (Salgado Kent & D'Cruz 2021). However, there has been a decrease in the number of haulouts on the closest haulout site to CS (Carnac Island). The increased frequency of human-seal interactions on Carnac Island, where vessel landing is permitted, relative to other metropolitan sites has been documented (Osterrieder et al. 2017). For example, Seal Island,

which is also in close proximity to CS, is within the highly protected Shoalwater Islands Marine Park. These human-seal interactions are likely to be the cause of the decrease in haulouts at Carnac Island, and further management measures have been proposed to combat this (Kent & Crabtree 2008, Osterrieder et al. 2017, Salgado Kent & D’Cruz 2021). While climate change has been identified as a possible contributing factor limiting the recovery of Australian sea lions at a national level (DSEWPC 2013), the trends within the Perth metropolitan populations are generally attributed to other anthropogenic factors.

4.3.11 Indo-Pacific bottlenose dolphin

Within the Perth metropolitan region, the Indo-Pacific bottlenose dolphin (*Tursiops aduncus*) population is spatially structured, with CS supporting resident dolphins which are generally distinct from the dolphins north of Gage Roads or those in the Swan-Canning Estuary (Chabanne et al. 2017). Population numbers in CS were estimated in two studies between 1993-1997 and then 2011-2015 and were generally stable (Finn 2005, Chabanne et al. 2017), however, with such a limited time series there are insufficient data to relate to changes in environmental conditions.

While not specific to the Perth metropolitan population, there are examples of dolphins changing their behaviour or being impacted by previous temporary climate events elsewhere in WA. During the 2009 strong El Niño event there was a rapid decline in the abundance of Bunbury resident dolphins, which temporarily emigrated offshore (Sprogis et al. 2018). As the Leeuwin Current is weaker during El Niño events and the SSTs are lower than normal, the authors hypothesised that with lower productivity the dolphins had to search more extensively for adequate prey. However, this six-year study also observed no negative impact of warmer and stronger Leeuwin Current La Niña years. Following the 2011 MHW a long-term monitoring study in Shark Bay (~800 km north of CS) observed a substantial decrease in bottlenose dolphin survival and reproductive rates (Wild et al. 2019). The study determined that survival rates remained lower than average for seven years after the heatwave, potentially due to considerable seagrass loss (~36% of seagrass meadows in Shark Bay were damaged) (Wild et al. 2019, Strydom et al. 2020). Wild et al. (2019) showed that climate change related impacts to the habitats and prey that dolphins utilise can in turn, negatively impact the dolphin populations. While Shark Bay is considerably warmer than CS, MHWs have also caused seagrasses loss in CS (Section 4.1.5), so its possible bottlenose dolphins may be equally sensitive within CS to loss of important habitats caused by climate change.

4.4 Climate change modelling projections downscaled to the coastal environment.

Data from the WWMSA project *Provision of multi-decadal ocean boundary conditions and field measurements* provided open ocean boundary conditions for 2000-2020 and future climate scenarios (to 2100) under two Shared Socioeconomic Pathways (SSP) emission scenarios: (i) SSP2 which assumed historical patterns of development; and (ii) SSP5 assumed a ‘high’ emission scenario.

The time series of temperature and salinity from CS over the simulation period (2000-2022) observed the 2011 extreme MHW had a maximum water temperature of 27.03°C, with elevated water temperatures continuing until 2014. There was also a salinity minimum (34.8 ‰) associated with this event. The minimum temperature occurred in 2016 (15.0°C) which was the start of a 4-year marine cold spell (Feng et al. 2021).

The SST predictions to 2100 indicate that the rate of SST increase is estimated to be 0.015 and 0.031°C per annum, under SSP2 and SSP5, respectively. However, as the modelling predicts no major changes in salinity or wind climate it is probable that coastal currents will be relatively unchanged.

4.5 Risk assessment of the effects of climate change on the key biota

The climate change risk assessment of 14 fisheries species and five species which are iconic to the Perth region identified sandy sprat, little penguin, Australian sardine and southern garfish as those at severe risk of being negatively impacted by climate change within CS (Table 7 & Appendix 2). Sensitivity

scores were based on species traits, while exposure scores were based on factors such as: the species current range (Figure 41 & Figure 42); published climate related impacts on the species from elsewhere in WA (Table 8) and globally; and consultation with relevant DPIRD and external experts. The predicted climate change associated impacts on each species within CS are summarised in Table 8. Some species that were ranked as severe or high risk are near the northern edge of their range in CS (e.g. sandy sprat, southern garfish and little penguins; Figure 41 & Figure 42). Should warmer temperatures cause a range contraction, this could cause breeding failure, abundance to be reduced or the species to temporarily leave CS.

Table 7. Climate change risk scores for a range of key fishery and iconic species within CS. The full scorecards with accompanying confidence levels and justifications are presented in Appendix 2. Species have been ordered based on overall risk score. Final risk rankings based on Table 4.

Species	Sensitivity score	Sensitivity rank	Exposure score	Overall risk score	Risk rank
Sandy sprat (<i>Hyperlophus vittatus</i>)	8.77	5	4	20	Severe
Little penguin (<i>Eudyptula minor</i>)	8.55	5	4	20	
Australian sardine (<i>Sardinops sagax</i>)	8.37	5	4	20	
Southern garfish (<i>Hyporhamphus melanochir</i>)	7.35	4	4	16	
Snapper (<i>Pagurus auratus</i>)	7.35	4	3	12	High
King George whiting (<i>Sillaginodes punctata</i>)	7.1	3	4	12	
Australian herring (<i>Arripis georgianus</i>)	7.23	3	3	9	Medium
Blue swimmer crab (<i>Portunus armatus</i>)	7.77	4	2	8	
West Australian seahorse (<i>Hippocampus subelongatus</i>)	7.68	4	2	8	
Spotted pipefish (<i>Stigmatopora argus</i>)	7.35	3	2	6	
Australian sea lion (<i>Neophoca cinerea</i>)	6.91	2	3	6	
Southern calamari (<i>Sepioteuthis australis</i>)	6.65	2	3	6	
Western king prawn (<i>Penaeus latisulcatus</i>)	8.25	5	1	5	
Tailor (<i>Pomamtomus saltatrix</i>)	6.62	2	2	4	Low
Sea mullet (<i>Mugil cephalus</i>)	6.95	3	1	3	
Indo-Pacific bottlenose dolphin (<i>Tursiops aduncus</i>)	6.58	1	3	3	
Scaly mackerel (<i>Sardinella lemuru</i>)	6.7	2	1	2	Negligible
Western rock octopus (<i>Octopus djinda</i>)	6.53	1	1	1	
Yellowfin whiting (<i>Sillago schomburgkii</i>)	6.45	1	1	1	

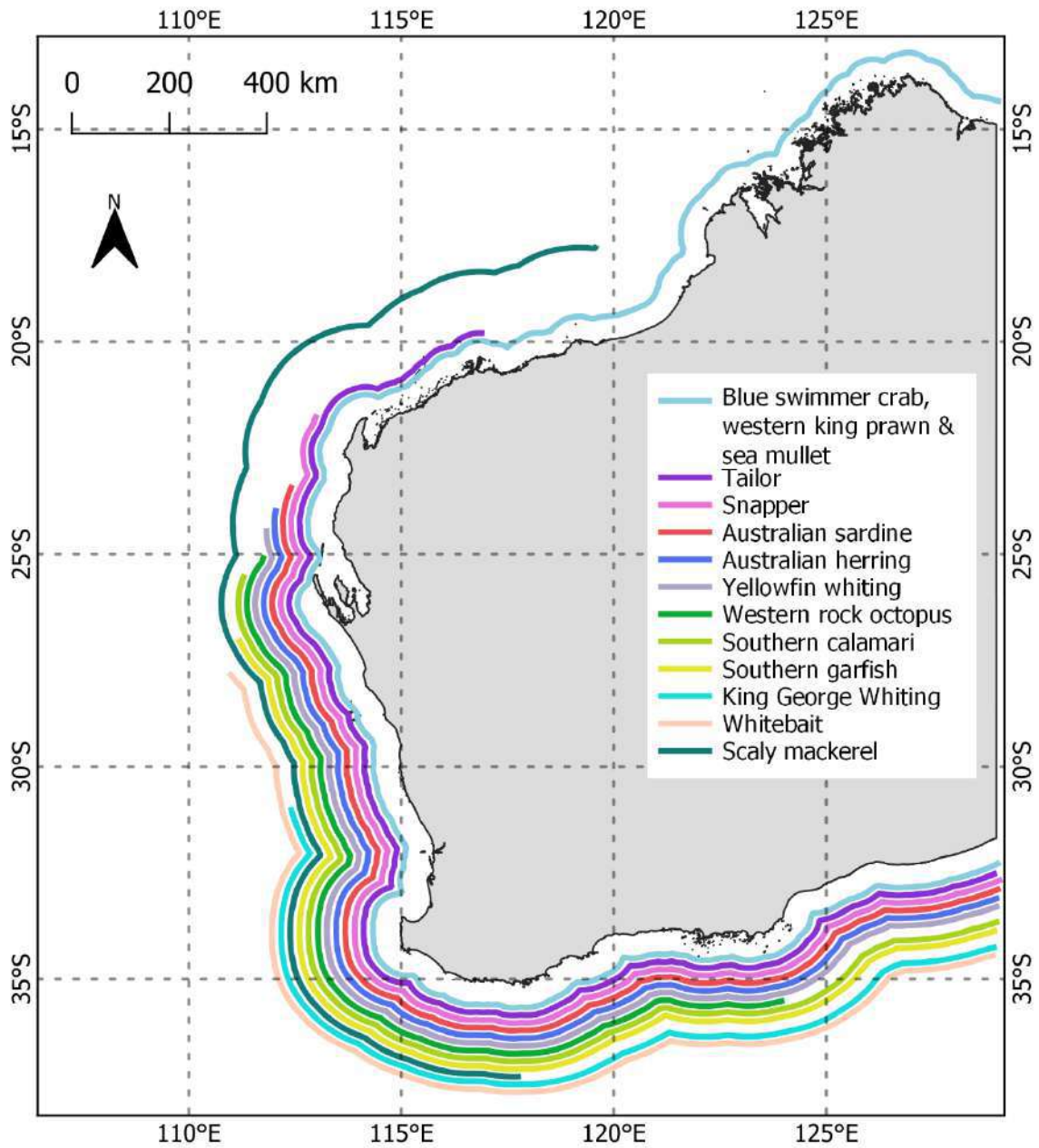


Figure 41. Approximate ranges within WA of key fisheries species assessed in Section 4.5. Extents were downloaded from the CSIRO Fishmap database (CSIRO 2023).

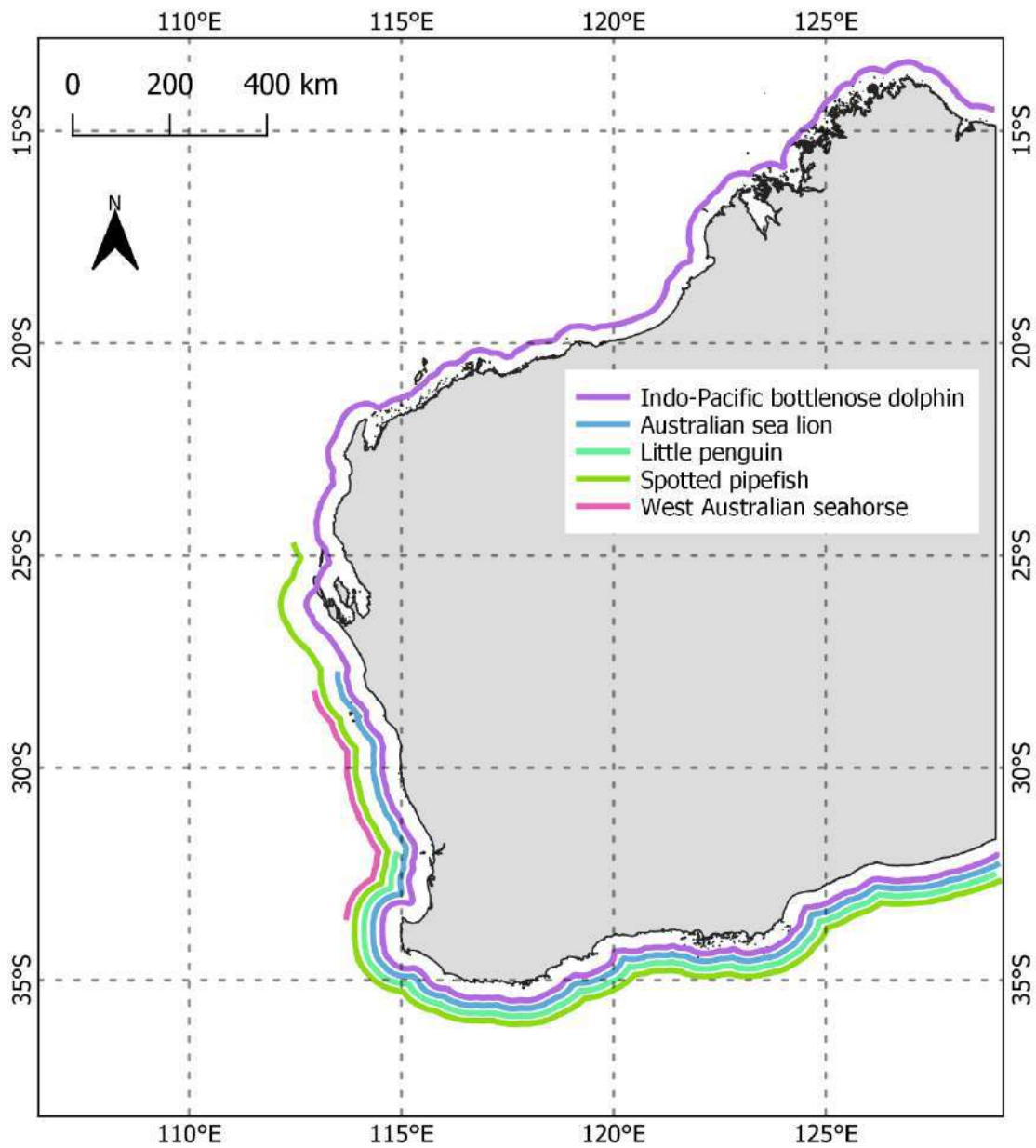


Figure 42. Approximate ranges within WA of iconic species assessed in Section 4.5. Extents were downloaded from the CSIRO Fishmap database (CSIRO 2023), the Species Profile and Threats Database (<https://www.environment.gov.au/cqi-bin/sprat/public/sprat.pl>).

Table 8. Summary of previously observed impacts of climate change to the species within WA, and CS specific predicted impacts of climate change. Species have been ordered based on overall risk score.

Species	Current WA climate change impacts	Predicted CS specific climate change impacts
Risk rank: Severe		
Sandy sprat	<ul style="list-style-type: none"> • Positive relationship between strength of the Leeuwin Current the previous year and relative catch of sandy sprat (Caputi et al., 1996; Lenanton et al., 2009). • Based on the small number of locations still supporting sandy sprat, the species is thought to have undergone a dramatic range contraction in WA. 	<ul style="list-style-type: none"> • There are limited data available, however based on commercial data the species appears to be less prevalent north of CS, and the metropolitan stock is listed as environmentally limited. • It is possible a weakening Leeuwin Current could reduce recruitment in CS. • Reduced rainfall may also result in less sandy sprat being flushed into CS from the Swan-Canning Estuary system.
Little penguins	<ul style="list-style-type: none"> • MHWs impacted the Penguin Island breeding colony by: reducing breeding participation, reducing breeding success, causing starvation and altering diet composition (Cannell et al. 2023). • Penguin Island breeding colony had lowest success rate during 2011 MHW (Cannell et al. 2012, 2023). • Increased mortality of Penguin Island penguins during prolonged high temperature events (Cannell et al. 2011). • Increased SST in April and May correlate with lower breeding success later that year (Cannell et al. 2012). • The presence of a novel protozoal parasite following the 2011 MHW may have been introduced by the changed diet (Cannell et al. 2023). 	<ul style="list-style-type: none"> • Garden Island and Penguin Island colonies are at northern and physiological limit of species extent (Figure 42). Further warming and increased frequency of MHWs will negatively impact the species, increasing mortality, decreasing number of eggs laid and percentage of eggs surviving to fledglings. • Ambient air temperatures >30°C can lead to heat stress (Clitheroe 2021), and hyperthermia caused by consecutive days >35°C (Cannell et al. 2016). Both of which are common already in Perth and it is likely this cause of mortality may increase in frequency in the future. • The species is also highly sensitive to fish availability, having to expend more energy to forage or switching diets when preferred diet is not available. It is likely that modified fish recruitments and distributions may in turn affect little penguins that forage within CS.
Australian sardine	<ul style="list-style-type: none"> • Anecdotal reports of catch composition changing to the more tropical scaly mackerel species which is attributed to warmer SST (Caputi et al. 2015b). 	<ul style="list-style-type: none"> • CS is near the northern limit of this species' range (Figure 41), and it is likely Australian sardines will become less abundant in WCB including CS, with this species' niche potentially filled by the tropical scaly mackerel (Caputi et al. 2015b). • Spawning has been linked to water temperatures of 14-21°C (Caputi et al. 2015b), which may restrict the spawning season in Perth metropolitan region in future.

Southern garfish	<ul style="list-style-type: none"> • Long-term rise in summer SST and the 2011 MHW in particular, thought to negatively impact stocks in CS (Smith et al. 2017). 	<ul style="list-style-type: none"> • Based on past events the stock in CS appears to be sensitive to MHWs and rising SST. Projected warming is likely to negatively impact the stocks. • The species is also reliant on seagrass for egg development, so further seagrass die-off associated with MHWs may negatively impact recruitment.
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Risk rank: High

Snapper	<ul style="list-style-type: none"> • Significant snapper mortalities observed in Shark Bay during the 2011 MHW where SST approached the species lethal limit (32°C) (Caputi et al. 2015b). • Snapper is a warm-temperate species, and adaptable to wide range of environmental conditions. Most climate change impacts anticipated to occur at the northern (Gascoyne Region) and southern limits of its range (Caputi et al. 2015b). • During the coolest spring-summer in 40 years, snapper did not spawn in 2005 on the south coast of WA (Wakefield et al. 2015). 	<ul style="list-style-type: none"> • As there is a strong relationship between snapper spawning activity and water temperature (Wakefield et al. 2015), it is possible that warming SST may alter how the species uses CS as a spawning and nursery site. For example, by changing the spawning period.
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King George whiting	<ul style="list-style-type: none"> • The species exhibited strong recruitment in Mangles Bay in 1999, 2000 and 2008 which were years of strong Leeuwin Current (Brown et al. 2013). 	<ul style="list-style-type: none"> • Predicted weakening of the Leeuwin Current may negatively impact recruitment of this species within CS. • As the species is reliant on seagrass as nursery habitat, it is possible that further seagrass loss associated with MHWs could impact this species. • As CS is near the northern limit of the species range (Figure 41), the species may also be susceptible to increasing water temperature.
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Risk rank: Medium

Australian herring	<ul style="list-style-type: none"> • Stock-recruitment-environment relationship showed increased recruitment during warming conditions (Duffy et al. 2021), suggesting the species may initially benefit from gradual warming associated with climate change. • 2011 MHW observed to negatively impact recruitment or alter migrations (Smith et al. 2013). 	<ul style="list-style-type: none"> • Conflicting lines of evidence which may reflect different responses of Australian herring stocks to a gradual warming, which may be beneficial, as opposed to acute events (such as MHWs and strengthening currents) which are likely to negatively impact the species. • Increasing frequency of MHWs may negatively impact Australian herring populations.
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	<ul style="list-style-type: none"> • Variation in the strength of the Leeuwin Current is believed to influence the distribution of juveniles and adult spawning stock (Caputi et al. 2015b). 	<ul style="list-style-type: none"> • The species is found over a wide latitudinal and temperature range with CS in the northern half of the range. Reduced adult stock abundance in the WCB is likely, including CS (Caputi et al. 2015b).
Blue swimmer crab	<ul style="list-style-type: none"> • Increased summer SST has negative effect in Shark Bay (Chandrapavan et al., 2019) and a positive effect on south coast. • Warmer SST years in CS have elevated recruitment (Johnston et al. 2020). 	<ul style="list-style-type: none"> • Warmer SST could improve recruitment in CS (Caputi et al. 2015b). • Decreased rainfall may reduce the number of crabs flushed from the Swan River into CS (Caputi et al. 2015b). • MHW induced seagrass loss could reduce available habitat for juveniles, reduce recruitment and reduce prey species (Caputi et al. 2015b).
West Australian seahorse	<ul style="list-style-type: none"> • No data available. 	<ul style="list-style-type: none"> • May be susceptible to changes in habitat (e.g. loss, reduced canopy density or change of seagrass type as a result of MHWs), however West Australian seahorses use a range of other habitats and artificial structures. • Unlikely to be sensitive to increasing SST, however, little is known about the tolerances of the species. • The West Australian seahorse are highly specialised feeders (Kendrick & Hyndes 2005), which may have limited capacity to change feeding habits if climate change affects prey species. • Should climate change negatively impact the West Australian seahorse population in CS, this could have a disproportionately high impact on the species, considering CS and Swan River supports the largest known populations of this species.
Spotted pipefish	<ul style="list-style-type: none"> • No data available. 	<ul style="list-style-type: none"> • May be susceptible to changes in habitat (e.g. loss or change of seagrass during MHWs), however, given the short life cycle and early maturation this species is well suited to recolonization as seagrass habitats recover. • The spotted pipefish are highly specialised feeders (Kendrick & Hyndes 2005), which may have limited capacity to change feeding habits if climate change affects prey species.
Southern calamari	<ul style="list-style-type: none"> • Weak positive relationship between CPUE of squid (predominantly southern calamari) and temperature in the SCB and WCB (Yeoh et al. 2021). 	<ul style="list-style-type: none"> • Limited information is available. • The species metabolism may be limited in water temperatures >22°C (Fuentes 2021), which CS already exceeds during the summer months (Figure 5). Therefore, it is possible the

	<ul style="list-style-type: none"> • Metabolism may be limited in temperatures above 22°C (Fuentes 2021). 	<p>higher water temperatures within CS may negatively impact CS squid populations or displace squid to outside CS during warmer months.</p> <ul style="list-style-type: none"> • Seagrass, which is used by the species for egg development, has also been susceptible to MHW related die-off.
Australian sea lions	<ul style="list-style-type: none"> • Long-term population reductions in Abrolhos Islands, possibly linked to increasing water temperatures over last 200 years (Campbell 2005). 	<ul style="list-style-type: none"> • Limited data, but species is susceptible to changes in food webs and prey availability (Goldsworthy et al. 2021), which may change in the future in CS. • Climate change impacts on the Jurien Bay breeding colony, such as increased ambient air temperatures causing heat stress on pups and reduced breeding space due to sea level rise may impact population and reduce the number of sea lions in the CS region.
Western king prawn	<ul style="list-style-type: none"> • Positive relationship between SST and recruitment in Shark Bay but in Exmouth (where temperatures are >2°C) there was a negative relationship with SST (Caputi et al. 2016). • In northern prawn fisheries, increased water temperatures decrease penaeid growth and survival (Hobday et al. 2008). • Seagrass cover important for some penaeid stocks (Hobday et al. 2008). 	<ul style="list-style-type: none"> • Temperature increase unlikely to negatively affect western king prawn in CS given the range of the species and may have a positive effect.
Risk rank: Low		
Tailor	<ul style="list-style-type: none"> • Limited information available. 	<ul style="list-style-type: none"> • Limited data. • It is possible a weakening Leeuwin Current may impact recruitment within CS, although it is difficult to predict what changes the impacts of climate change will be for this species.
Sea mullet	<ul style="list-style-type: none"> • Timing of migration along WCB shifted by 1-2 months later since 1970s, coinciding with delay in onset of cool season (Duffy et al. 2022). • Possible evidence of a southward range shift from Gascoyne Coast Bioregion to WCB following 2011 MHW (Duffy et al. 2022), although this could be explained by other factors such as market fluctuations 	<ul style="list-style-type: none"> • Limited data, although the species is generally considered to tolerate a wide range of salinity and temperature conditions. Based on the extensive global distribution of this species and known tolerance levels its unlikely climate change will negatively impact the species within CS.

	and fisheries targeting different species.	
Indo-pacific bottlenose dolphins	<ul style="list-style-type: none"> • Long term decrease in survival and reproduction rates in Shark Bay following 2011 MHW due to loss of important seagrass habitats (Wild et al. 2019). • Bottlenose dolphins in Bunbury temporarily emigrated when prey became less available during an El Niño event (Sprogis et al. 2018). 	<ul style="list-style-type: none"> • Possibility that CS bottlenose dolphin population will be negatively impacted by changes to prey and habitat availability which both may be sensitive to climate change.
Risk rank: Negligible risk		
Scaly mackerel	<ul style="list-style-type: none"> • Anecdotal reports of catch composition changing to the more tropical scaly mackerel species which is attributed to warmer SST (Caputi et al. 2015b). 	<ul style="list-style-type: none"> • The species is more widely distributed north of CS (Figure 41), and it is possible the abundance of scaly mackerel will increase in the WCB, including CS, and displace Australian sardine (Caputi et al. 2015b).
Western rock octopus	<ul style="list-style-type: none"> • Octopus were larger in the Perth area during the 2011 MHW than in all subsequent years (A. Hart, DPIRD, <i>unpublished data</i>). • A negative relationship has been observed between SST and the intensity of octopus predation on Western rock lobsters (S. de Lestang, DPIRD, <i>unpublished data</i>). Potentially indicating, more octopus or more active octopus during cooler years. 	<ul style="list-style-type: none"> • As ecological opportunists with broad larval dispersal, high fecundity and fast growth the species may be resilient to the impacts of climate change.
Yellowfin whiting	<ul style="list-style-type: none"> • Gradual poleward shift in centre of abundance since 1950 which has been attributed to rising water temperatures. Long-term rises in abundance in Peel-Harvey Estuary and Swan-Canning Estuary have been observed (Smith et al. 2019). • Very strong recruitment in WCB in years following 2011 MHW (Duffy et al. 2022). • Increased self-recruitment in more southern populations associated with higher temperatures and longer spawning season (Smith et al. 2019). 	<ul style="list-style-type: none"> • Likely to increase in abundance within CS as warmer temperatures extend the spawning period within Perth metropolitan region.

A factor that was raised for many species was their reliance on specific habitats or prey, which may decrease in the future under climate change. For example, the impact of the 2011 MHW on seagrass in CS was well documented and given MHWs are likely to become more frequent and intense its likely further shocks will occur and in turn potentially impact species reliant on these. For example, both blue swimmer crab and Indo-Pacific bottlenose dolphins are species which also utilise seagrass habitats in CS while having ranges that extend into the tropics (Figure 41 & Figure 42). So, while the species itself may not be sensitive to increasing SST or MHWs, and in the case of blue swimmer crab warmer waters may enhance recruitment (Johnston et al. 2020), climate change impacts to important habitats within CS may still negatively impact the species. Likewise, little penguins have been observed to have increased mortality during warm years, linked to both reduced prey availability (Cannell et al. 2023) and hyperthermia due to ambient air temperatures (Cannell et al. 2016).

Climate change is likely to cause a poleward expansion or contraction for many species. However, this study has assessed the risk of climate change on species within a relatively small geographic area, within which some species may arrive (see case study 4.3.8 Redmap species), while others may become less abundant (such as those ranked as Severe and High risk). Given the importance of CS economically, recreationally, and to a lesser extent as a commercial fishery, the risk assessment approach can help to identify which species are more at risk within CS to prioritize further research or target management. However, it is also worth acknowledging that while some species within CS may be at risk from climate change, species at the southern extent of their range conditions may become more abundant, and the stock as a whole may remain healthy.

Climate change is likely to influence when certain species are present in CS. Given the limited exchange of water with the surrounding ocean, the conditions within CS can differ from inside compared to outside. In particular, during summer CS can be warmer and have lower oxygen than the surrounding ocean. It is therefore possible that the timing may change of when some species, like southern calamari and snapper, are present within CS, but the stock overall may not be affected. For example, the metabolism of southern calamari appears to be limited in water temperatures $>22^{\circ}\text{C}$ (Fuentes 2021), so it is possible that squid may move out of CS to cooler conditions during the warmest months.

The fisheries species included in the risk assessment were based on those that have historically been targeted within CS and have reasonable information, in terms of both knowledge of their biological traits and how the species has responded to changing environmental conditions. However, fourteen species is a subset of those historically targeted by commercial fishers in CS (Figure 26). Changes in prey abundance were identified as a potentially important factor in several species' exposure scores, and therefore understanding how a broader range of species may respond to climate change would be beneficial, particularly for prey species of higher trophic level animals (e.g. little penguins, Australian sea lions and Indo-Pacific bottlenose dolphins). As is evident from the available time series data (Section 4.2) and species specific case studies (Section 4.3), there only exists a limited number of time series within CS from which to gain these long-term insights.

Within WA the 2011 MHW caused a broad range of visible and widespread changes to the marine environment, prompting many publications about how climate change is impacting WA's marine ecosystems (e.g. Caputi et al. 2014, Lenanton et al. 2017, Smith et al. 2019, Wild et al. 2019). The acute impacts of this event caused many of the species' responses detailed in Table 8. There is a potential distinction between these acute and episodic events and the more gradual changes associated with climate change. For instance, years of warmer SST in CS have resulted in elevated recruitment of blue swimmer crabs (Johnston et al. 2020), however, future events such as the 2011 MHW, which caused widespread seagrass die-off, have the potential to negatively impact blue swimmer crab stocks given the importance of this habitat to crabs in CS. Since the 2011 MHW WA experienced a multi-year marine cold-spell (Feng et al. 2021), however, the WCB and CS specifically are yet to experience another MHW of a similar magnitude from which to gain further knowledge. Some species may be able to adapt to gradual long-term effects of climate change such as SST increases, however the same species will struggle with dealing with major changes in SST over a short period such as a MHW event.

4.6 Risk assessment of the effects of climate change on invasive marine species

The Asian green mussel (*Perna viridis*), charru mussel (*Mytella strigata*), Asian paddle crab (*Charybdis japonica*), and carpet sea squirt (*Didemnum vexillum*), representative of mussels, crab and colonial ascidian taxa respectively, were chosen as high-risk IMS relevant to WA and subject to climate change risk assessments (Table 9 & Appendix 3). Each of these species exhibit characteristics common to IMS such as high reproductive capacity, wide physiological tolerances and generalist feeding strategies. Asian green and charru mussels are listed on the Australian Priority Marine Pest List (MPSC 2018), while the carpet sea squirt is listed on the National Priority list of Exotic Environmental Pests, Weeds and Diseases (ABARES 2021). All four species were considered insensitive to the projected changes associated with climate change in CS. The Asian green mussel, charru mussel and Asian paddle crab all have the potential to pose an increased risk in CS as warmer water temperatures may be more suitable for tropical species to establish. While warmer conditions may negatively affect the growth and reproduction of the carpet sea squirt within CS in the future, its unlikely temperatures will exceed the upper tolerance limits for this species (31°C; Herborg et al. 2009).

Table 9. Climate change risk scores for four IMS considered to pose a threat to CS. The full scorecards with accompanying confidence levels and justifications are presented in Appendix 3. The sensitivity rank is based on the sensitivity total score relative to all species assessed (Table 7). Species have been ordered based on overall risk score, lower scores indicating less sensitive (i.e. they may benefit from climate change).

Species	Sensitivity					Sensitivity Rank	Exposure	Overall risk score
	Abundance	Distribution	Phenology	Physiology	Total score			
Asian paddle crab (<i>Charybdis japonica</i>)	1.4	1.75	1.5	1.67	6.32	1	1	1
Carpet sea squirt (<i>Didemnum vexillum</i>)	1.0	1.75	1.75	1.67	6.17	1	2	2
Asian green mussel (<i>Perna viridis</i>)	1.4	2	1.75	1.83	6.98	3	1	3
Charru mussel (<i>Mytella strigata</i>)	1.4	2	1.75	1.83	6.98	3	1	3

Asian green mussels are a large (<160 mm), distinctive mussel species grown as significant aquaculture stock in Asia, and found in the wild, throughout south-east Asia. The species is native to India, China, Thailand, Malaysia, Philippines and the Arabian Sea and has been introduced to the USA, Caribbean Sea, Venezuela, Japan, and South Africa (MPSC 2018). The mussels form dense populations capable of growing on almost any hard substrate and under favourable environmental conditions have high growth rates and reproductive output. Asian green mussels tolerate a range of physiological conditions including low nutrients, low salinity, and high contaminant environments (Segnini de Bravo et al. 1998). The mussels can tolerate temperatures ranging from 15.0-32.5°C, with peak gonad development linked to increased temperatures (~30°C; Rajagopal et al. 2006). Spawning typically occurs early summer triggered by warmer waters, though there are reports of more frequent and sporadic spawning in tropical and temperate regions (Rajagopal et al. 1998). Veliger larvae remain in the water column approximately two weeks before settling as juveniles. Asian green mussels have the potential to alter habitats and community structure in introduced environments, out compete native species for nutrients and habitat, as well as introduce new parasites and disease. The Asian green mussel has repeatedly been detected on international vessels operating in CS and throughout WA, representing an ongoing source of risk (McDonald 2012, Wellington pers. comm.). Asian green mussels have not

established a population in WA to date, however, warming oceans have been predicted to increase the geographic distribution of this species (Rajagopal et al. 2006).

The charru mussel is a moderately large mussel (average size 22-68 mm) found in intertidal and subtidal coastal waters and estuaries. The species is native to tropical south and central America and has spread to both southeast Asia and the south-eastern United States (Lim et al. 2018). Recent introductions to Singapore, Thailand and Taiwan have reported rapid population increases of this species and competition the Asian green mussel, a native aquaculture species (Sanpanich & Wells 2019). Similar to Asian green mussels, the charru mussel is fast growing and highly fecund, reaching sexual maturity at ~12.5 mm. Spawning can occur during warmer months, with production of eggs and sperm produced year-round. The larvae remain in the water column for 10-15 days before settlement. The charru mussel grows in dense clusters on both hard substrates and in soft sediments, it is tolerant to wide fluctuations in salinity and temperature and has been observed to compete with native sessile invertebrates in its invaded range (Huang et al. 2021b). While no populations of charru mussel have been reported in Australia to date, the species was added to the Australian Priority Marine Pest List in 2020.

The Asian paddle crab is an aggressive swimming crab, native to coastal temperate regions of the western Pacific such as China, Japan, Korea, Taiwan, Malaysia, and Thailand (Smith et al. 2003b). The species has been introduced in northern New Zealand with detections recorded on both east and west coasts (Hilliham 2021). The Asian paddle crab can grow to 120 mm CW, reaching maturity at ~40-50 mm CW. Females have multiple broods a year with 200,000 to 500,000 eggs on average. In its native distribution, the species spawns in spring and autumn when temperatures are above 20°C (Smith et al. 2003b). Planktonic larvae develop into juveniles after a minimum 17 days (Fowler et al. 2011). The species has a wide physiological tolerance range (4–34°C temperature, 14–33 ppt) capable of reproducing multiple times per year within its ~3-year life cycle (Fowler et al. 2011). Asian paddle crab typically inhabits intertidal and sublittoral habitats. Vessels provide the primary pathway for spread, both through biofouling on vessel hulls and juveniles capable of surviving in ballast water (Hewitt et al. 2009). The Asian paddle crab was first reported by recreational fishers in the Swan River in 2012, with three individual specimens identified (Hourston et al. 2015). The last reported detection was in 2018 (Simpson et al. 2023). The species was not detected during the 2012-2022 DPIRD delimiting surveillance for the species. Annual surveillance for the species has failed to detect a viable population, but the species remains a high-risk IMS due to environmental compatibility and the threat of competitive behaviour traits amongst native crab species.

Carpet sea squirt is a colonial ascidian species, capable of growing on and modifying natural and artificial substrates, colonising infrastructure, vessels, and other sessile organisms by forming encrusting mats and lobed masses. It is regarded as a successful invader due to its capacity for growth and reproduction in favourable environmental conditions and ability to colonise and alter a range of habitats. Carpet sea squirt is a temperate species native to Japan, but has now established in many coastal environments globally (Lambert 2009), with invasive populations recorded in New Zealand, both east and west coasts of the USA and Canada, Great Britain, and mainland Europe (McKenzie et al. 2017). Carpet sea squirt can reproduce sexually and asexually (Fletcher et al. 2013), with asexual reproduction occurring either through budding, or by fragments and lobed masses breaking off, allowing living tissue to disperse, resettle and grow into new colonies. Fragments are capable of surviving extended periods adrift before resettling (Fletcher et al. 2013). Like many other invasive colonial ascidians, it is hermaphroditic and ovoviviparous, with spawning linked to food availability and temperature. Larvae, when released from the colony swim towards light, however upon settlement the larvae are positively geotactic and negatively phototactic, seeking areas out of direct light such as the underside of structures and shaded areas (McKenzie et al. 2017). The reproductive cues of season and temperature vary with geographic locations, for example, although reproductive cycles are attuned to temperate and cold-water environments, in New Zealand, carpet sea squirt has recorded at least a 9-month reproductive season. The first detection of carpet sea squirt in Australia was

recorded at HMAS Stirling Garden Island in 2021. In early 2023, the carpet sea squirt was detected on Australian Marine Complex infrastructure within CS, triggering a level 2 incident response and notification to CCIMPE. Subsequently the species was detected at a naval base in NSW (DAFF, 2023).

Climate change may make marine invasions less predictable, as the environmental underpinnings that have been used to predict species shifts become less coherent. Often, the true physiological tolerances of IMS are unknown until the species established itself in new environments. Although climate change shifts may provide opportunities for many species, temperate IMS may increasingly struggle to adapt or establish. For many invertebrate shelled IMS, ocean acidification may increase mortality. Warmer conditions can imbue accelerated growth rates and reproductive opportunities for some species, giving them a competitive edge. However, warmer conditions may also curtail the range and reproductive extent for those already at their upper limit.

The existing environmental and anthropogenic pressures impacting the CS environment have a cumulative effect on its resilience. The volume and frequency of shipping into CS is expected to continue to increase, while voyage transit times from environmentally compatible ports are likely to decrease. This increased connectivity will compound the opportunities for IMS to potentially enter new areas.

Although native species can often maintain dominance and outcompete invasive arrivals, additional stressors on the environment can impact the defences of existing flora and fauna, leading to a decrease in biodiversity and natural resilience within the system. This reduced resilience of the system can provide opportunities for adaptive and physiologically resilient IMS to establish and thrive in these disturbed environments. There are very few examples of successful eradication of invasives once established in the marine environment, and existing eradication techniques can often be wholly destructive to native flora and fauna as well.

5 Conclusion

When assessing the effects of the Westport development on the biota in CS, it is important to consider a range of factors that may affect the biota to enable a proper assessment of the cause(s) of any future changes observed. These factors can be short-term (annual) effects (e.g. MHWs or storm impacts) or long-term (decadal) effects, such as climate change trends causing species range retreat or expansion. As climate change impacts the CS environment and water temperatures warm, some tropical species that cannot overwinter in the current conditions may be able to establish sustaining populations, leading to domestic range shifts (poleward expansion) as well as novel introductions. Other currently abundant species may exceed their physiological tolerances in the future, causing the species to decline in abundance or disappear from CS. This project provides an understanding of many of the factors affecting some of the key species in CS (commercial and recreational fisheries species, species iconic to the region and four example invasive marine species) and assesses the risk to these biota from a changing climate.

The study has highlighted warming water temperatures as the main climate change effect in CS, with the WWMSF project *Provision of multi-decadal ocean boundary conditions and field measurements* indicating this trend (SST increasing by 0.015 and 0.031°C per annum under SSP2 and SSP5 respectively) is likely to continue this century. Increasing water temperatures also elevates the risk of MHW events, such as the extreme 2011 event that had a major effect on the marine ecosystem in the lower west coast.

The study has also indicated possible environmental regime shifts having occurred because of historical industry management decisions in CS, resulting in a major loss of seagrass and an increase in productivity (increased chlorophyll-*a*, nitrogen and phosphorus). However, subsequent tightening of industry regulations in recent decades, then reduced anthropogenic nutrient inputs (e.g. nitrogen) by 95% causing a reduction in productivity. Should this reduced level of input persist, it is unlikely primary productivity will return to peak levels observed. This reduced productivity has seen a significant decrease in blue swimmer crab abundance in CS, which was historically an important commercial and recreational fishery. Over a similar period, comparable decreases in productivity were also observed in CS mussel aquaculture, and a fall in western king prawn abundance.

The warming trend is having a negative impact on species near the northern end of their range such as southern garfish and little penguin. However, it may benefit some tropical species such as rabbitfish and there could be some benefit for blue swimmer crab although its abundance could still be limited by reduced chlorophyll levels in CS.

There has been a decreasing commercial catch trend in CS for many species that can be attributed to management actions resulting in decreasing fishing effort, with some species also affected by changing environmental conditions. The major exception to the decreasing catches has been the octopus fishery which has rapidly increased in last 20 years.

Snapper within the Perth region appear to have highly variable recruitment, with seven strong year classes between 1991 and 2018. These strong year classes are observed in age data from recreational and commercial landings, and more recently in fisheries-independent BRUV and trawl data. However, what causes these years to be particularly successful remains an ongoing area of research, and preliminary analyses within this study found that environmental conditions of temperature, salinity, and chlorophyll-*a* within CS during the peak larval stage were not correlated with recruitment success.

Climate change risk assessments using a traits-based assessment methodology were applied to 14 fisheries species and five species iconic to the Perth region. The species identified as potentially the most sensitive to a warming climate (Severe risk) include sandy sprat, little penguin, Australian sardine and southern garfish. Snapper and King George whiting were identified as High risk.

The risk assessment identified a number of potential benefits to certain species, like blue swimmer crab and western king prawn, but due to potential changes to important sensitive habitats (in

particular seagrass), they were still identified as Medium risk. Species which were identified as Negligible risk or may benefit from a warming climate, include scaly mackerel, western rock octopus and yellowfin whiting.

The climate change risk assessment methodology was also applied to four IMS, previously identified as a threat to the Perth region, to explore which factors of climate change may be important for these species in the CS environment. The Asian green mussel, charru mussel, Asian paddle crab, and carpet sea squirt, were all considered to be insensitive to the projected changes associated with climate change in CS. In addition, considering their wide physiological tolerances and presence throughout tropical regions, the Asian green mussel, charru mussel and Asian paddle crab all have the potential to pose an increased risk in CS as warmer water temperatures may be more suitable for tropical species to establish.

This study has drawn upon a range of datasets collected in a piecemeal fashion by various government agencies to investigate whether there are observed changes in the fauna within CS that could be associated with climate change. However, a commonly encountered challenge of these analyses was how best to standardise these datasets into long term indices, when the surveys providing data were periodically changing, and when there were spatial or temporal mismatches in biological and environmental datasets. For instance, since 1971 when the first large otter-trawl surveys were conducted in CS, the geographic area being sampled has expanded, the trawl distances shortened, the species being recorded have changed and the months the trawls were conducted have frequently changed (Figure 2). These changes would have contributed to the large error margins in the blue swimmer crab and western king prawn annual indices (Figure 32 & Figure 33 respectively). Similarly, since the conception of the nearshore fish recruitment index project, the surveys have ceased sampling at one of the two sites within CS and expanded from recording abundances of a select number of species to recording abundances of all species observed (Gaughan et al. 2006). In terms of the environmental datasets, there have been clear long terms changes for some of the water quality parameters within CS (i.e. chlorophyll-a (Figure 11), nitrogen (Figure 9) and phosphorus (Figure 10) concentrations). However, much of the water quality information in CS were derived from the CSMC samples, which were limited to the summer months, therefore, there was a temporal mismatch between when environmental data were available and important seasons for key life stages of many of the species of interest (e.g. snapper and blue swimmer crab spawning). Therefore, an important conclusion of this report is that, in order to more comprehensively understand the effects climate change are already having on the biota within CS, an expanded environmental and biological monitoring program would be required, which considered a broader range of species than can be pieced together from the current ongoing fisheries focussed surveys. For instance, prior to the current WWMSF projects, there were only three intervals where a broad range of invertebrate and fish species abundances were recorded from the large otter-trawls since the first survey in 1971 (1971-1972; Penn pers. comm.), 1977-1978 (Dybdahl 1979) and 2007-2008 (Johnston et al. 2008)). While recording all species abundances present in the trawls would be more time consuming and costly, periodically collecting full community data like this may identify changes to species that are important to the functioning of the ecosystem, but not of fisheries importance. An ongoing monitoring plan that would improve our understanding of the impacts of climate change within CS, should also consider whether additional funding is also available to repeat other sample programs within the current WWMSF, relating to the benthos, and invertebrates and fish communities.

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7 Appendices

7.1 Appendix 1

CSMC summer indices

Method and results:

The CSMC have taken in-situ measurements of water quality during the summer months (December-March) within CS since December 1982. These consisted of weekly samples collected at between 8 and 18 sites within CS south of Woodman Point (Figure 43). The specific parameters measured, and number of sites visited during that time have varied, with six years having no measurements at all, and additional metrics added over the four decades of sampling. For each site a measurement of temperature ($^{\circ}\text{C}$), salinity (psu), dissolved oxygen (mg L^{-1}), turbidity (NTU) and pH were recorded at the water surface and bottom (50 cm below the surface and 50 cm above the seabed, respectively). Chlorophyll-*a* ($\mu\text{g L}^{-1}$), nitrogen ($\mu\text{g L}^{-1}$), and phosphorus ($\mu\text{g L}^{-1}$) samples represent the full water column and were collected using an extendable hose lowered at a constant rate through the water column.

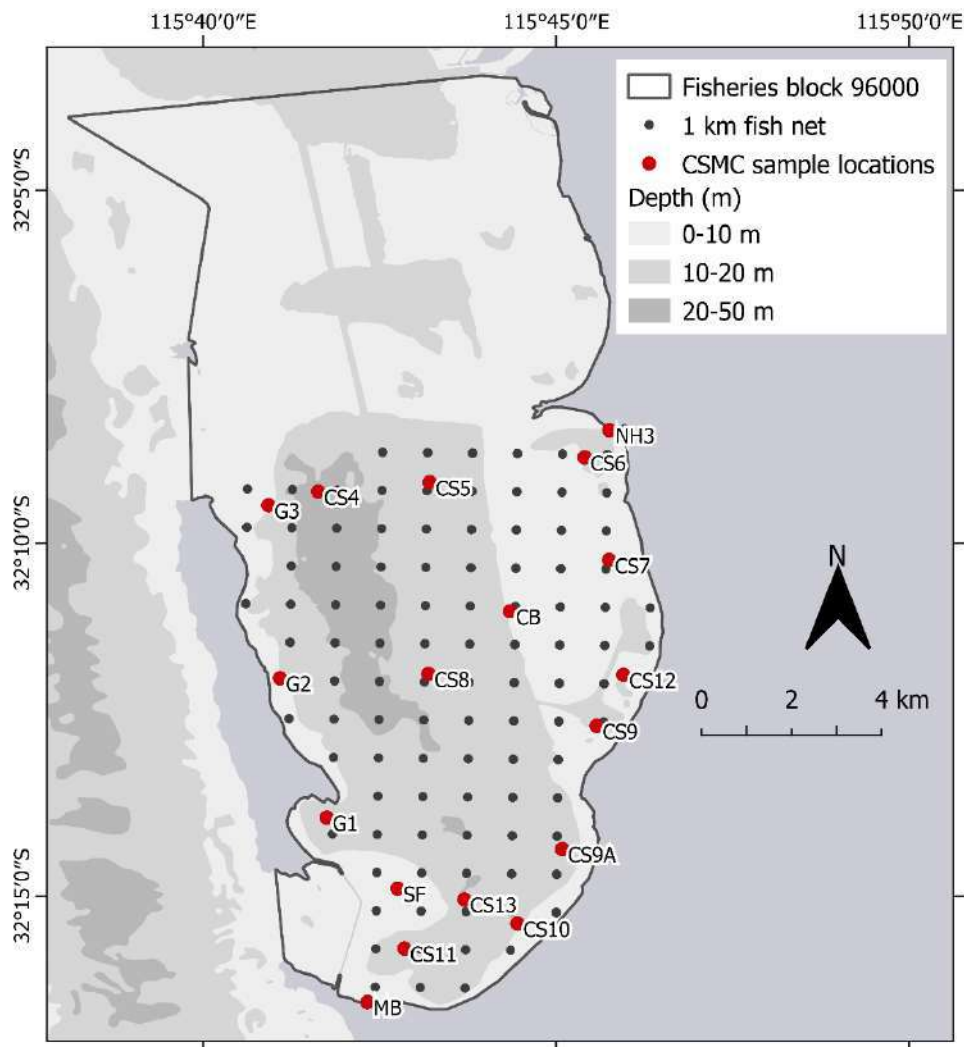


Figure 43. CSMC water quality sample locations used between 1982-2022. The black dots show the 1 km grid projected onto CS, from which the spatially balanced index values were calculated from.

To prepare data for analysis, records containing a ‘<’ symbol indicating the concentration was below the detectable limit were converted to half the minimum detectable value.

Yearly summer index values were generated for each parameter using Generalised Additive Models (GAMs). GAMs were fitted with the water quality parameter as the response variable and explanatory variables of summer season (year based on January date), time of year (as a decimal day of year starting from December 1st), and eastings and northings (of the samples). Smoothing parameters were applied using the REML function in mgcv (Wood 2012). Where overfitting of the model produced unrealistic predictions for unsampled years (as determined by the operator), the number of knots (k) for the year variable was specified. The response variables for chlorophyll-*a*, total nitrogen, total phosphorus and turbidity were log-transformed to achieve a normal distribution.

To generate spatially balanced index values, models were then predicted onto a 1 km grid for CS (Figure 43) and a mean was calculated for each parameter for the summer season. In years where no measurements were recorded a seasonal index value was estimated using a linear interpolation of the neighbouring years.

Not all variables recorded in the CSMC dataset could have annual indices generated, for various reasons including: systematic changes in the data indicating a change of measurement method or change of units, limited time series or large multi-year gaps in the data and limited variability in the recorded values.

Annual water quality indices are presented in Section 4.1.3, and a summary of model fit for each parameter is presented in Table 10.

Table 10. Summary of each GAM model fit to calculate seasonal indices for each water quality parameter using CSMC data. The degrees of freedom (df), model F statistics (F) and P-values (P) are given for each term. _s denotes smooth terms with year included as a factor. The model term dday – decimal day of year.

<i>SST ~ easting + northing + dday + year. R² = 0.63</i>			
Predictor	edf/df	F	P
easting _s	3.35	9.6	<0.001
northings _s	4.38	9.6	<0.001
dday _s	7.43	933.1	<0.001
year	29	85.2	<0.001

<i>log(Chla) ~ easting + northing + dday + year. R² = 0.53</i>			
Predictor	edf/df	F	P
easting _s	8.22	186.7	<0.001
northings _s	7.34	158.6	<0.001
dday _s	4.98	186.7	<0.001
year	33	51.9	<0.001

log(total nitrogen) ~ easting + northing + dday + year. R² = 0.74

Predictor	edf/df	F	P
easting _s	4.22	43.7	<0.001
northing _s	8.45	73.7	<0.001
dday _s	1.00	74.1	<0.001
year	31	483.3	<0.001

log(total phosphorus) ~ easting + northing + dday + year. R² = 0.73

Predictor	edf/df	F	P
easting _s	5.09	77.2	<0.001
northing _s	7.40	94.4	<0.001
dday _s	5.29	11.3	<0.001
year	31	436.6	<0.001

salinity ~ easting + northing + dday + year. R² = 0.77

Predictor	edf/df	F	P
easting _s	4.52	26.5	<0.001
northing _s	6.69	24.2	<0.001
dday _s	8.53	1256.8	<0.001
year	29	284.2	<0.001

Bottom dis.oxygen ~ easting + northing + dday + year. R² = 0.44

Predictor	edf/df	F	P
easting _s	8.59	68.8	<0.001
northing _s	6.71	101.0	<0.001
dday _s	6.17	178.7	<0.001
year	29	66.3	<0.001

pH ~ easting + northing + dday + year. R² = 0.39

Predictor	edf/df	F	P
easting _s	1.00	32.3	<0.001
northing _s	2.95	4.3	<0.01
dday _s	6.70	17.0	<0.001
year	17	146.4	<0.001

log(turbidity) ~ easting + northing + dday + year. R² = 0.17

Predictor	edf/df	F	P
easting _s	2.42	35.0	<0.001
northing _s	6.98	24.1	<0.001
dday _s	6.04	7.5	<0.001
year	11	21.8	<0.001

7.2 Appendix 2

Sensitivity scores for key biota species

For each sensitivity attribute, each species was scored based on the risk levels described in Table 2 and Fulton et al. (2020). Exposure was scored based on the levels outlined in Table 3.

Common name: Blue swimmer crab Species: <i>Portunus armatus</i>		Risk category (sensitivity and capacity to respond to change)		Comments - Level of certainty and data availability (H, M, L)
Sensitivity attribute		Risk level	Score	
Abundance	Fecundity - egg production	>20,000 eggs per year	1	H
	Recruitment period – successful recruitment event that sustains the abundance of the fishery	Consistent recruitment events every 1-2 years	1	H
	Average age at maturity	≤2 years	1	H
	Generalist vs. specialist – food and habitat	Reliance on either habitat or prey	2	H
	Sensitivity to ocean acidification	Shelled species	3	H
Average score: 1.6				
Distribution	Capacity for larval dispersal or duration – hatching to settlement (benthic sp.), hatching to yolk sac re-adsorption (pelagic sp.)	2-8 weeks	2	H
	Capacity for adult/juvenile movement – lifetime range post-larval stage	<10 km	3	H
	Physiological tolerance – latitudinal coverage of adult sp. As a proxy of environmental tolerance	>20° latitude	1	H
	Spatial availability of unoccupied habitat for most critical life stage - ability to shift distributional range	Limited unoccupied habitat 2-6° latitude or longitude	2	H
Average score: 2				
Phenology	Environmental variable as a phenological cue for spawning or breeding – cue include salinity, temperature, current, & freshwater flows	Strong correlation of spawning to environmental variable	3	H - temperature
	Environmental variable as a phenological cue for settlement or metamorphosis	Strong correlation of spawning to environmental variable	3	H - temperature
	Temporal mismatches of lifecycle events - duration of spawning, breeding or moulting season	Wide duration; 2-4 months	2	H – Sep-Dec/Jan
	Migration (seasonal and spawning)	Migration is common for some of the population	2	H
Average score: 2.5				
Physiology	Fat and muscle content (capacity for energy storage)	Capacity breeder	1	L
	Body size	Small (<20 cm)	3	H
	Metabolic capacity	High metabolic capacity	1	L - Fast growth rate and moulting multiple times in first 18 months

	Disease or parasite load	Medium disease and parasite load	2	M – In tropical areas sexual reproduction can be inhibited by a parasitic barnacle (<i>Sacculina granifera</i>). Chitinoclastic shell disease can also occur in poor environmental conditions (Johnston et al., 2020)
	Physiological tolerance and response curve	High tolerance	1	Survives in a wide range of estuarine conditions.
	Oxygen sensitivity	Intermediate sensitivity	2	Can tolerate oxygen deprivation at high (19°C) and low (13°C) temperatures (Kangas 2000)
Average score: 1.67				
Staff contact name: Dr Danielle Johnston			Total sensitivity score: 7.77	
Exposure: Blue swimmer crab range extends from the south coast to Nickol Bay (Pilbara) and the likely warmer ocean temperatures within CS will likely increase recruitment and spawning success and growth rates in CS as these are both reliant on temperature. Possible negative impacts within CS include: reduced rainfall and therefore Swan River flows, flushing less mature females from the estuary into northern CS (Caputi et al. 2015); and, further die-off of seagrass in CS during more frequent and intense MHWs which provide valuable habitat for juvenile crabs.			Exposure score: 2	

Common name: Southern calamari Species: <i>Sepioteuthis australis</i> Sensitivity attribute		Risk category (sensitivity and capacity to respond to change)		Comments - Level of certainty and data availability (H, M, L)
		Risk level	Score	
Abundance	Fecundity - egg production	100-20,000 eggs per year	2	H
	Recruitment period – successful recruitment event that sustains the abundance of the fishery	Consistent recruitment events every 1-2 years	1	H
	Average age at maturity	≤2 years	1	H – 4-6 months (Coulson et al. 2012)
	Generalist vs. specialist – food and habitat	Reliance on either habitat or prey	2	H – Predominantly associated with seagrass habitats and lay eggs directly on seagrass (Yeoh et al. 2021). Clear water also important for feeding and mating
	Sensitivity to ocean acidification	Not shelled and no reliance on shelled species	1	L – The influence of acidification on squid statoliths is poorly researched (Kaplan et al. 2013)
	Average score: 1.4			
Distribution	Capacity for larval dispersal or duration – hatching to settlement (benthic sp.), hatching to yolk sac re-adsorption (pelagic sp.)	<2 weeks or no larval stage	3	H
	Capacity for adult/juvenile movement – lifetime range post-larval stage	10-1000 km	2	M
	Physiological tolerance – latitudinal coverage of adult sp. As a proxy of environmental tolerance	10-20° latitude	2	H
	Spatial availability of unoccupied habitat for most critical life stage - ability to shift distributional range	No unoccupied habitat; 0-2° latitude or longitude	3	H
	Average score: 2.5			
Phenology	Environmental variable as a phenological cue for spawning or breeding – cue include salinity, temperature, current, & freshwater flows	Weak correlation of spawning to environmental variable	2	H – Single batch spawning observed in warmer waters whereas multiple batch spawning observed in cooler waters
	Environmental variable as a phenological cue for settlement or metamorphosis	No apparent correlation to environmental variable	1	H
	Temporal mismatches of lifecycle events - duration of spawning, breeding or moulting season	Continuous duration; >4 months	1	H – Year-round
	Migration (seasonal and spawning)	No migration	1	L – Individuals may utilize different areas at different times of year
Average score: 1.25				
Physiology	Fat and muscle content (capacity for energy storage)	High fat and muscle content (capital breeder)	1	M – Based on rapid growth rate
	Body size	Medium (20-100 cm)	2	H
	Metabolic capacity	High metabolic capacity	1	M – Based on growth rate

	Disease or parasite load	Low disease and parasitic load	1	M – Not well studied
	Physiological tolerance and response curve	Medium tolerance	2	M – Plastic physiological response to increased temperature but negatively impacted over 22°C (Fuentes 2021)
	Oxygen sensitivity	Intermediate sensitivity	2	L – Thought to be low based on high oxygen consumption rates and low blood oxygen carrying capacity of squids in general (Fuentes 2021)
				Average score: 1.5
Staff contact name: Dr Daniel Yeoh			Total sensitivity score: 6.65	
Exposure: Reliance on seagrass for egg development mean further seagrass loss within CS could be important for this species. Within the WCB a positive relationship between CPUE and temperature has been observed, which was more pronounced on the south coast (Yeoh et al. 2021). However, the species metabolism may be limited in temperatures above 22°C (Fuentes 2021). As climate change will prolong the period during the summer that water temperatures exceed 22°C within CS this may negatively impact southern calamari, potentially causing them to move out of CS or become less active during these high temperature periods.			Exposure score: 3	

Common name: Western rock octopus Species: <i>Octopus djinda</i> Sensitivity attribute		Risk category (sensitivity and capacity to respond to change)		Comments - Level of certainty and data availability (H, M, L)
		Risk level	Score	
Abundance	Fecundity - egg production	>20,000 eggs per year	1	H
	Recruitment period – successful recruitment event that sustains the abundance of the fishery	Consistent recruitment events every 1-2 years	1	H
	Average age at maturity	≤ years	1	H
	Generalist vs. specialist – food and habitat	Reliance on neither habitat or prey	1	H
	Sensitivity to ocean acidification	Not shelled, but reliant on shelled species (as prey or habitat).	2	H
				Average score: 1.2
Distribution	Capacity for larval dispersal or duration – hatching to settlement (benthic sp.), hatching to yolk sac re-adsorption (pelagic sp.)	>2 months	1	H –Paralarval stage ~60 days
	Capacity for adult/juvenile movement – lifetime range post-larval stage	10-1000 km	2	H
	Physiological tolerance – latitudinal coverage of adult sp. As a proxy of environmental tolerance	<10° latitude	3	M – Known range of recently described species from Shark Bay to Cape Le Grand
	Spatial availability of unoccupied habitat for most critical life stage - ability to shift distributional range	Substantial unoccupied habitat; >6° latitude or longitude	1	M – Highly adaptable species that could extend range or move into deeper habitats with changing climate
				Average score: 1.75
Phenology	Environmental variable as a phenological cue for spawning or breeding – cue include salinity, temperature, current, & freshwater flows	Weak apparent correlation of spawning to environmental variable	2	H – Continual spawner with pulses linked to temperature (Leporati et al. 2015)
	Environmental variable as a phenological cue for settlement or metamorphosis	No apparent correlation to environmental variable	1	H
	Temporal mismatches of lifecycle events - duration of spawning, breeding or moulting season	Continuous duration; >4 months	1	H
	Migration (seasonal and spawning)	Migration is common for the whole population	3	L – The species is thought to move in and out of CS at different life stages which is reflected in size distribution changes in depth. But data on movement patterns are limited
				Average score: 1.75
Physiology	Fat and muscle content (capacity for energy storage)	Intermediate	2	L – High growth rate, but species breeding appears to be dependent on age. Limited information available
	Body size	Medium (20–100 cm)	2	H
	Metabolic capacity	High metabolic capacity ³	1	H

Disease or parasite load	Medium disease and parasite load	2	L – Limited information for this species, although on species of parasite has been noted in CS (Claybrook 2020)
Physiological tolerance and response curve	Medium tolerance	2	L – Limited data available. Assumed tolerance based on species range
Oxygen sensitivity	Intermediate sensitivity (2–5 ml/l O ₂)	2	L – No data available. Score based on species presence in shallow and deeper environments
Average score: 1.83			
Staff contact name: Dr Anthony Hart		Total sensitivity score: 6.53	
Exposure: The range of western rock octopus indicates that the species is well adapted to higher temperatures than are currently observed in CS. During the 2011 MHW the octopus caught by commercial fishers in the Perth area were larger than in any year since (A. Hart, <i>unpublished data</i>). As ecological opportunists, climate change may prove beneficial, however, ocean acidification may prove harmful at the paralarval stage and indirectly impact the species by reducing prey.		Exposure score: 1	

Common name: Western king prawn Species: <i>Penaeus latisulcatus</i> Sensitivity attribute		Risk category (sensitivity and capacity to respond to change)		Comments - Level of certainty and data availability (H, M, L)
		Risk level	Score	
Abundance	Fecundity - egg production	>20,000 eggs per year	1	H
	Recruitment period – successful recruitment event that sustains the abundance of the fishery	Occasional and variable recruitment period	2	H
	Average age at maturity	≤2 years	1	H
	Generalist vs. specialist – food and habitat	Reliance on either habitat or prey	2	H
	Sensitivity to ocean acidification	Shelled species	3	H
	Average score: 1.8			
Distribution	Capacity for larval dispersal or duration – hatching to settlement (benthic sp.), hatching to yolk sac re-adsorption (pelagic sp.)	2–8 weeks	2	H
	Capacity for adult/juvenile movement – lifetime range post-larval stage	10-1000 km	2	M
	Physiological tolerance – latitudinal coverage of adult sp. As a proxy of environmental tolerance	10-20° latitude	2	H
	Spatial availability of unoccupied habitat for most critical life stage - ability to shift distributional range	Limited unoccupied habitat; 2-6° latitude or longitude	2	M
	Average score: 2			
Phenology	Environmental variable as a phenological cue for spawning or breeding – cue include salinity, temperature, current, & freshwater flows	Strong correlation of spawning to environmental variable	3	M – Spawning linked to temperatures >17°C (Penn 1980)
	Environmental variable as a phenological cue for settlement or metamorphosis	Strong correlation to environmental variable	3	H
	Temporal mismatches of lifecycle events - duration of spawning, breeding or moulting season	Continuous duration; >4 months	1	H – Oct-May (Penn 1980)
	Migration (seasonal and spawning)	Migration is common for some of the population	2	L – Small scale movements from shallow areas to deeper central basin is thought to occur in CS (Penn 1980)
	Average score: 2.25			
Physiology	Fat and muscle content (capacity for energy storage)	Intermediate	2	L
	Body size	Small (<20 cm)	3	H
	Metabolic capacity	Low metabolic capacity ³	3	M
	Disease or parasite load	Low disease and parasite load	1	L – Limited information for this species
	Physiological tolerance and response curve	High tolerance	1	M
	Oxygen sensitivity	Low sensitivity	1	M
	Average score: 2.2			
Staff contact name: Dr Nick Caputi			Total sensitivity score: 8.25	
Exposure: Considering the range of western king prawn, this species may benefit from increased SST increasing recruitment.			Exposure score: 1	

Common name: Snapper Species: <i>Chrysophrys auratus</i> Sensitivity attribute		Risk category (sensitivity and capacity to respond to change)		Comments - Level of certainty and data availability (H, M, L)
		Risk level	Score	
Abundance	Fecundity - egg production	>20,000 eggs per year	1	H
	Recruitment period – successful recruitment event that sustains the abundance of the fishery	Consistent recruitment events every 1-2 years	1	H
	Average age at maturity	2-10 years	2	H
	Generalist vs. specialist – food and habitat	Reliance on either habitat or prey	2	H – Habitat reliance
	Sensitivity to ocean acidification	Not shelled, but reliant on shelled species (as prey or habitat).	2	H
				Average score: 1.6
Distribution	Capacity for larval dispersal or duration – hatching to settlement (benthic sp.), hatching to yolk sac re-adsorption (pelagic sp.)	2-8 weeks	2	H
	Capacity for adult/juvenile movement – lifetime range post-larval stage	10-1000 km	2	H
	Physiological tolerance – latitudinal coverage of adult sp. As a proxy of environmental tolerance	>20° latitude	1	H
	Spatial availability of unoccupied habitat for most critical life stage - ability to shift distributional range	No unoccupied habitat; 0-2° latitude and longitude	3	H
				Average score: 2
Phenology	Environmental variable as a phenological cue for spawning or breeding – cue include salinity, temperature, current, & freshwater flows	Strong correlation of spawning to environmental variable	3	H – Temperature and currents
	Environmental variable as a phenological cue for settlement or metamorphosis	Weak correlation of spawning to environmental variable	2	H - Temperature
	Temporal mismatches of lifecycle events - duration of spawning, breeding or moulting season	Wide duration; 2-4 months	2	H – Sep-Dec
	Migration (seasonal and spawning)	Migration is common for some of the population	2	H
				Average score: 2.25
Physiology	Fat and muscle content (capacity for energy storage)	Intermediate	2	H
	Body size	Medium (20–100 cm)	2	H
	Metabolic capacity	Medium metabolic capacity	2	H
	Disease or parasite load	Low disease and parasite load	1	H
	Physiological tolerance and response curve	High tolerance	1	H
	Oxygen sensitivity	Low sensitivity (<2 ml/l O ₂)	1	H
				Average score: 1.5
Staff contact name: Dr David Fairclough			Total sensitivity score: 7.35	
Exposure: There is a known strong relationship between water temperature and spawning activity in snapper. Acute events (such as MHWs) during the spawning period could have localised impacts on migration and spawning behaviour, spawning success (egg production/fertilisation success) and/or recruitment (survival of early life history stages). Genomic differences between snapper in CS and those on the mid-west coast (Bertram et al. 2022) may indicate lower physiological tolerance to maximum temperatures tolerated by more northern snapper stocks. Long-term changes in water temperature may influence sizes achieved at different stages of life, as lengths at age are generally lower in more northern latitudes (Wakefield et al. 2015). As snapper is a highly mobile species, permanent elevated or extreme temperatures may alter its use of CS as a spawning or nursery environment.			Exposure score: 3	

Common name: Southern garfish Species: <i>Hyporhamphus melanochir</i> Sensitivity attribute		Risk category (sensitivity and capacity to respond to change)		Comments - Level of certainty and data availability (H, M, L)
		Risk level	Score	
Abundance	Fecundity - egg production	100-20,000 eggs per year	2	H
	Recruitment period – successful recruitment event that sustains the abundance of the fishery	Consistent recruitment events every 1-2 years	1	H
	Average age at maturity	≤2 years	1	H - ~12 months in WCB
	Generalist vs. specialist – food and habitat	Reliance on either habitat or prey	2	H – Seagrass habitat reliance
	Sensitivity to ocean acidification	Not shelled, but reliant on shelled species (as prey or habitat).	2	H – Diet includes crustaceans
				Average score: 1.6
Distribution	Capacity for larval dispersal or duration – hatching to settlement (benthic sp.), hatching to yolk sac re-adsorption (pelagic sp.)	<2 weeks or no larval stage	3	H
	Capacity for adult/juvenile movement – lifetime range post-larval stage	10-1000 km	2	H
	Physiological tolerance – latitudinal coverage of adult sp. As a proxy of environmental tolerance	<10 latitude	3	H – CS is on northern limit of range (this may be due to availability of habitat)
	Spatial availability of unoccupied habitat for most critical life stage - ability to shift distributional range	No unoccupied habitat; 0-2° latitude and longitude	3	H
				Average score: 2.75
Phenology	Environmental variable as a phenological cue for spawning or breeding – cue include salinity, temperature, current, & freshwater flows	Strong correlation of spawning to environmental variable	3	H – Temperature
	Environmental variable as a phenological cue for settlement or metamorphosis	No apparent correlation to environmental variable	1	H
	Temporal mismatches of lifecycle events - duration of spawning, breeding or moulting season	>4 months	1	H – Sep-Apr
	Migration (seasonal and spawning)	No migration	1	H
				Average score: 1.5
Physiology	Fat and muscle content (capacity for energy storage)	Intermediate	2	M
	Body size	Medium (20–100 cm)	2	H
	Metabolic capacity	Medium metabolic capacity	2	L – Inferred from lifespan and growth rate
	Disease or parasite load	Low disease and parasite load	1	L
	Physiological tolerance and response curve	High tolerance	1	L – Limited data. Assumed based on being a nearshore species and tolerant to changes in chlorophyll
	Oxygen sensitivity	Low sensitivity (<2 ml/l O ₂)	1	L – Inferred from range and persistence within estuaries such as Wilson Inlet

	Average score: 1.5
Staff contact name: Dr Rodney Duffy and Amber Quinn	Total sensitivity score: 7.35
Exposure: The long-term rise in SST and increasing frequency of MHWs are likely to negatively impact southern garfish stocks in CS. In addition, the reliance on seagrass for egg development mean further seagrass loss due to MHWs within CS could be important for this species.	Exposure score: 4

Common name: Australian herring Species: <i>Arripis georgianus</i> Sensitivity attribute		Risk category (sensitivity and capacity to respond to change)		Comments - Level of certainty and data availability (H, M, L)
		Risk level	Score	
Abundance	Fecundity - egg production	>20,000 eggs per year	1	H
	Recruitment period – successful recruitment event that sustains the abundance of the fishery	Consistent recruitment events every 1-2 years	1	H – Although recruitment strength does vary year to year
	Average age at maturity	2-10 years	2	H
	Generalist vs. specialist – food and habitat	Reliance on neither habitat or prey	1	M
	Sensitivity to ocean acidification	Not shelled, but reliant on shelled species (as prey or habitat).	2	H
				Average score: 1.4
Distribution	Capacity for larval dispersal or duration – hatching to settlement (benthic sp.), hatching to yolk sac re-adsorption (pelagic sp.)	2–8 weeks	2	H – Larval dispersal dependent on strength of Leeuwin Current
	Capacity for adult/juvenile movement – lifetime range post-larval stage	>1000 km	1	H
	Physiological tolerance – latitudinal coverage of adult sp. As a proxy of environmental tolerance	10-20° latitude	2	H
	Spatial availability of unoccupied habitat for most critical life stage - ability to shift distributional range	Limited unoccupied habitat; 2–6° latitude or longitude	2	H
				Average score: 1.75
Phenology	Environmental variable as a phenological cue for spawning or breeding – cue include salinity, temperature, current, & freshwater flows	Strong correlation of spawning to environmental variable	3	H
	Environmental variable as a phenological cue for settlement or metamorphosis	Weak correlation to environmental variable	2	H
	Temporal mismatches of lifecycle events - duration of spawning, breeding or moulting season	Brief duration; <2 months	3	H – May-Jun
	Migration (seasonal and spawning)	Migration is common for whole population	3	H
				Average score: 2.75
Physiology	Fat and muscle content (capacity for energy storage)	High fat and muscle content (capital breeder)	1	M – Variable body condition based on location (e.g. in Wilson Inlet) and timing relative to spawning
	Body size	Medium (20–100 cm)	2	H
	Metabolic capacity	Medium metabolic capacity	2	M – Based on species being very active swimmer with maturity at 3-4 years
	Disease or parasite load	Low disease and parasite load	1	M –17 metazoan parasites observed in Australian herring, but no known issues (Hutson et al. 2011)
	Physiological tolerance and response curve	High tolerance	1	M – Based on diverse range of habitats used. Highly mobile and may avoid poor conditions

	Oxygen sensitivity	Low sensitivity (<2 ml/l O ₂)	1	L – Limited data
				Average score: 1.33
Staff contact name: Dr Rodney Duffy and Amber Quinn			Total sensitivity score: 7.23	
Exposure: Increased recruitment occurred under warming conditions (Duffy et al. 2021), suggesting this species may initially benefit from gradual warming associated with climate change. However, a strong relationship between environmental factors and recruitment have also been observed, so there is the potential for acute events (such as changes to Leeuwin Current strength and MHWs) to negatively impact recruitments. Australian herring spawn where temperatures are suitable, and where the larvae then settle is dependent on the strength of the Leeuwin Current. While the species stock is likely to be resilient to the effects of climate change, localized impacts within CS may occur, as this highly mobile species can readily move to areas where conditions are suitable.			Exposure score: 3	

Common name: Australian sardine (pilchard) Species: <i>Sardinops sagax</i> Sensitivity attribute		Risk category (sensitivity and capacity to respond to change)		Comments - Level of certainty and data availability (H, M, L)
		Risk level	Score	
Abundance	Fecundity - egg production	>20,000 eggs per year	1	H
	Recruitment period – successful recruitment event that sustains the abundance of the fishery	Consistent recruitment events every 1-2 years	1	H
	Average age at maturity	≤2 years	1	H
	Generalist vs. specialist – food and habitat	Reliance on neither habitat or prey	1	M
	Sensitivity to ocean acidification	Not shelled, but reliant on shelled species (as prey or habitat).	2	M
Average score: 1.2				
Distribution	Capacity for larval dispersal or duration – hatching to settlement (benthic sp.), hatching to yolk sac re-adsorption (pelagic sp.)	2–8 weeks	2	H
	Capacity for adult/juvenile movement – lifetime range post-larval stage	10-1000 km	2	M
	Physiological tolerance – latitudinal coverage of adult sp. As a proxy of environmental tolerance	<10° latitude	3	H
	Spatial availability of unoccupied habitat for most critical life stage - ability to shift distributional range	Limited unoccupied habitat; 2–6° latitude or longitude	2	M
Average score: 2.25				
Phenology	Environmental variable as a phenological cue for spawning or breeding – cue include salinity, temperature, current, & freshwater flows	Weak correlation of spawning to environmental variable	3	H.
	Environmental variable as a phenological cue for settlement or metamorphosis	Weak correlation to environmental variable	2	H
	Temporal mismatches of lifecycle events - duration of spawning, breeding or moulting season	Wide duration; 2–4 months	2	H
	Migration (seasonal and spawning)	Migration is common for some of the population	2	H
Average score: 2.25				
Physiology	Fat and muscle content (capacity for energy storage)	Intermediate	2	M - Winter spawner but can also spawn at other times of year.
	Body size	Small (<20 cm)	3	H
	Metabolic capacity	Medium metabolic capacity	2	M – ~0.09 mL O ₂ g ⁻¹ h ⁻¹ at 17.5°C (Logerwell 2001)
	Disease or parasite load	High disease and parasite load	3	H – Herpesvirus caused two mass mortalities in 1990's (Gaughan et al. 2000)
	Physiological tolerance and response curve	Low tolerance	3	M - Require temperate oceanic conditions. Do not tolerate fluctuations in salinity or higher temperature from Leeuwin Current
Oxygen sensitivity	High sensitivity (>5 ml/l O ₂)	3	L – Inferred from lack of tolerance of warmer waters	

	Average score: 2.67
Staff contact name: Jeffrey Norriss	Total sensitivity score: 8.38
<p>Exposure: Australian sardines are known to be highly sensitive to changing environmental conditions. In the northeast Pacific, this species underwent rapid changes to its recruitment, distribution and diet during a warm temperature anomaly known as the “blob” event in 2014 (Leising et al. 2015, Brodeur et al. 2019). In the northeast Pacific, the species is predicted to dramatically shift its range towards the pole (Petatan-Ramirez et al. 2019). CS is near the northern limit of this species’ range and the Perth region is the most northerly area where this species is commercially caught in WA. Further warming may cause the species range to contract, and the abundance within CS to decrease.</p>	Exposure score: 4

Common name: Scaly mackerel Species: <i>Sardinella lemuru</i> Sensitivity attribute		Risk category (sensitivity and capacity to respond to change)		Comments - Level of certainty and data availability (H, M, L)
		Risk level	Score	
Abundance	Fecundity - egg production	>20,000 eggs per year	1	H
	Recruitment period – successful recruitment event that sustains the abundance of the fishery	Consistent recruitment events every 1-2 years	1	H
	Average age at maturity	≤2 years	1	H
	Generalist vs. specialist – food and habitat	Reliance on neither habitat or prey	1	M
	Sensitivity to ocean acidification	Not shelled, but reliant on shelled species (as prey or habitat).	2	M
				Average score: 1.2
Distribution	Capacity for larval dispersal or duration – hatching to settlement (benthic sp.), hatching to yolk sac re-adsorption (pelagic sp.)	2–8 weeks	2	H - ~1 month (Pata et al. 2021)
	Capacity for adult/juvenile movement – lifetime range post-larval stage	10-1000 km	2	M
	Physiological tolerance – latitudinal coverage of adult sp. As a proxy of environmental tolerance	>20° latitude	1	H
	Spatial availability of unoccupied habitat for most critical life stage - ability to shift distributional range	Limited unoccupied habitat; 2–6° latitude or longitude	2	M
				Average score: 1.75
Phenology	Environmental variable as a phenological cue for spawning or breeding – cue include salinity, temperature, current, & freshwater flows	Weak correlation of spawning to environmental variable	2	M – Gaughan and Mitchell (2000) suggest temperature and the Leeuwin Current is important
	Environmental variable as a phenological cue for settlement or metamorphosis	Weak correlation to environmental variable	2	L – Gaughan and Mitchell (2000) hypothesise that temperature and the Leeuwin Current is important
	Temporal mismatches of lifecycle events - duration of spawning, breeding or moulting season	Brief duration; <2 months	3	M – Can occur from Dec -Mar, but with peak as short as 2 weeks (Gaughan & Mitchell 2000)
	Migration (seasonal and spawning)	Migration is common for some of the population	2	H
				Average score: 2.25
Physiology	Fat and muscle content (capacity for energy storage)	Intermediate	2	L
	Body size	Small (<20 cm)	3	H
	Metabolic capacity	Medium metabolic capacity ³	1	M - Highly mobile and fast to mature. Stock range is Fremantle to Carnarvon
	Disease or parasite load	Low disease and parasite load	1	M - Unknown

	Physiological tolerance and response curve	High tolerance	1	M - Large geographic range. Tolerance of higher temperatures and is known to move into the river mouth
	Oxygen sensitivity	Low sensitivity (<2 ml/l O ₂)	1	M – Tolerance of high temperature tropical water
				Average score: 1.5
Staff contact name: Jeffrey Norriss			Total sensitivity score: 6.7	
Exposure: This is a tropical species with CS near the southern extent of the range, and there is minimal catch south of CS. Scaly mackerel are highly mobile and appear to be tolerant of a wide range of conditions, and are likely to benefit from further warming within CS.			Exposure score: 1	

Common name: Sandy sprat (whitebait) Species: <i>Hyperlophus vittatus</i> Sensitivity attribute		Risk category (sensitivity and capacity to respond to change)		Comments - Level of certainty and data availability (H, M, L)
		Risk level	Score	
Abundance	Fecundity - egg production	>20,000 eggs per year	1	H
	Recruitment period – successful recruitment event that sustains the abundance of the fishery	Occasional and variable recruitment period	2	H
	Average age at maturity	≤2 years	1	H
	Generalist vs. specialist – food and habitat	Reliance on either habitat or prey	2	M – Proximity to freshwater inputs
	Sensitivity to ocean acidification	Not shelled, but reliant on shelled species (as prey or habitat).	2	M
				Average score: 1.6
Distribution	Capacity for larval dispersal or duration – hatching to settlement (benthic sp.), hatching to yolk sac re-adsorption (pelagic sp.)	<2 weeks or no larval stage	3	M – Larval stage ~10 days
	Capacity for adult/juvenile movement – lifetime range post-larval stage	10-1000 km	2	M
	Physiological tolerance – latitudinal coverage of adult sp. As a proxy of environmental tolerance	<10° latitude	3	H
	Spatial availability of unoccupied habitat for most critical life stage - ability to shift distributional range	Limited unoccupied habitat; 2–6° latitude or longitude	2	M
				Average score: 2.5
Phenology	Environmental variable as a phenological cue for spawning or breeding – cue include salinity, temperature, current, & freshwater flows	Weak correlation of spawning to environmental variable	3	M – Spawns between 15.0-22.6°C, but mainly in cooler water 17.0-18.5°C. Possible cue being freshwater flows
	Environmental variable as a phenological cue for settlement or metamorphosis	Weak correlation to environmental variable	2	L
	Temporal mismatches of lifecycle events - duration of spawning, breeding or moulting season	Brief duration; <2 months	3	H – May-Sep with peak Jun/Jul
	Migration (seasonal and spawning)	Migration is common for some of the population	2	M – Juveniles utilize shallow inshore regions then migrate to deeper waters with increasing size (Goh 1992)
				Average score: 2.5
Physiology	Fat and muscle content (capacity for energy storage)	Low energy storage (income breeder)	3	M – Species exhibits highly variable recruitment, rapidly reproducing when conditions are suitable
	Body size	Small (<20 cm)	3	H
	Metabolic capacity	Medium metabolic capacity	2	L – Data are limited. Assumed as it is a small and not highly mobile species but rapidly matures
	Disease or parasite load	Low disease and parasite load	1	H – None documented

	Physiological tolerance and response curve	Medium tolerance	2	L – Limited data. Present in Swan Estuary when saline
	Oxygen sensitivity	Intermediate (2-5 ml/l O ₂)	2	L – No data available. Cooler water species, in nearshore ocean water
				Average score: 2.17
Staff contact name: Dr Rodney Duffy and Amber Quinn			Total sensitivity score: 8.77	
Exposure: Fishery has undergone a dramatic range retraction with only a small number of locations supporting commercial fisheries. Sandy sprat appear to be less prevalent north of CS than they were historically, and the fisheries stocks are listed as 'environmentally limited'. Although the mechanism of this effect is unknown it is thought that environmental variability is an important factor for the stock, and the species is already responding to the effects of climate change (DPIRD, <i>unpublished data</i>). Predicted reduced freshwater flows from the Swan River are expected to negatively impact the species in CS.			Exposure score: 4	

Common name: Sea mullet Species: <i>Mugil cephalus</i> Sensitivity attribute		Risk category (sensitivity and capacity to respond to change)		Comments - Level of certainty and data availability (H, M, L)
		Risk level	Score	
Abundance	Fecundity - egg production	>20,000 eggs per year	1	H
	Recruitment period – successful recruitment event that sustains the abundance of the fishery	Consistent recruitment events every 1-2 years	1	H
	Average age at maturity	2-10 years	2	H - 3-4 years
	Generalist vs. specialist – food and habitat	Reliance on neither habitat or prey	1	H
	Sensitivity to ocean acidification	Not shelled, but reliant on shelled species (as prey or habitat)	1	H
				Average score: 1.2
Distribution	Capacity for larval dispersal or duration – hatching to settlement (benthic sp.), hatching to yolk sac re-adsorption (pelagic sp.)	<2 weeks or no larval stage	3	H
	Capacity for adult/juvenile movement – lifetime range post-larval stage	10-1000 km	2	H - <100 km is typical (Duffy et al. 2022)
	Physiological tolerance – latitudinal coverage of adult sp. As a proxy of environmental tolerance	10°-20° latitude	2	M – Enigmatic taxa with separate populations poorly understood (Duffy et al. 2022)
	Spatial availability of unoccupied habitat for most critical life stage - ability to shift distributional range	No unoccupied habitat; 0-2° latitude or longitude	3	H
				Average score: 2.5
Phenology	Environmental variable as a phenological cue for spawning or breeding – cue include salinity, temperature, current, & freshwater flows	Weak correlation of spawning to environmental variable	2	M – Persistent offshore winds
	Environmental variable as a phenological cue for settlement or metamorphosis	No apparent correlation to environmental variable	1	H
	Temporal mismatches of lifecycle events - duration of spawning, breeding or moulting season	Continuous duration; >4 months	1	H – Mar-Nov in WCB (Duffy et al. 2022)
	Migration (seasonal and spawning)	Migration is common for the whole population	3	H – Migration in late summer from estuaries and then north to spawn in open waters
				Average score: 1.75
Physiology	Fat and muscle content (capacity for energy storage)	Intermediate	2	M – Interrupted feeding can result in mature fish not participating in spawning run (Duffy et al. 2022). If estuaries remain closed sea mullet can reabsorb gonads thereby delaying spawning
	Body size	Medium (20-100 cm)	2	H
	Metabolic capacity	Medium metabolic capacity	2	L
	Disease or parasite load	Low disease and parasite load	1	H – No known parasites

	Physiological tolerance and response curve	High tolerance	1	H – Can spawn in a wide range of temperatures, and survive in salinity levels of 0–80 ppt (Duffy et al. 2022)
	Oxygen sensitivity	Low sensitivity (<2 ml/l O ₂)	1	L – Assumed as estuarine species
				Average score: 1.5
Staff contact name: Dr Rodney Duffy and Amber Quinn			Total sensitivity score: 6.95	
Exposure: Since the 1970s the timing of sea mullet migrations in the WCB have shifted by 1-2 months (Duffy et al. 2022), potentially already showing adaptations to a changing climate. In general, sea mullet are very robust and able to tolerate a wide range of salinity and temperature conditions. As the species range extends to Shark Bay, and are globally distributed it is unlikely the changing conditions within CS will negatively impact the species.			Exposure score: 1	

Common name: Yellowfin whiting Species: <i>Sillago schomburgkii</i> Sensitivity attribute		Risk category (sensitivity and capacity to respond to change)		Comments - Level of certainty and data availability (H, M, L)
		Risk level	Score	
Abundance	Fecundity - egg production	>20,000 eggs per year	1	H
	Recruitment period – successful recruitment event that sustains the abundance of the fishery	Consistent recruitment events every 1–2 years	1	H
	Average age at maturity	≤2 years	1	H
	Generalist vs. specialist – food and habitat	Reliance on neither habitat or prey	1	H – Juveniles use a range of shallow habitats and adults school over sandy habitats
	Sensitivity to ocean acidification	Not shelled, but reliant on shelled species (as prey or habitat)	2	M
	Average score: 1.2			
Distribution	Capacity for larval dispersal or duration – hatching to settlement (benthic sp.), hatching to yolk sac re-adsorption (pelagic sp.)	2-8 weeks	2	M – Shallow and estuarine spawning may limit larval dispersal (Duffy et al. 2022)
	Capacity for adult/juvenile movement – lifetime range post-larval stage	10-1000 km	2	H – Low connectivity between populations separated by only 10's of km (Duffy et al. 2022)
	Physiological tolerance – latitudinal coverage of adult sp. As a proxy of environmental tolerance	10°-20° latitude	2	H
	Spatial availability of unoccupied habitat for most critical life stage - ability to shift distributional range	No unoccupied habitat; 0-2° latitude or longitude	3	M
	Average score: 2.25			
Phenology	Environmental variable as a phenological cue for spawning or breeding – cue include salinity, temperature, current, & freshwater flows	Strong correlation of spawning to environmental variable	3	H – Temperatures between 20–26°C (Smith et al. 2019)
	Environmental variable as a phenological cue for settlement or metamorphosis	No apparent correlation to environmental variable	1	M
	Temporal mismatches of lifecycle events - duration of spawning, breeding or moulting season	Continuous duration; >4 months	1	H – Nov-Mar in Perth metropolitan region
	Migration (seasonal and spawning)	No migration	1	M – No evidence of alongshore migration but adults may move out of estuaries to spawn (Duffy et al. 2022)
	Average score: 1.5			
Physiology	Fat and muscle content (capacity for energy storage)	Intermediate	2	L
	Body size	Medium (20–100 cm)	2	H
	Metabolic capacity	Medium metabolic capacity	2	L
	Disease or parasite load	Low disease and parasite load	1	H – No known parasites
	Physiological tolerance and response curve	High tolerance	1	H – Based on tolerances in estuarine conditions

	Oxygen sensitivity	Low sensitivity (<2 ml/l O ₂)	1	H – Based on tolerances in estuarine conditions
				Average score: 1.5
Staff contact name: Dr Rodney Duffy and Amber Quinn			Total sensitivity score: 6.45	
Exposure: Temperature appears to be an important factor for yellowfin whiting, with fish exhibiting slower growth rates in winter months in the WCB and spawning for longer periods in warmer areas of the species range. In recent years a range extension further south and a movement in the center of distribution have been observed, associated with a warming climate (Smith et al. 2019). It is likely yellowfin whiting will be positively impacted by climate change in CS if previously documented trends continue.			Exposure score: 1	

Common name: King George whiting Species: <i>Sillaginodes punctata</i> Sensitivity attribute		Risk category (sensitivity and capacity to respond to change)		Comments - Level of certainty and data availability (H, M, L)
		Risk level	Score	
Abundance	Fecundity - egg production	>20,000 eggs per year	1	H
	Recruitment period – successful recruitment event that sustains the abundance of the fishery	Occasional and variable recruitment period	2	H – Based on nearshore recruitment index (Brown et al. 2013)
	Average age at maturity	2-10 years	2	H
	Generalist vs. specialist – food and habitat	Reliance on neither habitat or prey	1	H – Although the species is known to use different habitats at different life stages
	Sensitivity to ocean acidification	Not shelled, but reliant on shelled species (as prey or habitat)	2	H – Based on diet
	Average score: 1.6			
Distribution	Capacity for larval dispersal or duration – hatching to settlement (benthic sp.), hatching to yolk sac re-adsorption (pelagic sp.)	>2 months	1	H
	Capacity for adult/juvenile movement – lifetime range post-larval stage	10-1000 km	2	H
	Physiological tolerance – latitudinal coverage of adult sp. As a proxy of environmental tolerance	<10° latitude	3	H
	Spatial availability of unoccupied habitat for most critical life stage - ability to shift distributional range	No unoccupied habitat; 0-2° latitude or longitude	3	H
	Average score: 2.25			
Phenology	Environmental variable as a phenological cue for spawning or breeding – cue include salinity, temperature, current, & freshwater flows	Weak correlation of spawning to environmental variable	2	M – Winter spawners which spawn in the WCB later than in SA
	Environmental variable as a phenological cue for settlement or metamorphosis	Weak correlation to environmental variable	2	L – Settle in shallow habitats, estuaries and marine embayments
	Temporal mismatches of lifecycle events - duration of spawning, breeding or moulting season	Wide duration; 2-4 months	2	H – Predominantly May-Aug in WCB
	Migration (seasonal and spawning)	No migration	1	L – Recruitment in WCB thought to be localized, but some evidence that King George whiting may be capable of moving long distances to spawn (Brown et al. 2013)
	Average score: 1.75			
Physiology	Fat and muscle content (capacity for energy storage)	Intermediate	2	L – No data
	Body size	Medium (20–100 cm)	2	H
	Metabolic capacity	Medium metabolic capacity	2	M
	Disease or parasite load	Low disease and parasite load	1	M

	Physiological tolerance and response curve	High tolerance	1	M – Based on tolerance of estuarine environments
	Oxygen sensitivity	Low sensitivity (<2 ml/l O ₂)	1	M – Assumed based on tolerance of estuarine conditions
				Average score: 1.5
Staff contact name: Dr Rodney Duffy and Amber Quinn			Total sensitivity score: 7.1	
Exposure: King George whiting are generally a south coast species with CS near the northern edge of the species range for recruitment (Jurien Bay). The species exhibited strong recruitment in Mangles Bay in 1999, 2000 and 2008 which were years of strong Leeuwin Current (Brown et al. 2013). Projected weakening of the Leeuwin Current may negatively impact recruitment. In south-eastern Australia strong recruitment has been correlated with warmer SST and associated with increased larval growth and survival rates (Brown et al. 2013). In addition, the species is reliant on seagrass as nursery habitats, and it is possible that further seagrass loss due to MHWs within CS could be important for this species. Therefore, within CS the species may be negatively impacted by climate change, although there are limited data for this species on the west coast.			Exposure score: 4	

Common name: Tailor Species: <i>Pomamtomus saltatrix</i> Sensitivity attribute		Risk category (sensitivity and capacity to respond to change)		Comments - Level of certainty and data availability (H, M, L)
		Risk level	Score	
Abundance	Fecundity - egg production	>20,000 eggs per year	1	H
	Recruitment period – successful recruitment event that sustains the abundance of the fishery	Occasional and variable recruitment period	2	H – In Perth metropolitan region winter recruitment highly variable, whereas summer recruitment more stable year to year (Smith et al. 2013)
	Average age at maturity	≤2 years	1	H
	Generalist vs. specialist – food and habitat	Reliance on neither habitat or prey	1	H
	Sensitivity to ocean acidification	Not shelled and no reliance on shelled species	1	H
	Average score: 1.2			
Distribution	Capacity for larval dispersal or duration – hatching to settlement (benthic sp.), hatching to yolk sac re-adsorption (pelagic sp.)	2–8 weeks	2	H - ~25-28 days (Smith et al. 2013)
	Capacity for adult/juvenile movement – lifetime range post-larval stage	10-1000 km	2	H – Northward and southward adult migrations >600 km (Smith et al. 2013)
	Physiological tolerance – latitudinal coverage of adult sp. As a proxy of environmental tolerance	10-20° latitude	2	H – Exmouth to Augusta
	Spatial availability of unoccupied habitat for most critical life stage - ability to shift distributional range	No unoccupied habitat; 0-2° latitude or longitude	3	H - Highly mobile and utilize a range of habitats
Average score: 2.25				
Phenology	Environmental variable as a phenological cue for spawning or breeding – cue include salinity, temperature, current, & freshwater flows	Weak correlation of spawning to environmental variable	2	M – Spawning associated with water temperatures of 18-24°C (Smith et al. 2013)
	Environmental variable as a phenological cue for settlement or metamorphosis	No apparent correlation to environmental variable	1	M
	Temporal mismatches of lifecycle events - duration of spawning, breeding or moulting season	Continuous duration; >4 months	1	H – 1-2 distinct cohorts per year
	Migration (seasonal and spawning)	Migration is common for some of the population	2	M – Migration occurs on the east coast but the strength of migration on the west coast is uncertain
Average score: 1.5				
Physiology	Fat and muscle content (capacity for energy storage)	High capacity	1	H – Inferred from variable body condition, especially those individuals within estuaries
	Body size	Medium (20-100 cm)	2	H
	Metabolic capacity	High metabolic capacity	1	M – Assumed from high growth rate and high activity levels

	Disease or parasite load	Low disease and parasite load	1	M
	Physiological tolerance and response curve	Low tolerance	3	L - Oceanic fish, with juveniles in estuaries. Prefers more saline water
	Oxygen sensitivity	Intermediate	2	L – Limited data
Average score: 1.67				
Staff contact name: Dr Rodney Duffy and Amber Quinn			Total sensitivity score: 6.62	
Exposure: The environmental factors important to tailor recruitment are poorly understood, and there are limited information on how tailor use CS as the area is not a key fishing ground for the species. Recruitment in the WCB including Perth metropolitan region is influenced by favourable dispersal conditions from northern spawning grounds in the Gascoyne Region. The range of tailor extends past Shark Bay, and therefore the species is not expected to be impacted by rising temperatures within CS. However, it is possible a weakening Leeuwin Current may impact recruitment in CS. The species does not appear to have increased in abundance at the south of the species range, and given the complexity of tailor recruitment in the Perth metropolitan region, it is difficult to predict what impact if any climate change may have on tailor within CS. The exposure is scored as a two, indicating some negative changes are possible.			Exposure score: 2	

Common name: West Australian seahorse Species: <i>Hippocampus subelongatus</i> Sensitivity attribute		Risk category (sensitivity and capacity to respond to change)		Comments - Level of certainty and data availability (H, M, L)
		Risk level	Score	
Abundance	Fecundity - egg production	100-20,000 eggs per year	2	H – Multiple broods per season of 31-639 per brood
	Recruitment period – successful recruitment event that sustains the abundance of the fishery	Consistent recruitment events every 1-2 years	1	H
	Average age at maturity	≤2 years	1	H – 9-12 months (Moore 2001)
	Generalist vs. specialist – food and habitat	Reliance on either habitat or prey	2	H – Estuaries, rocky reefs, seagrasses and artificial habitats
	Sensitivity to ocean acidification	Not shelled, but reliant on shelled species (as prey or habitat)	2	H – Primarily crustacean diet (Kendrick & Hyndes 2005)
Average score: 1.6				
Distribution	Capacity for larval dispersal or duration – hatching to settlement (benthic sp.), hatching to yolk sac re-adsorption (pelagic sp.)	<2 weeks or no larval stage	3	H
	Capacity for adult/juvenile movement – lifetime range post-larval stage	<10 km	3	H – Home range size <100 m ²
	Physiological tolerance – latitudinal coverage of adult sp. As a proxy of environmental tolerance	<10° latitude	3	H - Augusta – Shark Bay
	Spatial availability of unoccupied habitat for most critical life stage - ability to shift distributional range	No unoccupied habitat; 0-2° latitude or longitude	3	L – Patchily distributed with three strongholds (Shark Bay, Swan Estuary and CS)
Average score: 3				
Phenology	Environmental variable as a phenological cue for spawning or breeding – cue include salinity, temperature, current, & freshwater flows	Weak correlation of spawning to environmental variable	2	M – Although breeding season varies with environmental conditions, and difficulty spawning in captivity may be due to lack of environmental cues (Moore 2001)
	Environmental variable as a phenological cue for settlement or metamorphosis	No apparent correlation to environmental variable	1	M
	Temporal mismatches of lifecycle events - duration of spawning, breeding or moulting season	Continuous duration; >4 months	1	H
	Migration (seasonal and spawning)	No migration	1	H
Average score: 1.25				
Physiology	Fat and muscle content (capacity for energy storage)	Intermediate	2	L
	Body size	Small (<20 cm)	3	H – Although rarely up to 25 cm
	Metabolic capacity	Low metabolic capacity ³	3	L – Assumed from activity levels and size

	Disease or parasite load	Low disease and parasite load	1	L – Unknown
	Physiological tolerance and response curve	High tolerance	1	M – Estuarine species, although they will abandon the Swan Estuary in the winter (Moore 2001)
	Oxygen sensitivity	Low sensitivity (<2 ml/l O ₂)	1	L – Assumed from presence in Swan Estuary during summer months
Average score: 1.83				
Staff contact name: Dr Glenn Moore (Western Australian Museum)			Total sensitivity score: 7.68	
Exposure: Based on the species range, Augusta to Shark Bay, it is unlikely that warmer waters would be an issue for this species. While some syngnathids are very habitat specific, the West Australian seahorse uses a variety of habitats, including artificial structures, so may have low sensitivity to expected climate change related habitat changes within CS, such as seagrass die-offs following MHWs. Although the species range and habitat requirements suggest West Australian seahorse are unlikely to be negatively impacted by climate change, with so little known about the species this assessment may need revision as more is learnt about the species. For example, knowledge about the environmental requirements and tolerances of this species are limited, such as how it responds to extreme weather events which are likely to occur in CS in the future (i.e. MHWs, decreased salinity from unseasonal summer rainfall and river flow). Syngnathids, including West Australian seahorse, are highly specialised feeders (Kendrick & Hyndes 2005), which may have limited capacity to change feeding habits if climate change affects prey species. Should climate change negatively impact the West Australian seahorse population in CS, this could have a disproportionately high impact on the species, considering CS and Swan River supports the largest known populations of this species.			Exposure score: 2	

Common name: Spotted pipefish Species: <i>Stigmatopora argus</i> Sensitivity attribute		Risk category (sensitivity and capacity to respond to change)		Comments - Level of certainty and data availability (H, M, L)
		Risk level	Score	
Abundance	Fecundity - egg production	100-20,000 eggs per year	2	M – Maximum brood size 41 eggs, but spawns continuously once mature
	Recruitment period – successful recruitment event that sustains the abundance of the fishery	Consistent recruitment events every 1-2 years	1	H – Continuous recruitment
	Average age at maturity	≤2 years	1	H – age at maturity is 35 days
	Generalist vs. specialist – food and habitat	Reliance on either habitat or prey	2	H – Predominantly seagrass meadows
	Sensitivity to ocean acidification	Not shelled, but reliant on shelled species (as prey or habitat)	2	H – Primarily crustaceans
				Average score: 1.6
Distribution	Capacity for larval dispersal or duration – hatching to settlement (benthic sp.), hatching to yolk sac re-adsorption (pelagic sp.)	<2 weeks or no larval stage	3	L
	Capacity for adult/juvenile movement – lifetime range post-larval stage	<10 km	3	M
	Physiological tolerance – latitudinal coverage of adult sp. As a proxy of environmental tolerance	10-20° latitude	2	H – Shark Bay to Tasmania
	Spatial availability of unoccupied habitat for most critical life stage - ability to shift distributional range	No unoccupied habitat; 0-2° latitude or longitude	3	L
				Average score: 2.75
Phenology	Environmental variable as a phenological cue for spawning or breeding – cue include salinity, temperature, current, & freshwater flows	No apparent correlation of spawning to environmental variable	1	M – Continuous spawning
	Environmental variable as a phenological cue for settlement or metamorphosis	No apparent correlation to environmental variable	1	M
	Temporal mismatches of lifecycle events - duration of spawning, breeding or moulting season	Continuous duration; >4 months	1	H
	Migration (seasonal and spawning)	No migration	1	M – Although the movement of individuals from narrow leaved to broad leaved seagrass habitats has been reported (Kendrick & Hyndes 2003)
				Average score: 1
Physiology	Fat and muscle content (capacity for energy storage)	Low energy storage (income breeder)	3	L – Assumed from continuous breeder with short lifespan
	Body size	Small (<20 cm)	3	M – maturity size ~13 cm but can reach 26 cm
	Metabolic capacity	High metabolic capacity	1	L – Assumed based on rapid growth rate of 2 mm d ⁻¹ (Parkinson & Booth 2016)

	Disease or parasite load	Low disease and parasite load	1	L - Unknown
	Physiological tolerance and response curve	Medium tolerance	2	L
	Oxygen sensitivity	Intermediate (2–5 ml/l O ₂)	2	L
				Average score: 2
Staff contact name: Dr Glenn Moore (Western Australian Museum)			Total sensitivity score: 7.35	
Exposure: Spotted pipefish have been observed in Shark Bay, suggesting they are able to tolerate considerably warmer temperatures than CS. However, increased frequency and intensity of MHWs, which have caused seagrass die-offs in CS could reduce the amount of suitable habitat for this species. Spotted pipefish short life cycle and early maturation mean the species is well suited to rapid recolonisation and population increases once seagrass bed recover (Parkinson & Booth 2016). Syngnathids, including spotted pipefish, are highly specialised feeders (Kendrick & Hyndes 2005), which may have limited capacity to change feeding habits if climate change affects prey species.			Exposure score: 2	

Common name: Little penguin Species: <i>Eudyptula minor</i> Sensitivity attribute		Risk category (sensitivity and capacity to respond to change)		Comments - Level of certainty and data availability (H, M, L)
		Risk level	Score	
Abundance	Fecundity - egg production	<100 eggs per year	3	H - <4 eggs per year
	Recruitment period – successful recruitment event that sustains the abundance of the fishery	Occasional and variable recruitment period	2	H – Failed breeding likely when conditions are unsuitable
	Average age at maturity	2-10 years	2	H – 2-3 years
	Generalist vs. specialist – food and habitat	Reliance on either habitat or prey	2	H – Generalist feeder but require food within 30 km of colony and there are limited nesting sites within WA
	Sensitivity to ocean acidification	Not shelled and no reliance on shelled species	1	H
	Average score: 2			
Distribution	Capacity for larval dispersal or duration – hatching to settlement (benthic sp.), hatching to yolk sac re-adsorption (pelagic sp.)	<2 weeks or no larval stage	3	H
	Capacity for adult/juvenile movement – lifetime range post-larval stage	10-1000 km	2	H – Within CS adults will search <10 km from nest when rearing chicks
	Physiological tolerance – latitudinal coverage of adult sp. As a proxy of environmental tolerance	<10° latitude	3	H
	Spatial availability of unoccupied habitat for most critical life stage - ability to shift distributional range	No unoccupied habitat; 0-2° latitude or longitude	3	H – Fidelity to nest sites
Average score: 2.75				
Phenology	Environmental variable as a phenological cue for spawning or breeding – cue include salinity, temperature, current, & freshwater flows	Weak correlation of spawning to environmental variable	2	H – Penguin Island breeding more successful in cooler years (Cannell et al. 2012). High SST in autumn and high turbidity have been observed to interrupt breeding in Garden and Penguin Island colonies
	Environmental variable as a phenological cue for settlement or metamorphosis	NA	NA	
	Temporal mismatches of lifecycle events - duration of spawning, breeding or moulting season	Continuous duration; >4 months	1	M – Breeding in May-Nov, with eggs laid Jun-Sep the most successful
	Migration (seasonal and spawning)	Migration is common for the whole population	3	L – Juveniles movements are unknown until they return sexually mature, and temporary migration of adults post-moult may occur.
Average score: 2				

Physiology	Fat and muscle content (capacity for energy storage)	High fat and muscle content (capacity breeder)	1	H – (Joly et al. 2023)
	Body size	Medium (20–100 cm)	2	H
	Metabolic capacity	High metabolic capacity	1	H
	Disease or parasite load	Medium disease and parasite load	2	M – Mortality attributed to parasites is observed (Cannell et al. 2016, 2023)
	Physiological tolerance and response curve	Low tolerance	3	M – High mortality during MHWs (Cannell et al. 2012). Low tolerance to air temperatures over 30°C (Clitheroe 2021)
	Oxygen sensitivity	NA	NA	
	Average score: 1.8			
Staff contact name: Dr Belinda Cannell (UWA)			Total sensitivity score: 8.55	
Exposure: Little penguins foraging within CS are at the edge of the species’ range and temperature tolerances. The recent MHWs in 1999 and 2011 caused a range of negative impacts on the Penguin Island and Garden Island colonies (summarised in case study 4.3.9). Since the 2011 MHW the population of the Penguin Island colony has decreased by 80% which has largely been attributed to the high mortality caused by the MHW and failed breeding during that season. The penguins are also highly susceptible to hyperthermia during incubation, with higher ambient air temperatures in the future also posing a significant risk during the nesting period. Finally, the little penguins are highly dependent on the availability of prey, which historically included multiple species (such as sandy sprat and southern garfish) which are themselves likely to be negatively impacted by climate change in CS.			Exposure score: 4	

Common name: Australian sea lion Species: <i>Neophoca cinerea</i> Sensitivity attribute		Risk category (sensitivity and capacity to respond to change)		Comments - Level of certainty and data availability (H, M, L)
		Risk level	Score	
Abundance	Fecundity - egg production	<100 eggs per year	3	H
	Recruitment period – successful recruitment event that sustains the abundance of the fishery	Consistent recruitment events every 1-2 years	1	H
	Average age at maturity	2-10 years	2	H
	Generalist vs. specialist – food and habitat	Reliance on neither habitat or prey	1	H
	Sensitivity to ocean acidification	Not shelled and no reliance on shelled species	1	M – Although crustaceans contribute to their diet
	Average score: 1.6			
Distribution	Capacity for larval dispersal or duration – hatching to settlement (benthic sp.), hatching to yolk sac re-adsorption (pelagic sp.)	<2 weeks or no larval stage	3	H
	Capacity for adult/juvenile movement – lifetime range post-larval stage	10-1000 km	2	H – Males using Carnac Island thought to be from Jurien Bay region (Campbell 2005)
	Physiological tolerance – latitudinal coverage of adult sp. As a proxy of environmental tolerance	<10° latitude	3	M – Houtman Abrolhos to South Australia
	Spatial availability of unoccupied habitat for most critical life stage - ability to shift distributional range	Substantial unoccupied habitat; >6° latitude or longitude	1	M – Previous range more extensive prior to hunting (Campbell 2005)
Average score: 2.25				
Phenology	Environmental variable as a phenological cue for spawning or breeding – cue include salinity, temperature, current, & freshwater flows	No apparent correlation of spawning to environmental variable	1	M – Asynchronous 17.5-month breeding cycle (Campbell 2005)
	Environmental variable as a phenological cue for settlement or metamorphosis	NA	NA	
	Temporal mismatches of lifecycle events - duration of spawning, breeding or moulting season	Wide duration; 2-4 months	2	L – Although Carnac Island is no longer a breeding site
	Migration (seasonal and spawning)	Migration is common for some of the population	2	H – Migrating males predominantly use Carnac Island
Average score: 1.66				
Physiology	Fat and muscle content (capacity for energy storage)	High fat and muscle content (capacity breeder)	1	H
	Body size	Large (>100 cm)	1	H
	Metabolic capacity	High metabolic capacity	1	H
	Disease or parasite load	Medium disease and parasite load	2	M – Disease and illness causes significant mortality in pups (Campbell 2005)
	Physiological tolerance and response curve	Medium tolerance	2	L
	Oxygen sensitivity	NA	NA	

	Average score: 1.4
Staff contact name:	Total sensitivity score: 6.91
<p>Exposure:</p> <p>There is limited research about how climate change may affect Australian sea lions, particularly within WA. A South Australian study observed an increase in SST of 1°C, resulting in lower pup survival (Goldsworthy et al. 2009), which is thought to relate to the foraging area being less productive during these warmer periods. Ocean currents influence prey availability, and its potential the weakening of the Leeuwin Current could be significant although no direct links have been observed (Schumann et al. 2013). Loss of habitat on low lying breeding sites has been identified as a risk by decreasing reproductive output of a colony (Goldsworthy et al. 2009), and this may be important for the WA population as a whole. While sea level rise may also reduce the available habitat on Carnac Island for males to haulout on. Warmer summers during the breeding season may also increase pup mortality due to dehydration and heat stress (Goldsworthy et al. 2009). As the Perth metropolitan sea lions are part of the Jurien Bay population, which is near the northern limit of the species range, increased mortality may in turn reduce the number of males using Carnac Island and CS. Goldworth et al. (2009) assessed the likelihood of climate change impacts on the species to be high and the potential consequences to be severe, however, acknowledge that there is a high degree of uncertainty. Determining the exposure score for this current risk assessment, a negative impact of climate change is possible, but changes in the number and health of sea lions using CS will likely reflect the impacts of climate change on the wider population rather than relate to conditions within CS.</p>	Exposure score: 3

Common name: Indo-Pacific bottlenose dolphin Species: <i>Tursiops aduncus</i> Sensitivity attribute		Risk category (sensitivity and capacity to respond to change)		Comments - Level of certainty and data availability (H, M, L)
		Risk level	Score	
Abundance	Fecundity - egg production	<100 eggs per year	3	H
	Recruitment period – successful recruitment event that sustains the abundance of the fishery	Occasional and variable recruitment period	2	H
	Average age at maturity	2-10 years	2	H
	Generalist vs. specialist – food and habitat	Reliance on neither habitat or prey	1	H – Although preference for seagrass habitats in CS
	Sensitivity to ocean acidification	Not shelled and no reliance on shelled species	1	H
				Average score: 1.8
Distribution	Capacity for larval dispersal or duration – hatching to settlement (benthic sp.), hatching to yolk sac re-adsorption (pelagic sp.)	<2 weeks or no larval stage	3	H
	Capacity for adult/juvenile movement – lifetime range post-larval stage	10-1000 km	2	H - ~300 km
	Physiological tolerance – latitudinal coverage of adult sp. As a proxy of environmental tolerance	>20° latitude	1	H
	Spatial availability of unoccupied habitat for most critical life stage - ability to shift distributional range	No unoccupied habitat; 0-2° latitude or longitude	3	H
				Average score: 2.25
Phenology	Environmental variable as a phenological cue for spawning or breeding – cue include salinity, temperature, current, & freshwater flows	Weak correlation of spawning to environmental variable	2	M – Peak birth season in warmer months (summer/autumn)
	Environmental variable as a phenological cue for settlement or metamorphosis	NA	NA	
	Temporal mismatches of lifecycle events - duration of spawning, breeding or moulting season	Continuous duration; >4 months	1	H
	Migration (seasonal and spawning)	No migration	1	H – Subpopulation in CS year-round (Chabanne et al. 2017)
				Average score: 1.33
Physiology	Fat and muscle content (capacity for energy storage)	High fat and muscle content (capacity breeder)	1	H
	Body size	Large (>100 cm)	1	H
	Metabolic capacity	High metabolic capacity	1	H
	Disease or parasite load	Medium disease and parasite load	2	L – Cetacean morbillivirus potentially emerging disease in Perth populations (Stephens et al. 2014), having appeared in 2009 and 2019
	Physiological tolerance and response curve	High tolerance	1	H
	Oxygen sensitivity	NA	NA	
				Average score: 1.2

Staff contact name: Dr Delphine Chabanne (Murdoch University)	Total sensitivity score: 6.58
<p>Exposure: Indo-Pacific bottlenose dolphins have an extensive distribution north of CS and are unlikely to be directly impacted by warming water temperatures. However, elsewhere within WA bottlenose dolphins have been negatively impacted by changes in habitat and food availability brought about by MHWs (Wild et al. 2019). Within CS, changes to the extent of seagrass habitat in particular, which had widespread die-off during the 2011 MHW, could reduce the amount of foraging area and prey availability for the resident CS bottlenose dolphins. The Bunbury resident bottlenose dolphins were also observed to temporarily emigrate when prey became less available during an El Niño event (Sprogis et al. 2018). There is the possibility that similar environmental changes in CS could cause temporary migrations out of CS for the resident population. As bottlenose dolphins are long-lived, slow-reproducing and with long generation times, this species may be slow to adapt to changing conditions.</p>	Exposure score: 3

7.3 Appendix 3

Sensitivity scores for invasive marine species

For each sensitivity attribute, each species was scored based on the risk levels described in Table 2 and Fulton et al. (2020). Exposure was scored based on the levels outlined in Table 3.

Common name: Asian green mussel Species: <i>Perna viridis</i>		Risk category (sensitivity and capacity to respond to change)		Comments - Level of certainty and data availability (H, M, L)
Sensitivity attribute		Risk level	Score	
Abundance	Fecundity - egg production	>20,000 eggs per year	1	H
	Recruitment period – successful recruitment event that sustains the abundance of the fishery	Consistent recruitment events	1	H
	Average age at maturity	≤2 years	1	H
	Generalist vs. specialist – food and habitat	Reliance on neither habitat or prey	1	H
	Sensitivity to ocean acidification	Shelled species	3	H
Average score: 1.4				
Distribution	Capacity for larval dispersal or duration – hatching to settlement (benthic sp.), hatching to yolk sac re-adsorption (pelagic sp.)	2-8 weeks	2	H
	Capacity for adult/juvenile movement – lifetime range post-larval stage	<10 km once settled.	3	H
	Physiological tolerance – latitudinal coverage of adult sp. As a proxy of environmental tolerance	>20° latitude	1	H
	Spatial availability of unoccupied habitat for most critical life stage - ability to shift distributional range	Limited unoccupied habitat; 2-6° latitude or longitude	2	M
Average score: 2.0				
Phenology	Environmental variable as a phenological cue for spawning or breeding – cue include salinity, temperature, current, & freshwater flows	Strong correlation of spawning to environmental variable	3	H
	Environmental variable as a phenological cue for settlement or metamorphosis	No apparent correlation to environmental variable	1	H
	Temporal mismatches of lifecycle events - duration of spawning, breeding or moulting season	Wide duration; 2-4 months	2	H
	Migration (seasonal and spawning)	No migration	1	H
Average score: 1.75				
Physiology	Fat and muscle content (capacity for energy storage)	Intermediate	2	M - Ability to survive in low nutrient environments e.g. on vessels
	Body size	Small (<20 cm)	3	H
	Metabolic capacity	High metabolic capacity	1	H - Fast growth rate
	Disease or parasite load	Medium disease and parasitic load	2	H
	Physiological tolerance and response curve	High tolerance	1	H
	Oxygen sensitivity	Intermediate (2-5 ml/O ₂)	2	H
Average score: 1.83				
Staff contact name: Claire Wellington			Total sensitivity score: 6.98	
Exposure: Asian green mussels have a wide tolerance range in salinity and temperature in their native range, and as a tropical species, are likely to adapt to increasing temperature shift across a broad latitudinal range. Opportunistic introduction into new, suitable environments may facilitate establishment as Asian green mussels have a high tolerance to contaminants.			Exposure score: 1	

Common name: Charru mussel Species: <i>Mytella strigata</i> Sensitivity attribute		Risk category (sensitivity and capacity to respond to change)		Comments - Level of certainty and data availability (H, M, L)
		Risk level	Score	
Abundance	Fecundity - egg production	>20,000 eggs per year	1	H
	Recruitment period – successful recruitment event that sustains the abundance of the fishery	Consistent recruitment events	1	H
	Average age at maturity	≤2 years	1	H
	Generalist vs. specialist – food and habitat	Reliance on neither habitat or prey	1	H
	Sensitivity to ocean acidification	Shelled species	3	H
	Average score: 1.4			
Distribution	Capacity for larval dispersal or duration – hatching to settlement (benthic sp.), hatching to yolk sac re-adsorption (pelagic sp.)	2-8 weeks	2	H
	Capacity for adult/juvenile movement – lifetime range post-larval stage	<10 km once settled	3	H
	Physiological tolerance – latitudinal coverage of adult sp. As a proxy of environmental tolerance	>20° latitude	1	H
	Spatial availability of unoccupied habitat for most critical life stage - ability to shift distributional range	Limited unoccupied habitat 2-6° latitude or longitude	2	M
Average score: 2.0				
Phenology	Environmental variable as a phenological cue for spawning or breeding – cue include salinity, temperature, current, & freshwater flows	Strong correlation of spawning to environmental variable	3	H
	Environmental variable as a phenological cue for settlement or metamorphosis	No apparent correlation to environmental variable	1	H
	Temporal mismatches of lifecycle events - duration of spawning, breeding or moulting season	Wide duration; 2-4 months	2	H
	Migration (seasonal and spawning)	No migration	1	H
Average score: 1.75				
Physiology	Fat and muscle content (capacity for energy storage)	Intermediate	2	M
	Body size	Small (<20 cm)	3	H
	Metabolic capacity	High metabolic capacity	1	H - Fast growth rate
	Disease or parasite load	Medium disease and parasitic load	2	M
	Physiological tolerance and response curve	High tolerance	1	H
	Oxygen sensitivity	Intermediate (2-5 ml/O ₂)	2	H
Average score: 1.83				
Staff contact name: Claire Wellington			Total sensitivity score: 6.98	
Exposure: Charru mussels have a wide tolerance range in salinity and temperature, and as a tropical species, are likely to adapt to increasing temperature shift across a broad latitudinal range. The species were recently reported as a potential threat to aquaculture species Asian green mussel in southeast Asia where it competes for habitat and resources (Sanpanich & Wells 2019). Charru mussels form dense clusters colonising hard substrates as well as soft sediments and are a potential threat to native invertebrate species in invaded ranges.			Exposure score: 1	

Common name: Asian paddle crab Species: <i>Charybdis japonica</i>		Risk category (sensitivity and capacity to respond to change)		Comments - Level of certainty and data availability (H, M, L)
Sensitivity attribute		Risk level	Score	
Abundance	Fecundity - egg production	>20,000 eggs per year	1	H
	Recruitment period – successful recruitment event that sustains the abundance of the fishery	Consistent recruitment events every 1-2 years	1	H
	Average age at maturity	≤2 years	1	H
	Generalist vs. specialist – food and habitat	Reliance on neither habitat or prey	1	H
	Sensitivity to ocean acidification	Shelled species	3	H
	Average score: 1.4			
Distribution	Capacity for larval dispersal or duration – hatching to settlement (benthic sp.), hatching to yolk sac re-adsorption (pelagic sp.)	2-8 weeks	2	H
	Capacity for adult/juvenile movement – lifetime range post-larval stage	10-1000 km	2	L - Inhabit a wide distribution in their native range
	Physiological tolerance – latitudinal coverage of adult sp. As a proxy of environmental tolerance	>20° latitude	1	H
	Spatial availability of unoccupied habitat for most critical life stage - ability to shift distributional range	Limited unoccupied habitat 2-6° latitude or longitude	2	M - Aggressive competitor
Average score: 1.75				
Phenology	Environmental variable as a phenological cue for spawning or breeding – cue include salinity, temperature, current, & freshwater flows	No apparent correlation of spawning to environmental variable	1	M
	Environmental variable as a phenological cue for settlement or metamorphosis	Weak correlation to environmental variable	2	H
	Temporal mismatches of lifecycle events - duration of spawning, breeding or moulting season	Wide duration; 2-4 months	2	H
	Migration (seasonal and spawning)	No migration	1	H
Average score: 1.5				
Physiology	Fat and muscle content (capacity for energy storage)	High fat and muscle content (capital breeder)	1	M
	Body size	Small (<20 cm)	3	H
	Metabolic capacity	High metabolic capacity	1	H
	Disease or parasite load	Medium disease and parasitic load	2	H
	Physiological tolerance and response curve	High tolerance	1	M
	Oxygen sensitivity	Intermediate (2-5 ml/O ₂)	2	L - No direct reference
Average score: 1.67				
Staff contact name: Claire Wellington			Total sensitivity score: 6.32	
Exposure: Poleward range expansions have been recorded for native <i>Charybdis</i> species in WA facilitated by La Nina events (Hewitt et al. 2018). The Asian paddle crab has a broad distribution and temperature tolerance range likely to adapt to climate shifts related to temperature. Despite individual specimens recorded in the Swan-Canning Estuary, no viable populations have been observed in WA. It is considered an aggressive swimming crab, capable of out competing other crab species in both resources and habitat.			Exposure score: 1	

Common name: Carpet sea squirt Species: <i>Didemnum vexillum</i>		Risk category (sensitivity and capacity to respond to change)		Comments - Level of certainty and data availability (H, M, L)
Sensitivity attribute		Risk level	Score	
Abundance	Fecundity - egg production	>20,000 eggs per year	1	H - Capable of sexual & asexual reproduction
	Recruitment period – successful recruitment event that sustains the abundance of the fishery	Consistent recruitment events every 1-2 years	1	H
	Average age at maturity	≤2 years	1	H
	Generalist vs. specialist – food and habitat	Reliance on neither habitat or prey	1	H
	Sensitivity to ocean acidification	Not shelled and no reliance on shelled species	1	H
	Average score: 1.0			
Distribution	Capacity for larval dispersal or duration – hatching to settlement (benthic sp.), hatching to yolk sac re-adsorption (pelagic sp.)	2-8 weeks	2	H
	Capacity for adult/juvenile movement – lifetime range post-larval stage	<10 km	3	H - However, fragmentation can extend dispersal range
	Physiological tolerance – latitudinal coverage of adult sp. As a proxy of environmental tolerance	>20° latitude	1	H
	Spatial availability of unoccupied habitat for most critical life stage - ability to shift distributional range	Substantial unoccupied habitat; >6° latitude or longitude	1	H - Ability to colonise wide range of habitats
Average score: 1.75				
Phenology	Environmental variable as a phenological cue for spawning or breeding – cue include salinity, temperature, current, & freshwater flows	Strong correlation of spawning to environmental variable	3	H
	Environmental variable as a phenological cue for settlement or metamorphosis	Weak correlation of spawning to environmental variable	2	H
	Temporal mismatches of lifecycle events - duration of spawning, breeding or moulting season	Continuous duration; >4 months	1	H
	Migration (seasonal and spawning)	No migration	1	H
Average score: 1.75				
Physiology	Fat and muscle content (capacity for energy storage)	Intermediate	2	M
	Body size	Small (<20 cm)	3	H - Although colony sizes can grow much larger
	Metabolic capacity	High metabolic capacity	1	H - Fast growth rate
	Disease or parasite load	Low disease and parasitic load	1	M
	Physiological tolerance and response curve	High tolerance	1	M
	Oxygen sensitivity	Intermediate (2-5 ml/O ₂)	2	H
Average score: 1.67				
Staff contact name: Claire Wellington			Total sensitivity score: 6.17	
Exposure: Carpet sea squirt was recently detected, and found to be reproductive, in CS. The species has a field observed temperature tolerance of 1-24°C, although may tolerate higher temperatures (Herborg et al. 2009). As a temperate species, warmer conditions may negatively affect growth and reproduction, curtailing immediate and northern range expansion. However, vessel mediated transport remains a high-			Exposure score: 2	

risk enabling introduction of the species to southern temperate waters where conditions may also be favourable.	
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